Controls Commissioning: When Good Isn't Good Enough

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Synopsis

The Building Management System (BMS) is the brains of every modern building and, like people; some are much smarter than others. Determining how smart your BMS is (and how smart it needs to be) can challenge many an engineer or Cx provider. What aspects of the BMS should be included in the owner's project requirements, basis of design, construction documents and specifications? Does the redundancy in the controls match the redundancy in the mechanical plant? Do processing functions take place at the local controller or are they broadcast? Does the controls contractor's submittal meet these objectives? How do the reductions proposed during value engineering affect function, reliability and expansion capability? Does the project team understand how critical bid leveling is for the controls contractor's quotes? These questions will be answered from the perspective of a critical facility where reliability and redundancy are essential to the project success. All too often the reality is that owners don't know what they're getting, the designers don't understand what they're specifying and only someone with a strong controls background is qualified to make sense of it all. Otherwise the controls contractors will deliver the lowest cost and lowest functioning system (Can my fox watch your henhouse?). Can commissioning save the day? Stay tuned.

About the Authors

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BMS as Brains

This paper was inspired by some recently completed and current projects. Many of the examples used herein are from hardened mission critical facilities and serve as an excellent case study of the positive impact of the Commissioning Authority (CxA) on the success of a complicated project. More to the point, in these types of facilities the impact affects life safety as well as meeting a long-term mission where downtime is simply not acceptable. The design professionals were quite experienced in the design of this type of facility and nothing stated herein is intended to diminish their skills or efforts. The controls sequences were clear and well-written and they met the Basis of Design (BoD). Where the process ran into difficulty was in how the BMS vendor implemented the design and what the owner was willing to accept.

Proper operation of the building management system (BMS) is critical to a facility meeting the Owner's Project Requirements (OPR). In order to meet the OPR and achieve project success, the CxA must be intimately familiar with various manufacturers' control systems, programming methods and what information, by inclusion or omission from the design, will affect cost, flexibility and the overall controls design in a way many owners and even design professionals are not familiar or comfortable with. The engineers can design a $20,000,000 mechanical infrastructure, but without a comparable control system, the full benefit of this investment will not be realized. The BMS is the brains of the building and a knowledgeable CxA can assure the owner gets as smart a building as he is willing to pay for.

This paper is not focused on the testing phase. The CxA has the greatest impact during design. An understanding of the details of control system design presented herein is essential for the CxA to positively impact a complicated project. Even design engineers may find these details of control system design difficult to understand. They are usually left up to the controls vendor to address. The problem with leaving these details up to the vendor is that the vendor will always choose the cheapest and consequently lowest functioning approach. What choice does he have? He is bidding against stiff competition. The CxA needs to assure there is adequate information at each stage of design/construction to keep the controls design on a par with the mechanical plant design. Specifically, the OPR and BoD construction documents must be clear enough and tight enough to achieve this goal. Furthermore, during construction, the CxA must exercise the same care in control system submittal reviews and construction inspections to assure the installation matches the design. Clear control sequences are not enough to assure project success.

Owner's Project Requirements

In a critical facility, redundancy and reliability have priority over energy efficiency. Air quality may have a vital importance as well, particularly where pressurization and/or the mitigation of chemical, biological and radiation hazards are integral to the facility's mission and the life safety of the occupants. Another area of concern developing in today's homeland security environment is surviving a high altitude electromagnetic pulse (HEMP). How does a controls scheme need to be modified to address the needs of such a hardened facility? These items will be identified in the OPR and will be addressed in the mechanical design.

The key to success is to get the controls design to parallel the mechanical design in these areas. For example, Tier IV is the highest level of availability and reliability for a critical facility in the data center world. System plus System or 2(N+1) is the level of redundancy required to meet this criteria, where N is the number of units required to meet design load. If the OPR calls for a Tier IV facility and the design load is 1200 tons of air conditioning, the mechanical designer may provide two physically separated chiller plants (the “2”). Two 600 ton chillers will meet design load (N) plus one additional redundant 600 ton chiller is the “+1” **in each plant**. That’s a total of 6 chillers to meet the load of 2 chillers.

Additionally, the controls system in a critical facility must be maintenance and fault tolerant. How will the controls design meet a comparable level of reliability, availability and maintainability? During development of the OPR, the CxA should push for clear statements about reliability, availability, maintainability and fault tolerance, specifically related to the control system. These points will then be carried over to, and detailed in the Basis of Design.

Basis of Design

The Basis of Design provides detail that fleshes out the OPR. For our chiller plant example above, this is where the loads are calculated and the chillers selected. The narrative for the chiller plant is written. **As a minimum there should be a section in the BoD dedicated to controls.** The type of control system should be identified. The systems or functions that will be controlled and monitored should also be identified. The controls narrative should include a description of the system architecture. Ideally, it would be a controls system architecture drawing. This is not presently the norm, as most design engineers don’t or can’t develop this drawing. The CxA should push for this level of detail, even if it means involving a vendor early in the project. In a critical facility particular attention should be paid to critical functions such as uninterrupted cooling, continuous positive building pressurization and special use areas. Below are some approaches to meeting these requirements. Understand these and you will be able to guide the design team to a high reliability facility.

Dedicated, Redundant Managers and the Heartbeat

The control system requires a level of redundancy that matches the HVAC equipment redundancy. This is accomplished by providing a lead and a redundant controller for every critical system. This system level controller is called a manager. Programming is mirrored between the two managers and the redundant controller is always on line to perform an instantaneous changeover on loss of the lead manager. Our chiller plant example is illustrated in Figure A. All chillers are controlled by the lead chiller manager. The lead chiller manager is connected to the redundant chiller manager through a transfer relay panel. Each individual chiller has a single control module. In this arrangement each chiller has one controller. Failure of a controller is equivalent to failure of a chiller and the redundancy matches.

The two managers are also connected with a hardwired heartbeat signal. The signal originates from the lead manager and is pulsed on regular intervals. The heartbeat continuously informs the redundant manager that the lead manager is "healthy." If the signal is interrupted (the heartbeat is lost), the redundant manager immediately assumes control functions. The transition takes place near real time and there is no loss of function. A similar arrangement is used for each critical system—primary pumps, secondary pumps, condenser water pumps, cooling towers, etc.

Assignment of equipment to a controller should be made with the objective of eliminating single points of failure. An example of the wrong way would be to put control of all chillers on a single controller. The loss of a singe control transformer or circuit breaker would render all chillers inoperable.

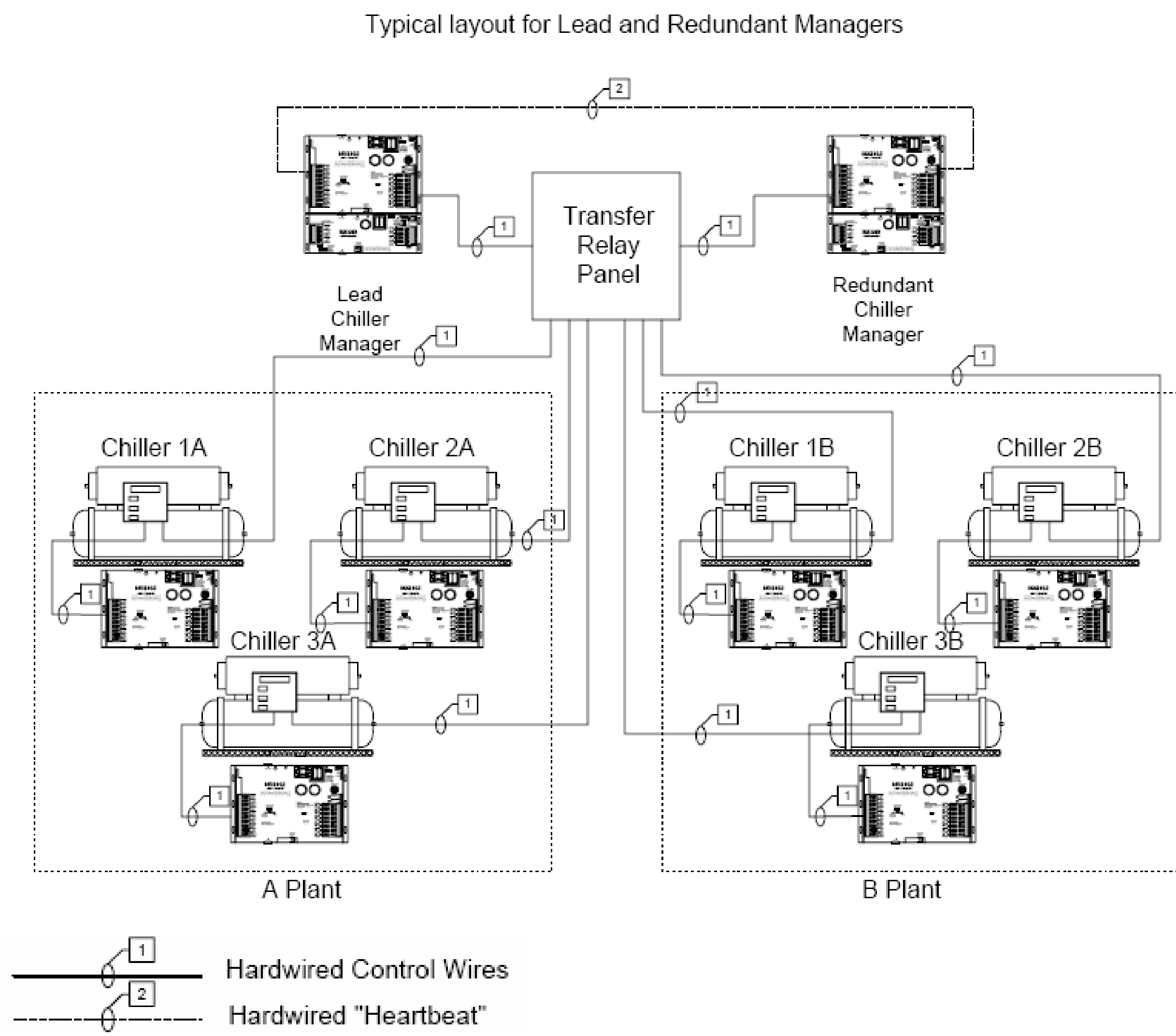

Figure A: Chiller Typical Layout for Lead and Redundant Managers

Broadcast Commands and Real Time Processing

In order to meet the requirements for availability, fault tolerance and maintainability, consideration must be given to where command decisions are made and how those commands are translated to equipment and actuators. Is a real-time response necessary? Can the network accommodate a network interruption concurrent with an equipment failure or power outage?

Calculations are often performed at a network engine (a processor that has communication responsibility across the network between controllers and acts as a gateway into the network) and are broadcast back and forth between the local controllers and the network engine. This creates delays in processing as well as three single points of failure (the communication network, the local controller and the network engine). A loss of any one of these three will result in control sequences either stopping or being improperly executed. So why would we design or approve such an architecture?

Broadcasting commands over a network is much cheaper than running conduit and pulling wires. In today's competitive environment, the pressure to cut costs is considerable. The question is do we want to save money, save data or save lives. When broadcasting commands instead of hard wiring, the network becomes a system wide single point of failure. On a failure of the network or network engine, commands do not reach the equipment. Look at the example of a chiller plant operating with two chillers on. Say one chiller failed concurrent with a network interruption. The chiller fails to its last command with the primary chilled water pump running and the isolation valves open. The system cannot acknowledge the failure, cannot start another chiller and cannot close the isolation valves. Half the system water is being supplied at the return water temperature, and half the required number of chillers are operating. The conditioned spaces will soon overheat. Clearly this system is not fault tolerant. The use of hard wired managers and hardwired local controllers eliminates these problems.

Some HVAC sequences require real time processing to work properly. What factors, particularly vendor specific factors, affect processing time? Does it make a difference if the I/O module is integrated onto the same circuit board as the processor? The answer is yes, and the problems associated with not having I/O integration at the controller level are compounded by the use of broadcast commands. Some manufacturers, including big names do not have I/O integration, but instead communicate over twisted pairs.

Low End Processors

Low end processors have several limitations, one being the number of points that can be wired into them and another being their processing capability. The manufacturer may state his gateway can handle "X" nodes, but does not address the processing power available per node. Data can be corrupted if too much data must be processed. Processes need to be partitioned onto different gateways and sub networks distributed to reduce traffic on communication buses. Figure B illustrates a simple distributed network above the chiller manager illustrated in Figure A. Providing architecture drawings such as these in the BoD will allow everyone the opportunity to clearly see how the design intent should be implemented.

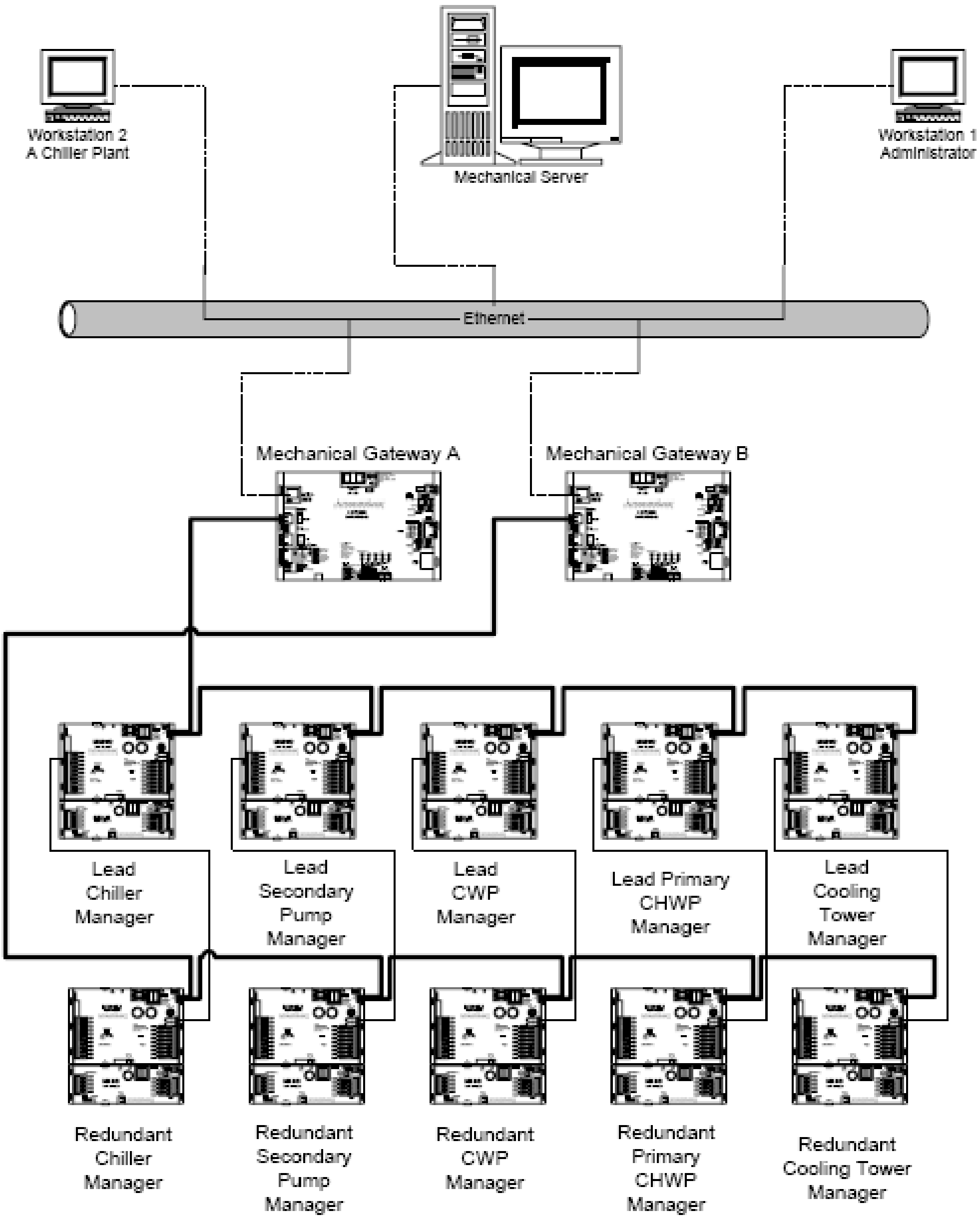

Figure B: Chiller Plant Lead and Redundant Manager Architecture

Low end processors cannot handle heavy processing. A major manufacturer uses a unitary controller that is quite adequate for controlling simple unitary equipment such as a single air handler. The processing requirements for a central plant control will typically exceed the capacity of the local controller. In this case the local controller sends data for processing across a network twisted pair to a network engine for remote processing. The commands come back across the twisted pair to the controller and then to the equipment through the I/O module, again through a twisted pair. Three single points of failure are created when using a network engine for remote processing: the local controller, the network application engine and the network wiring.

Without robust computing power, processors can take too long to cycle through their programs. Long processor cycle times can have an adverse impact on fast acting sequences. When the cycle time is too long, values can change state multiple times before being recognized by the processor. When this happens the sequence is executed improperly because the processor is using outdated values. In the case of a chiller plant, the processor may not recognize that a chiller is running before it locks it out on a failure routine, thereby taking an operating chiller off line. When this happens multiple times the consequences can be severe. Processing cycle times for HVAC sequences are typically much shorter than that needed for electrical systems, however for the critical facility environment real time response is imperative.

Point density is another limiting factor for low end processors. If one of these processors can't handle the required number of points for a particular application, multiple controllers must be interconnected through the network application engine. This means more twisted pairs and more delays in processing time. Such a process can take minutes and is far from real time. In a critical facility this is just unacceptable.

Integrated controls for chiller plants or other systems that require multiple pieces of equipment to work together demand a high concentration of physical points on one controller and robust and rapid processing power. It is a challenging assignment for the commissioning authority to assess these capabilities, but when accurately assessed before installation system reliability is increased dramatically and the OPR can be met.

An example from another type of facility clearly indicates these compounded problems that can occur with this type of low end controller. Say the process is building pressurization. The OPR states that the building must be maintained at a positive pressure at all times. There are two pressurization fans in a lead/lag arrangement. The lead fan is running and all is well. The control system uses low end controllers and some processing is at the network engine as described above. Upon failure of the lead fan, the loss of fan is sensed and transmitted up the line. This information is processed and a command is sent down the line to start the lag fan. All the while the building exhaust fans continues to run and the building pressure turns negative for over 5 minutes before the lag pressurization fan comes up to speed. What are the consequences of this delay? If either the network or network engine is compromised then the lag fan will not come on at all. If the pressurization fans push air through CBR filters, the loss of these fans allows contaminated air to be drawn into the building. This could cost lives.

Now replace the low end controller with a control module where the processing occurs locally and the I/O module is integrated into the processor and the controller can handle a high density of physical points. The time the building will experience a negative pressure is reduced to less than one minute. But what if this is still too long? Now add a fan manager to control all the pressurization and exhaust fans together based on building pressure. Sensors indicate the pressure is dropping due to the loss of the running pressurization fan and the manager reduces the speed of all the exhaust fans (or stops the fans) through hard wired connections, until the lag pressurization fan comes up to speed. Now the building will remain positively pressurized and the OPR is achieved. This type of sophisticated and integrated control is only possible if the controller has the capacity to handle a large number of hard wired inputs and outputs and has robust local computing power. Understand the impact of low end processors and you can assure the design will meet the OPR.

The way to address these issues is a line-by-line comparison of component performance for the various manufacturers being considered. Some major manufacturers are using technology that is 25 years old. Think about how your PC would perform if you were operating at processing speeds common in 1980 or if you had the same RAM now as you did back then. Make a table comparing communication speed, controller RAM, data sample storage capacity, point capacity, data width, etc. The results may surprise you. **Make this evaluation part of the BoD.** Include an architecture drawing like those illustrated herein. A picture is worth 1,000 words.

Software

Software is another area where there is considerable difference between vendors. Not all vendors are "equal." Many designers and owners focus on what they see, the operator interfaces or graphical user interface (GUI). Unfortunately, graphics are not a good indicator of performance. Anyone can produce a decent picture and it would be unwise to judge this book by its cover.

There are basically three types of programming; line code programming, menu based programming and graphical programming. All methods can yield acceptable performance; however, there are limitations with each method. Menu based programming is limited to some common equipment types (typical AHU, RTU, VAV box, etc.) and cannot handle complex central plants. Line code programming cannot be used in off-line simulations the way graphical programming can. Line code programming requires testing with live equipment. Some systems can be tested in small segments off-line. Simulations are discussed in more detail below. Some manufacturers are still using DOS based software (as opposed to Windows based). **Include an evaluation of software programming in the comparison described above.** If the owner's operations engineers are familiar with a particular system or type of programming, some weight should be given to that in evaluating vendors.

Design Phase

During the design phase there are several areas where the commissioning authority and design team would do well to focus their attention. Overall, the design should address more than full load performance. Accommodating day 1 partial loads as well as ultimate build-out from project inception are just as important. The following are a few key issues that will have a major impact on performance of the BMS system.

Simulations (Off-line Testing)

The bane of the commissioning authority is the programmer still programming when the CxA is trying to test. **To avoid this, specify that the vendor must demonstrate the operation of the controls system at a factory test.** This demonstration should address a cross section of equipment—one AHU, one chiller, etc. sufficient to demonstrate that the programming works. This may require a test setup with lights, potentiometers, etc. Specifying this factory witness test, with a test date sufficiently in advance of the on-site test dates, forces the vendor to complete their programming even if the site installation is not near ready for live testing. Requiring simulations also reduces the desire of the CxA to kill the programmer. Specify factory witness testing of the control system.

Control Sequences

There are as many ways of controlling a mechanical plant as there are design engineers. Sticking with our chiller plant example, how should the chillers be staged? Staging off of calculated secondary tonnage is preferable; using chiller kW or temperature difference across the chillers are both common and acceptable methodologies. Some methodologies are not acceptable in a critical facility. Take the example of staging on loss of chilled water set point. Say the chilled water supply set point is 45° and a second chiller stages on after the chilled water supply is 2°F above set point. The load increases until one chiller is fully loaded. The load continues to increase but the chiller cannot handle the additional load and both supply and return water temperatures starts to increase. As warmer return water reaches the air handling equipment heat transfer is reduced and the air supply temperature will increase. Therefore we have lost control of the space load before a second chiller stages on. Not only do we now have to meet the load, we are in a recovery situation. Additional capacity is needed to not only maintain the space temperature but to drop it. Eventually the second chiller will stage on, but will it ever stage off? Suppose the chiller also stages off when the chilled water supply temperature is 2°F below set point. How can the chiller lose set point on a reduction in load? It can't, and the compressor will just cycle off. With this control sequence the second chiller will never stage down.

This control sequence was actually written for a critical facility in Virginia. The shortcomings of this system were discovered during the commissioning process. When pointed out to the controls vendor, the sequences were completely rewritten utilizing temperature difference across the chillers as the staging methodology. On this project the owner had a relationship with the controls vendor that predated the project. Responsibility for the controls design was taken away from the mechanical designer and they had virtually no input into the design and no review of the written sequences. This was a recipe for failure and was averted by an astute commissioning authority with strong controls background.

Another informative example of when good isn't good enough is chiller plant recovery after a power failure. Upon emergency generator start a typical chiller plant may simply begin from a cold start, staging on chillers from no load with the common 15-20 minute time delays between each chiller. In a critical environment this is absolutely unacceptable. Space loads continuously generate heat and it would be impossible to recover control of space temperature if the chillers staged up that slowly. Instead, the chiller plant should immediately stage to its last operating position. This is accomplished by continually taking a “snapshot” of the operating condition of the plant. If two chillers and four secondary pumps were operating before the power interruption, then immediately upon power restoration the plant will start the same four secondary pumps and stage on the same two chillers almost simultaneously. This is the only way to recover space temperature quickly enough to avoid shutdown of servers and other IT equipment in a heavily loaded data center. In addition, the system should prevent staging up of additional chillers for 30 minutes to avoid unnecessary load on the generators.

During design phase commissioning, the commissioning authority has both the opportunity and responsibility to review the sequences of operation for the HVAC equipment. **By analyzing and assessing the sequences, the CxA can help avoid change orders that arise during construction because the programming is inadequate.** This raises the level of the quality of the job and helps to ensure, once again, the design is suitable for a critical facility and the OPR are met.

Vendor Interviews and Bid Leveling

Not all vendors are alike. Do we choose a vendor who is a big name or who is technologically up to date? Despite the big name, some vendors cannot accommodate mission critical applications because the mission critical industry is too small a portion of their portfolio. Vendors should be evaluated on their products (hardware and software) and also on their personnel and their culture. On a project completed a few years back, one of the big name vendors submitted a bid on a tight specification and their price was lower than the competition by more than $500,000. During the interview they swore up and down they would meet the spec and they were awarded the job. While preparing their submittals, the vendor was unable to convince the design engineer to accept the local controllers and network engines connected by twisted pairs and broadcast commands that did not meet the spec. Three weeks later the vendor abandoned the project by submitting a letter stating they could not meet the spec leaving everyone scrambling. That letter is hanging on my wall. That vendor is no longer in our firm’s specifications.

Bid leveling can help avoid this type of situation. Bid leveling should be performed by the controls designer, but he must be knowledgeable of each vendor’s system and all the issues addressed herein. Consideration must be given to the OPR when performing bid leveling. Comparisons are not just on price, but should address schedule and spec compliance. The bid leveling should include face-to-face interviews with each vendor. It is possible to conduct interviews with three vendors in one day, with proper preparation. This time spent interviewing vendors, plus some phone calls to the general contractor and the owner, is a small investment with an enormous return for the success of the project. Just keep in mind, the lowest cost system can be the lowest functioning system. **The CxA should see that bid leveling is performed.**

Value Engineering

Designing and building a control system for a critical facility is not cheap. The owner may want and expect a Cadillac but he has to be willing to pay for it. Many a construction manager or general contractor will look at the issues raised above and see a golden opportunity to save a lot of money and impress the owner with his value engineering skills. Moreover, if the CM or GC has come in with a guaranteed maximum price GMP for the project, he more than likely will fight hard to convince the owner to delete the more expensive requirements. Vendors also will try to eliminate many of the features unique to critical facilities. For many these items are seen as extravagant and may add $500,000 or more to the cost of the project. The CxA and even the controls designer must not be seen as defensive in protecting these requirements, but must justify them to the owner from project inception. Deletion of these features will reduce reliability, availability, expansion capability and performance. Though crucial to meeting the OPR they may be, the owner must be willing to pay for them. **It is the CxA's responsibility to assure the owner understands the consequences of value engineering on the control systems capability of meeting the OPR.**

Construction Phase

Submittal Review

By now everyone knows what the controls system is supposed to look like. Review of the controls submittal is of course the responsibility of the controls designer. This is the last chance to verify the vendor's understanding of the design intent in implementing the controls design. **Focus attention on the items detailed herein; the objectives itemized in the OPR and details in the BoD.** As with any other aspect of the project and any other submittal, the reviewer must be knowledgeable on the subject.

Testing

Testing of a complex mechanical chiller plant in a critical facility is more than following test procedures. The commissioning authority and the controls designer must have a depth of experience necessary to read through programming as sequences are occurring, to give guidance on setting timer durations and to have an overall feel for what is happening in the entire infrastructure under control of the BMS.

In Conclusion

How can the commissioning authority tie this all together? This paper details control issues the CxA needs to understand far in excess of control sequences.

- During development of the OPR, the CxA should push for clear statements about reliability, availability, maintainability and fault tolerance, specifically related to the control system.
- Assure there is a section in the BoD dedicated to controls.
- Push for a controls system architecture drawing to be included in the BoD.
- Understand the concepts of dedicated, redundant managers and the heartbeat and how to apply them.
- Understand how broadcast commands affect processing time and reliability.
- Evaluate control system vendors equipment for processing power and the impact on performance and reliability.
- Have the designers include a line-by-line comparison of component and software performance for all vendors being considered as part of the BoD.
- Add a requirement for factory simulation (off-line demonstration) testing of the programming to the specifications.
- Verify control sequences in normal and failure modes are adequate to meet the OPR.
- Have the project team include control system vendor interviews and bid leveling in the evaluation, don't just accept the vendor proposed as a sub to the mechanical contractor.
- Make sure the owner understands the consequences of value engineering on the capability of the control system to meet the OPR.
- Review the controls vendor submittals with a focus on the issues raised herein.

The controls design is integral to the success of the project. The key question to answer for a successful controls design is "who is driving the bus?" Is it the mechanical engineer? Is it a dedicated controls design firm? Is it the controls vendor? If the controls vendor is writing the controls spec, as they often do, then a critical element of the design is out of the hands of the designers. Most mechanical engineers don't have the depth of experience of a dedicated controls designer to evaluate vendors, their products and personnel. Fold up this paper and put it in your pocket and use it as a reference next time you are awarded a commissioning contract for a critical facility. Then you will have the knowledge to make a difference.

The commissioning authority's responsibility is to the owner. It is not necessary that the commissioning authority be a DDC controls expert, but if he/she has enough of an understanding of control systems hardware and software, then he can assure the owner gets what he expects. Then, good enough becomes great.