

Data Centers

Staying On-line: Data Center Commissioning

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Data centers require tight coordination between the trades, special consideration for redundancy and reliability, and carefully scripted commissioning of systems. Consider, for example, the issue of redundancy. For non-critical commercial facilities, the design for redundancy typically is approached on an equipment basis.

For example, in a chilled water plant with a 1,000 ton (3517 kW) load, three 500 ton (1760 kW) chillers may be provided to meet the requirement of N+1 redundancy. With this design, in theory, any chiller can be pulled out of service and the plant can continue to serve the design load. With an office building, this simplistic view of redundancy may be sufficient. Failure to meet the design load merely causes an inconvenience to tenants; it does not compromise the core business.

With data centers and other mission critical facilities, engineers are challenged

to think in terms of system failures, and more sophisticated techniques are required to analyze critical links. In our previous example, consider the failure of an electrical panel that serves two or all three of the chillers. Although the chillers were designed for N+1 redundancy, a failure of the electrical feed to more than one chiller can shut down the data center.

As compared to the office building, the risk of failure in data centers is compounded by several issues: 1) with high density loads, the time for recovery from equipment or system failure is much shorter; 2) the cost of failure is much higher; and, 3) as loads may cluster within any group of racks, redundancy must be provided in the “downstream” distribution system as well as the central plant.

This article presents a process that can be used to review and test the system design to achieve a high degree of system reliability. It also emphasizes the importance of close

coordination required in the design of the electrical, mechanical and control systems and summarizes the experience of two firms (one mechanical and one electrical) that have collaborated in the design and commissioning of many data centers.

A Commissioning Process

This article cannot comprehensively cover all of the steps in commissioning a data center, but it highlights the four key steps and provides examples from real projects for each. These steps are:

- Design review;
- Preparation for functional testing;

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- Implementation of the functional tests; and
- Review of trends and tests.

Obviously, these steps are part of an iterative process that must react to problems uncovered in the field. In our experience, no script can cover all of the contingencies that include field installation, control sequences, equipment internal controls and configuration, unit delays and unanticipated issues uncovered in the commissioning process.

Design Review

Whether acting as a third-party commissioning agent or as the engineers of record, we have found a peer review (either internal or external) by someone other than the actual designer to be an important part of the design process.

Having outside eyes take a fresh look at the design often uncovers design contingencies that the designer had not considered. In addition to the normal items under a peer review, a review of a data center must carefully consider failure modes, operation at part load and coordination of controls as discussed in the following paragraphs.

Failure Modes: Both the designer and reviewer need to consider what will happen on failure of any piece of equipment or support system. Data center support systems are complex and interwoven: the mechanical, electrical and control systems must be reviewed as a whole since failure in any one may cascade to failures in the others.

For instance, loss of utility power in a data center will cause the emergency generator systems to come on-line. The mechanical design must consider not only the continuation of cooling throughout the process but also the power-off and restart sequences of the mechanical

equipment to prevent overloading the generator when it comes on-line.

This is complicated by the internal lockout of mechanical cooling equipment, which might prevent or delay restart of a chiller or direct expansion (DX) unit if it fails on loss of power. Often the settings on these internal delays (or the number of restarts) have to be adjusted for fail-safe operation.

Many branches of engineering, including aerospace, materials science and industrial, provide formal training in the field of failure analysis. A brief Web search on “failure analysis” or “reliability analysis” results in a range of university programs, magazines, consulting firms and software. Unfortunately in the HVAC industry, we have little formal training, guidance or tools geared for this work.

Chapter 17, “Data Processing and Electronic Office Areas,” of the *2003 ASHRAE Handbook—HVAC Applications* simply states,

“System reliability is so vital that the potential cost of system failure may justify redundant systems, capacity, and/or components. The designer should identify potential points of failure that could cause the system to interrupt critical data processing applications and should provide redundant or back-up systems.”

Although the statement is true, the means for analyzing the modes of failure are not presented in the ASHRAE handbooks or guidelines.*

A rigorous analysis of system reliability requires statistical modeling of components and systems combined with a method of stepping through the array

*ASHRAE TC 9.9, Mission Critical Facilities, Technology Spaces and Electronic Equipment, is making a major revision to this Handbook chapter.

of possible fault propagation modes such as Monte Carlo (www.geocities.com/CollegePark/Quad/2435/history.html) or Fault Tree Analysis (http://reliability.sandia.gov/Reliability/Fault_Tree_Analysis/fault_tree_analysis.html).

Most mechanical and electrical designers do not perform these kinds of analyses, either because their fees in a competitive marketplace do not allow it, or because they do not have the required experience to make use of statistical tools. Another barrier is the lack of historical statistical data on equipment failure, which is a required input to some of these programs.

A simple failure analysis can be done by hand or implemented in a spreadsheet. The process needs to be thorough and methodical. Using the example central plant shown in *Figure 1*, we can see what happens if the control panel CP-1 fails. CP-1 controls the primary chilled water pump PCHP-1. With failure of this panel the pump also fails.

Chiller CH-1, in turn, relies on PCHP-1 and detects its failure as a loss of flow. Consequently, CH-1 shuts down.

Chillers 1, 2 and 3 run lead/lag/standby with each chiller having 50% of total capacity. As a result of CH-1 shutting down, the remaining chillers CH-2 and CH-3 will run and can still provide 100% total capacity. The central plant, therefore, is able to provide the design capacity on failure of control panel CP-1.

A failure of CP-3, on the other hand, would shut down both of the condenser water pumps (CWP-1 and CWP-2). The lack of condenser water flow would prevent any of the three chillers from running, leaving the plant with 0% capacity. This clearly is a design flaw that needs to be fixed.

A spreadsheet can be automated to simulate failure of each piece of equipment in turn. As each piece of equipment

is failed in the automation, the software also should note the failure of dependent equipment (e.g., a chiller that relies on the operation of a condenser water pump), then test if the remaining equipment has sufficient capacity to supply 100% of the load. The simulation should flag any piece of equipment that results in less than 100% design capacity when failed. This discovery should lead to the redesign of the system (such as the condenser water pumps in the earlier example).

While using common sense to analyze failures is possible, some weak links may be overlooked. This simplistic analysis neither accounts for the timed lockout for chiller restart discussed previously, nor does it cover the event of coincident failures of more than one piece of equipment.

Part-Load Operation: With data centers, consideration of how the equipment unloads is important. Although the computer equipment within the center tends to run close to full load, most centers are phased in with racks being installed in groups over time. Furthermore, many of the assumptions for the expected load density change shortly after the data center becomes operational, or sometimes during construction. Because of this, most data centers are built either with future capacity already installed, or with provisions for future capacity to be added in later construction phases. During startup, systems usually are running at part-load.

The design of the equipment and systems supporting the data center must take into account part-load operation during the initial startup, and (as appropriate) uninterrupted operation as subsequent phases are built out. For initial startup of the data center and each subsequent phase of build-out, the cooling systems must be evaluated for their ability to stay on-line and the provision of redundancy.

For pumps, fans and compressors (chillers and DX units) the review should ensure proper unloading controls are specified, and that the part-load operation is well away from the surge regions. To prevent temperature fluctuations and premature equipment failure, compression cooling should operate at the lowest anticipated load levels without excessive cycling.

For cooling towers, the reviewer should ensure that the tower cells are designed for the highest and lowest anticipated flows with proper coverage of the fill. Variable speed fans or tower bypass should be considered to keep the condenser water temperature stable under low loads.

Controls: Successful control of data center systems requires careful coordination of the control design for the mechanical and electrical equipment. A successful power down restart se-

quence requires the generators to communicate to the mechanical control system the loss of power and subsequent readiness of the generators to accept load. The mechanical and electrical bid documents must be reviewed to ensure that all interconnections and associated sequences are fully specified, communication protocols are matched on each end, and that the scope of work for each contractor is clearly outlined. Even within a trade, care must be taken to coordinate the passage of information between equipment from various manufacturers.

Another issue to consider is provision of uninterruptible power supply (UPS) power to the control system panels. This generally can be provided at a low incremental cost because the control panels are low wattage devices. Uninterrupted power to the control panels can greatly improve the stability of systems during the power down restart sequences.

Preparation for Functional Testing

Functional Test Scripts: Functional test scripts like the example shown in *Figure 2* should be developed for each major piece of equipment, all control reset sequences, all equipment staging, and all anticipated failure scenarios. Note these scripts supplement and don't replace the system prefunctional tests (like hydronic pressure testing of the chilled water piping), contractor startup or control system commissioning (such as the point-to-point verification and testing of sequences).

The example in *Figure 2* is a test script for secondary chilled water pumps. These pumps are controlled with variable speed drives and are designed to operate in parallel for better redundancy.

Load Banks: As previously discussed, the data center generally will not be fully loaded during system startup and commissioning. In most

cases, the computer systems are installed into the racks during the final phases of construction or just after commissioning, but provide little or no heat load for system testing. Load banks typically are used to introduce heat loads and to allow simultaneous testing of both electrical and cooling systems.

Renting and operating load banks is costly, and introduce risk—if cooling fails, load banks can quickly overheat a space and potentially trigger sprinkler systems. This means that the time for using load banks and associated operators must be minimized. For large projects, a sufficient number of load banks must be reserved in advance to ensure availability.

The mechanical, electrical and control systems must all be ready to run when load banks arrive and the functional tests are to be run:

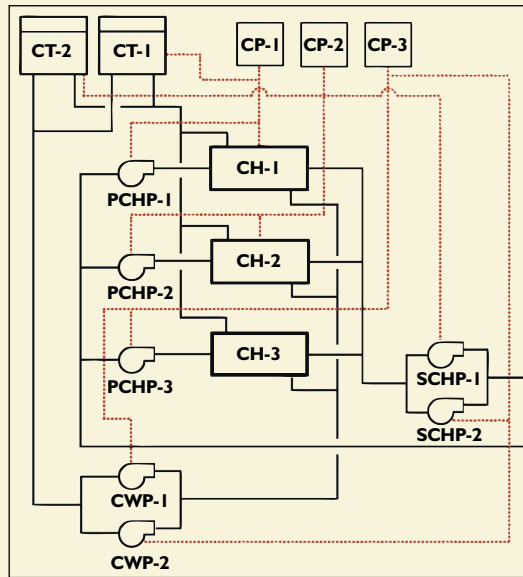


Figure 1: Schematic of example control plant.

A. Chilled Water System

1. Secondary chilled water pumps and associated VFDs:

a. Operation: Both pumps are designed to operate continuously. The control system shall modulate the speed of both pumps through the VFDs to control the differential pressure at the end of the piping system to a constant pressure setpoint.

b. Failure tests:

(1) Disconnect the differential pressure transmitter.

(a) Confirm that both pumps continue to operate at a constant speed (speed shall be per the last signal given).

(b) Confirm that the BAS is in alarm.

(c) Confirm that the owner's representative(s) have been paged.

(d) Confirm proper operation after the sensor has been reconnected.

(2) Disable the entire BAS (panels) in the building.

(a) Confirm that both pumps continue to operate at a constant speed (speed shall be per the last signal given).

(b) Confirm that the BAS is in alarm.

(c) Confirm that the owner's representative(s) have been paged.

(d) Confirm proper operation re-enabling the BAS in the building.

(3) Disable the BAS control panel serving the pump VFDs.

(a) Confirm that both pumps continue to operate at a constant speed (speed shall be per the last signal given).

(b) Confirm that the BAS is in alarm.

(c) Confirm that the owner's representative(s) have been paged.

(d) Confirm proper operation after re-enabling the control panel.

Figure 2: Functional test script for secondary chilled water pumps.

- The support systems, generators, UPS and power distribution systems must be complete.
- Control systems must be programmed and ready to trend equipment operation.
- Chillers and associated hydronic systems, as well as computer room air conditioner (CRAC) units, package units, DX systems and any other installed equipment must have completed startup and be ready for operation. Chillers will not stay on-line without significant load, so they can be run only once load banks are started.

Coordination of the Trades: Preparation for these tests is a multidisciplinary effort that requires input from both the design and construction teams. The functional tests cover not only individual pieces of equipment but also the entire integrated mechanical, electrical and control systems. Designers and contractors of these systems should provide input to the script well in advance of the scheduled commissioning dates.

We have found that holding regular commissioning meetings for several months before actual commissioning serves to raise awareness of critical issues in all of the team members. Engineers, owners, contractors and equipment vendors can use these meetings to agree on sequence of events, coordination of schedules and responsibilities of key players. Scheduling considerations should include these milestones:

- A date for power to all the mechanical and control systems;
- A final date for precommissioning of all systems, which includes the typical startup for each piece of equipment and testing of all control system wiring, I/O point status, programming, configuration of alarms and configuration of trending. The trends and alarms must be active during the functional tests.
- Arrival of load banks and duration of testing. Expected time to perform all testing, including:
 - Part-load and full-load (where possible) operation;
 - Sequenced failure of equipment, restart and return to

stable operation. This should be done for every piece of equipment;

- Automatic transfer switch (ATS) and UPS operation;
 - Generator operation; and
 - Complete power-down and automatic restart.
- Startup, prefunctional testing and functional testing of each system. The mechanical and controls contractors need to carefully coordinate the testing of their systems with the electrical contractors to ensure uninterrupted power is available during their tests. All three trades are typically testing their systems simultaneously.
 - Contingency time reserved for correction of errors and retesting.

Execution of Functional Tests

During the development of the functional test scripts a commissioning log should be created from the script that can be used to record the event. An example log is shown in *Figure 3*. This log should record the events that occur during testing in parallel with automatic monitoring and trend logs from control systems. Recorded information should include: date and time of testing, the participants, and the expected and actual outcomes for each test.

During testing, frequently unexpected results occur due to system attributes that were overlooked during design or introduced during construction. One such example is given in *Figure 3*. Test 1.b.3 illustrates the test of dual secondary chilled water pumps with variable speed drives. According to the control sequences, failing the control panel of the variable speed drives should result in maximum speed from both drives and a control system alarm to the operator.

Note that in this case, redundancy was designed not by providing separate control panels to both drives, but by allowing drives to run to maximum speed after loss of the control signal. As the actual test log shows, both drives initially went to zero speed and

Project:		Present:			
Eng:					
Date:					
Test No.	Pass/Fail	Time	Description	Variables	Result
1.b.3	Fail	June 28 12:04	Disable the BAS control panel serving the pump VFDs.		
			(a) Confirm that both pumps continue at constant speed.	speed=	0%
	Fail		(b) Confirm that the BAS is in alarm.	msg=	<none>
			(c) Confirm owner's representative(s) have been paged.		
	Fail		(d) Confirm operation after BAS has been reconnected.		
			Note that with eight different speeds, using three binary inputs at the drive. Two solutions exist:		
			(a) Never allow drives to be disabled during normal operation. Upon failure of panel, drive will no longer be enabled. Program drive to run to 60 Hz in this case. Drives should never be intentionally disabled during normal usage (there is no staging sequence), so the only disable command will occur on service. For service, the mechanic will switch local disconnect to "off" position. No drive disable through BAS is therefore ever required.		
			(b) Run a separate set of wires to each drive, using the second of three inputs on the drive, a failure condition can now be sensed in addition to an intentional disable command. The drive will then go to zero speed upon disable, 27 Hz on 0% speed input, and 60 Hz upon power failure at panel. This option is more elegant, but adds little effective functionality.		
	Fail	June 29 14:20	After resetting of drive interface, retest. Drives now go into error condition. Need to reprogram.		
	Fail	July 1 11:55	Drives remain in constant speed. However, after test (13:55), drives run to 0% speed before recovery. Need to adjust control program. See also test 5.b.9.		

Figure 3: Example of commissioning log used to record events that occurred during testing.

had to be reprogrammed twice on separate days to provide the desired response. Even then, the control system had to undergo some reprogramming to ensure the signal sent to the drives after restoration of the control panel did not disrupt operation.

This type of unanticipated failure underlines the need to test every piece of critical equipment. The iterative process of testing, noting failures, adjustment and retesting is required for reliable operation of critical systems. Sufficient time in the schedule needs to be allocated to allow correction of errors uncovered in testing, and subsequent retesting. In some cases, equipment may be operated in override mode, allowing other tests to proceed on schedule. In other cases, deficiencies may need to be corrected on site before tests can proceed.

It is important to have the right people on hand for every test so they can witness any failures and participate in the remediation and retesting. This includes the technicians from the associated trades, project managers, and the appropriate owner's representatives. This deployment needs to be carefully coordinated and scheduled well in advance.

For larger equipment such as chillers or UPS systems, factory representatives should also be on site for the tests. You often discover during the tests that reprogramming or reconfiguration of a piece of equipment is required to pass the test. For example, in one project the control contractor had landed the remote chilled water reset and demand limit signals on the chiller's control panel, but the chiller had not been programmed to look at the remote control inputs. Having the right people on site during the tests can significantly reduce the time for remediation and retesting.

Review of Trends and Tests

After functional testing is complete, the control system trend logs and error logs should be thoroughly analyzed. Many inter-related actions are only clear through review of trends since only a small fraction of system settings can be observed real-time during

the functional test. The loss of a chiller for example may have been caused by the loss of its chilled or condenser water pump. Since all three fail at once, the root cause may only become clear through review of the control system trends and the error logs from the chiller control panel and the variable speed drives.

Figure 4 depicts the chilled water equipment status and data center temperatures during functional testing of the generators and UPS systems. This figure shows two stages of generator testing: the first at 1,400 kW and the second 2,000 kW (the full build-out capacity of the data center in this phase of construction). This data center had not been fully built out, so complete testing at full load was not possible. Some of the electrical and mechanical equipment would not be installed until later phases of build-out. As a result, only the installed capacity could be tested.

For each stage of testing, there were two power outages for the chillers: when the power failed until the generator was brought on-line and again when the power was restored and the generator was switched off. Figure 4 shows progressive improvement in chiller restart and temperature control through these four events. This is due to changes in the control system programming (timing sequences) and tuning of the chiller restart delays. By the second tests, the chillers are barely off-line throughout the event.

In this example, the generator start sequence after a power outage could only be tested at part-load (only the first phase of data center build-out). The expected recovery time at full build-out and load was calculated using test results to ensure that room temperatures will not rise excessively. The temperature rise in the data center, as a result of the tested loads, is around 6°F (3°C) per minute. From this, the expected rise in temperature under full future load is calculated to be around 8°F (4.5°C) per minute, resulting in a maximum allowable downtime of two to three minutes for mechanical equipment. During the tests conducted, control systems and chiller controls were tuned to produce automatic restart of

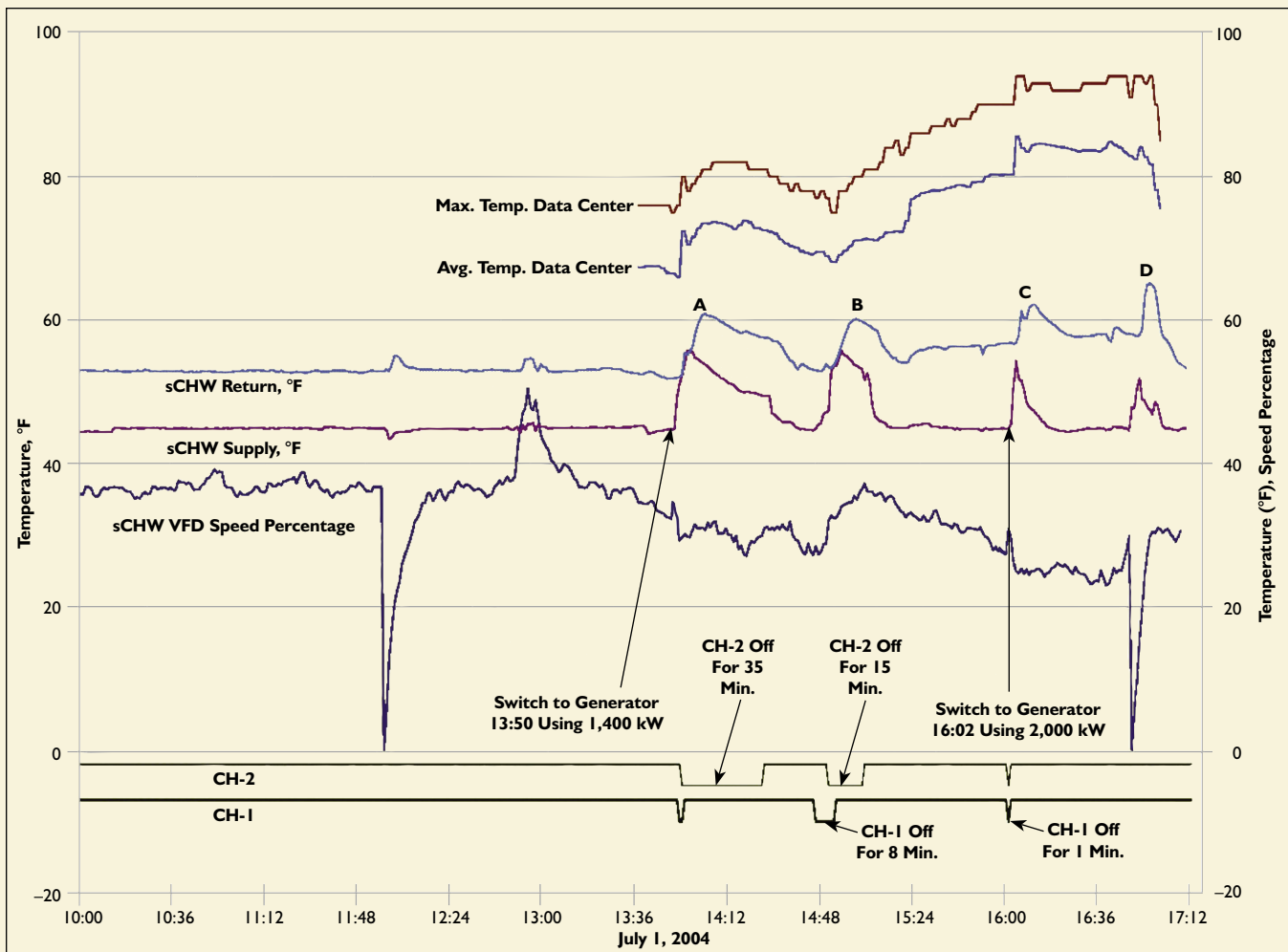


Figure 4: Trend report of functional testing of the generators and UPS systems.

all systems within two minutes after power failure, with a complete recovery to design conditions (pull-down) of about 10 minutes.

Documenting these results, and providing clear illustrations of errors encountered, provides not just a working system, but also valuable information for the facilities staff in running and maintaining the plant. It also provides better information than as-builts for future expansions and additional work.

Conclusion

In this article, we presented a process for the commissioning of the mechanical, electrical and control systems of a data center. Although the process is similar from project to project each design is unique and poses its own challenges. As discussed in this article, the design and commissioning of data centers requires a high level of coordination between the trades, not just the mechanical and electrical engineers but also the commissioning agent (if applicable), manufacturer's representatives and contractors. Reliability is possible but you have to be methodical in both design and testing. Keys to achieving this goal include:

- Examination and testing of the system redundancy;
- Strong collaboration between mechanical, electrical and controls trades;
- Clear and early communication with the construction team to schedule and coordinate the commissioning tests with equipment delivery, startup and control system installation;
- Testing of all major components and control sequences to ensure that the desired system reaction actually occurs;
- Careful interpretation of testing results to determine which systems need to be redesigned or retuned; and
- Clear documentation of the testing results with punch lists of items that need to be fixed.

With careful preparation and diligent teamwork, you can create a project that meets or exceeds the needs of your clients. For those that are interested in learning more about data center design, we recommend that you keep abreast of ASHRAE Technical Committee 9.9, Mission Critical Facilities. They have just completed two publications: "Thermal Guideline for Data Processing Environments" and "Datacom Equipment Power Trends and Cooling Applications" and are working on design guidelines for these facilities. ●