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S. Katipamula
D.D. Hatley
D.J. Hammerstrom
D.P. Chassin
R.G. Pratt

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Transactive Controls: A Market-Based GridWise^{TM} Controls for Building Systems

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Richland, Washington 99352

Abstract

In 2005, Battelle Memorial Institute, Pacific Northwest Division along with several utility and industry partners created the Pacific Northwest GridWise Test Bed. The purpose of the test bed is to cooperate with the U.S. Department of Energy (DOE) GridWise program by demonstrating advanced technologies for the efficient and reliable operation of the electric power grid in the Northwest. As part of this test bed, Pacific Northwest National Laboratory (PNNL) has been developing and demonstrating the control technologies to make homes and buildings more demand responsive.

While each demonstration has its own unique objectives, the main objective is to demonstrate how GridWise control technologies can make the electric power grid more reliable by providing a means to (1) better manage transmission constraints, (2) better manage peak load on distribution feeders to avoid local capacity expansion and (3) support ancillary services such as spinning and non-spinning reserves.

In this paper, we described a market-based control technology that can be implemented in an existing building automation system (BAS) with **little or no additional capital expenditure** and make commercial buildings more demand responsive. We also describe a single case study that qualitatively shows the value of the market-based controls.

Background

Most building systems in large commercial buildings (>100,000 square feet), including heating, ventilation and air conditioning (HVAC) systems, are controlled with building automation systems (BASs)[1]. A BAS has sensors to measure control variable(s) (e.g., temperature and flow rates), a controller with the capability to perform logical operations and produce control outputs, and controlled devices that accept the control signals and perform actions (e.g., open and close dampers and valves). In addition, the BAS may also have a global supervisory controller to perform high-level tasks (e.g., resetting temperature set points based on building conditions and scheduling on/off times).

BAS technology has evolved over the past 3 decades from pneumatic and mechanical devices to direct digital controls (DDC) or computer-based controllers and systems. Today's BAS systems consist of electronic devices with microprocessors and communication capabilities. Widespread use of powerful, low-cost microprocessors, use of standard cabling, and adoption of standard communication protocols (such as BACnet™ and LonWorks™) have led to today's improved BASs. Most modern BASs have powerful microprocessors in the field panels and controllers that may soon be embedded in sensors as well. Therefore, in addition to providing better functionality at a lower cost, these BASs also allow for distributing the processing and control

[1]BAS is also know by various other names such as energy management and control systems (EMCS), building management system (BMS), energy management system (EMS), and facility management system (FMS)

functions to the field panels and controllers without having to rely on a central supervisory controller for all functions.

Conventional DDC Controls

In a conventional (or non-transactive) control application, shown in Figure 1, the principal control elements are (Haines 1991[2]):

1. The supply air temperature, which is the controlled variable.
2. The dry-bulb temperature sensor.
3. The controller, which compares the sensed supply air temperature value with a fixed set point and uses the difference between the two to generate an output signal.
4. The controlled device, which in this case is cooling coil valve controlling the chilled water flow to the cooling coil.
5. The process plant, which in this case is the cooling coil and air stream.

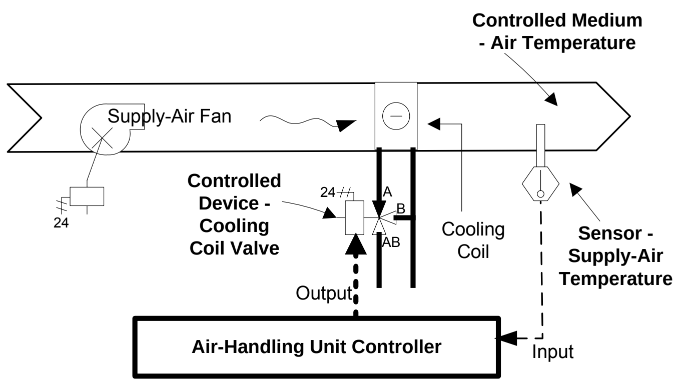


Figure 1 – Example Control Loop Schematic

As the supply air temperature changes, the difference between the measured supply air and the supply set point temperature changes; the controller uses the difference between the two values to generate an output signal that repositions the cooling coil valve. As the valve is repositioned, the supply air temperature changes, and eventually the measured temperature and the supply set point will be nearly equal. Note that the supply air temperature is the only controlled variable in a conventional control approach – the cost of providing comfort or the performance of the component or the system is not part of the decision making process.

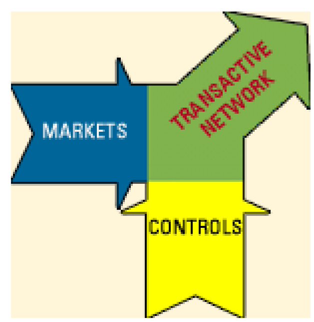
[2]Haines, R. 1991. *HVAC Controls*. TAB Professional and Reference Books, Blue Ridge Summit, PA.

What is Transactive Control?

Transaction (e.g., contract) networks[3] and agent-based systems present an opportunity to implement strategies in which highly “optimized[4]” control (both local and global) is an inherent attribute of the strategy rather than an explicitly programmed feature. The premise of transaction-based control is that interactions between various components in a complex energy system can be controlled by negotiating immediate and contingent contracts on a regular basis in lieu of or in addition to the conventional command and control. Each device is given the ability to negotiate deals with its peers, suppliers and customers to maximize revenues while minimizing costs. This is best illustrated by an example.

A typical building might have several chillers that supply a number of air handlers with chilled water on demand. If several air handlers require the full output of one chiller, and another air handler suddenly also requires cooling, traditional building control algorithms simply start up a second chiller to meet the demand and the building’s electrical load ratchets upward accordingly.

A transaction–based building control system behaves differently. Instead of honoring an absolute demand for more chilled water, the air handler requests such service in the form of a bid (expressed in dollars), increasing its bid in proportion to its “need” (divergence of the zone or supply air temperature from its set point). The chiller controls, with knowledge of the electric rate structure, can easily express the cost of service as the cost of the kWh to run the additional chiller plus the incremental kW demand charge (if it applies). If the zone served by this air handler just began to require cooling, its “need” is not very great at first, so it places a low value on its bid for service and the additional chiller stays off until the level of need increases[5]. Meanwhile, if another air handler satisfies its need for cooling, the cost of chilled water immediately drops below the bid price because a second chiller is no longer required, and the air handler awaiting service receives chilled water. Alternatively, a peer-to-peer transaction can take place in which an air handler with greater need for service displaces (literally outbids) another whose thermostat is nearly satisfied.



[3]Smith, R.G. 1980. “The Contract Net Protocol: High-Level Communication and Control in Distributed Problem Solver.” IEEE Transactions on Computers, Vol. C-29, NO. 12, pp. 1104-1113.

[4]By optimal control we don’t mean an exhaustive optimal control strategy, but “good enough” optimal control, where algorithms adequately capture beneficial impacts at significantly lower complexity and cost.

[5]This is true because the cost of starting another chiller will be greater than the bid placed by this zone for service.

In this way, the contract-based control system accomplishes several things. First, it inherently limits demand by providing the most “cost-effective” service[6]. In doing this, it inherently prioritizes service to the most important needs before serving less important ones. Second, it decreases energy demand and consumption by preventing the operation of an entire chiller to meet a small load (assuming that no AHU is willing to pay the additional cost of service to start the second chiller), where it operates inefficiently.

Third, contract-based controls inherently propagate cost impacts up and down through successive hierarchical levels of the system being controlled (in this example, a chiller or a boiler that provides cooling or heating, air handler that provides air circulation, and the zone). The impacts on the utility bill, which are easily estimated for the chiller operation, are used as the basis for expressing the costs of air handler and zone services. Using cost as a common denominator for control makes expression of what is effectively a multi-level optimization much simpler to express than an engineered solution would be. It allows controls to be expressed in local, modular terms while accounting for their global impact on the entire system.

In effect, the engineering decision-making process is subsumed by a market value-based decision-making process that indirectly injects global information conveyed by market activity into the local engineering parameters that govern the behavior of individual systems over multiple time scales.

Many HVAC systems are controlled by thermostats. The desired temperature is set by the customer and the thermostat uses current space temperature sensor information to control the damper position that controls the air flow (or turn the compressor on or off), thereby satisfying the heating and cooling needs of the zone. In a conventional control system, indoor temperature and indoor set point temperature are the only information required to control the amount of heating and cooling to the zone. However, in a transactive control system, the thermostat uses price information to make control decisions. Although much of the discussion so far has been for thermostatically controlled HVAC systems, transactive controls can be applied to non-thermostatically controlled systems as well (distributed generation, other load resources).

Transactive Control for Thermostatically Controlled Equipment

An application of the transactive control strategy to thermostatically controlled HVAC is explained with an example in this section and illustrated in Figure 2 (for cooling mode of operation, heating mode is a mirror image). As described previously, transactive control modifies conventional controls by explicitly using market information (bids/clearing prices[7]). In addition, transactive control allows the customer the choice to set the desired temperature (T_{set})

[6]By “cost-effective” we mean the best match for the level of service to the cost of service.
[7]The participating electric loads and generation capacity are bid into the power market, which reconciles loads and generation capacity to establish the market clearing price. The price of electricity at a point where the quantity demanded is equal to the quantity supplied is known as the market-clearing price, because it "clears away" any excess supply or excess demand.

and an acceptable range of indoor temperatures (T_{min} and T_{max}). The user is also allowed to develop a bid curve a priori. A bid curve functionally relates cost of service to comfort. The bid curve in the example illustration (Figure 2) is derived from the mean price[8] and the standard deviation of the price over a certain period and the minimum and maximum temperature set points. In addition, in this example, we assume that the minimum and maximum set points correspond to "k" standard deviations from the mean price. The value of "k" is user selectable; a low value of "k" leads to customer bids that are close to the mean price. If the value of "k" is high, the customer bids can be significantly different from the mean price. For example, a "very" high value of "k" will lead to very high bids when the zone temperature deviates from the desired zone temperature, which will ensure that the zone is always satisfied just like it would be in a conventional control.

Implementation of the transactive control strategy requires several steps, which are explained below. Although the illustration assumes that price of electricity is changing in real-time, transactive control can be easily applied to other dynamic rates, such as time-of-use, day-ahead and critical peak pricing with minor modifications.

The first step in the transactive control process is to observe the current indoor temperature and calculate the bid price for the service (comfort). The bid is based on the difference between the current zone temperature and the desired zone temperature and the user selected parameters (k, minimum and maximum set points), while the mean and standard deviations are external inputs from the market.

$$P_{bid} = \overline{P} + \left(T_{current} - T_{set}\right)\frac{2 \times k \times \sigma}{T_{\max} - T_{\min}}$$

where, P_{bid} is the bid price, P (bar) is the mean price of electricity, and σ is the standard deviation of the electricity price. The next step is to post the bid to the market; the market then establishes the market clearing price[9]. After receiving the market clearing price, the adjusted zone set point is calculated.

$$T_{set,\,a} = T_{set} + \left(P_{clear} - \overline{P}\right)\frac{T_{\max} - T_{\min}}{2 \times k \times \sigma}$$

The final step is to reset the zone set point to the new adjusted zone set point. Once the set point is adjusted, the conventional control takes over. This process (bid, clearing, adjusting) continues for each market clearing cycle.

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[8]The mean price is the average price of electricity over a certain period from the immediate past, for example, last 24 hours, last week or last month.

[9]Although market clearing is generally done by independent system operators or other independent entities, for transactive control the market can be cleared either externally using the independent entities or done internally at the building or system level. When clearing internally, the systems are bidding internal reallocation of the cost and services.

Note that $T_{set,a}$ can be higher or lower than the desired set point (T_{set}) based on the clearing price. In cooling mode, lowering the set point below the desired set point will increase the energy consumption (lowering the set point below desired cooling set point is done to pre-cool). Transactive control supports optimal pre-cooling and pre-heating if the future price of electricity is known. For some dynamic rate structures, the future price is known a priori; however, in case of real-time pricing it is an unknown. To pre-heat or pre-cool with real-time pricing, we need the ability to forecast or predict future price. In the absence of prediction capability, the adjusted zone temperature can be constrained such that no pre-cooling or pre-heating occurs.

Although there are a number of steps to successfully implement the transactive control process, all steps can be fully automated with the modern BASs. In the next section we describe a case study that implements transactive control in a commercial office building.

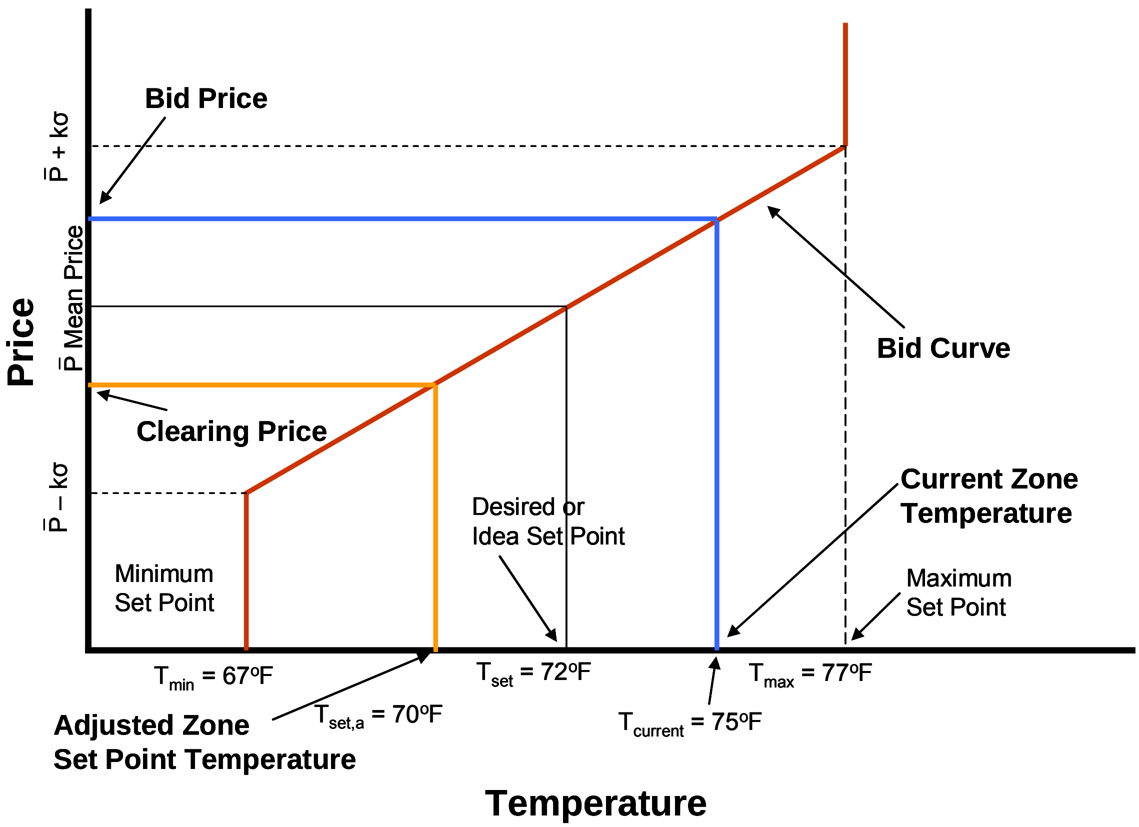


Figure 2 – Illustration of the Bid and the Response Strategy for Thermostatically Controlled HVAC Systems: Cooling Mode

Case Study of Transactive Control

In this section, we describe an implementation of our transactive control strategy in a commercial building in the state of Washington. The building is a mixed use building with office and laboratory spaces. The perimeter of the building is made of office spaces, while the core consists of laboratory spaces. The building is served by a heat pump chiller and boiler to supplement the heating needs when the heat pump chiller is not able to meet the entire heating needs. The office and laboratory spaces have independent HVAC systems. The office spaces are conditioned by a multi-zone variable air volume (VAV) air handling unit (AHU). Each office is served by a VAV terminal unit that is controlled by a zone thermostat. The VAV boxes also have a reheat coil to provide heating as well as reheat. For the office spaces, the zone temperature set points are different for heating and cooling periods and also during occupied periods (6:30 a.m. to 5:30 p.m.) and unoccupied periods (5:30 p.m. to 6:30 a.m.). The transactive control strategy was applied to the VAV system serving the office spaces. The building is controlled with BAS.

The transactive control strategy, described in the pervious section, was programmed at two levels in the BAS (zone level and building level). The bidding and calculation of adjusted set point occurs at the zone level; each zone bids independently of other zones. The user specified parameters (min and max zone temperatures are 65^{o}F and 80^{o}F, respectively and k=1) are entered for each zone. A zone level override is also provided, so that the user can choose to override transactive control strategy and fall back on the conventional controls. Another way to override the transactive control is to set the value of "k" very high (> 10), which also leads to conventional control.

Some aspects of the transactive control are implemented at the building level. The market price, the mean price and the standard deviation, for example, are posted from an external source at the building level. In addition, a building level override is also provided. Unlike the zone level, the override at the building level supersedes all transactive controls at all levels, including at the zone level.

Although power markets are generally cleared at an hourly interval, a real-time showdown market was created for this experiment that is cleared every 5 minutes. Bids from the zones are posted to the shadow market. After the market clears, the cleared price is posted to the building BAS. The communication between the market and the BAS is mediated through an OPC[10] server, as shown in Figure 3. To compare the response of conventional controls with transactive controls, the building was operated with conventional controls on Tuesday and Thursdays and transactive controls on Monday, Wednesday and Friday.

[10] OLE (Object Link and Embedding) for Process Control.

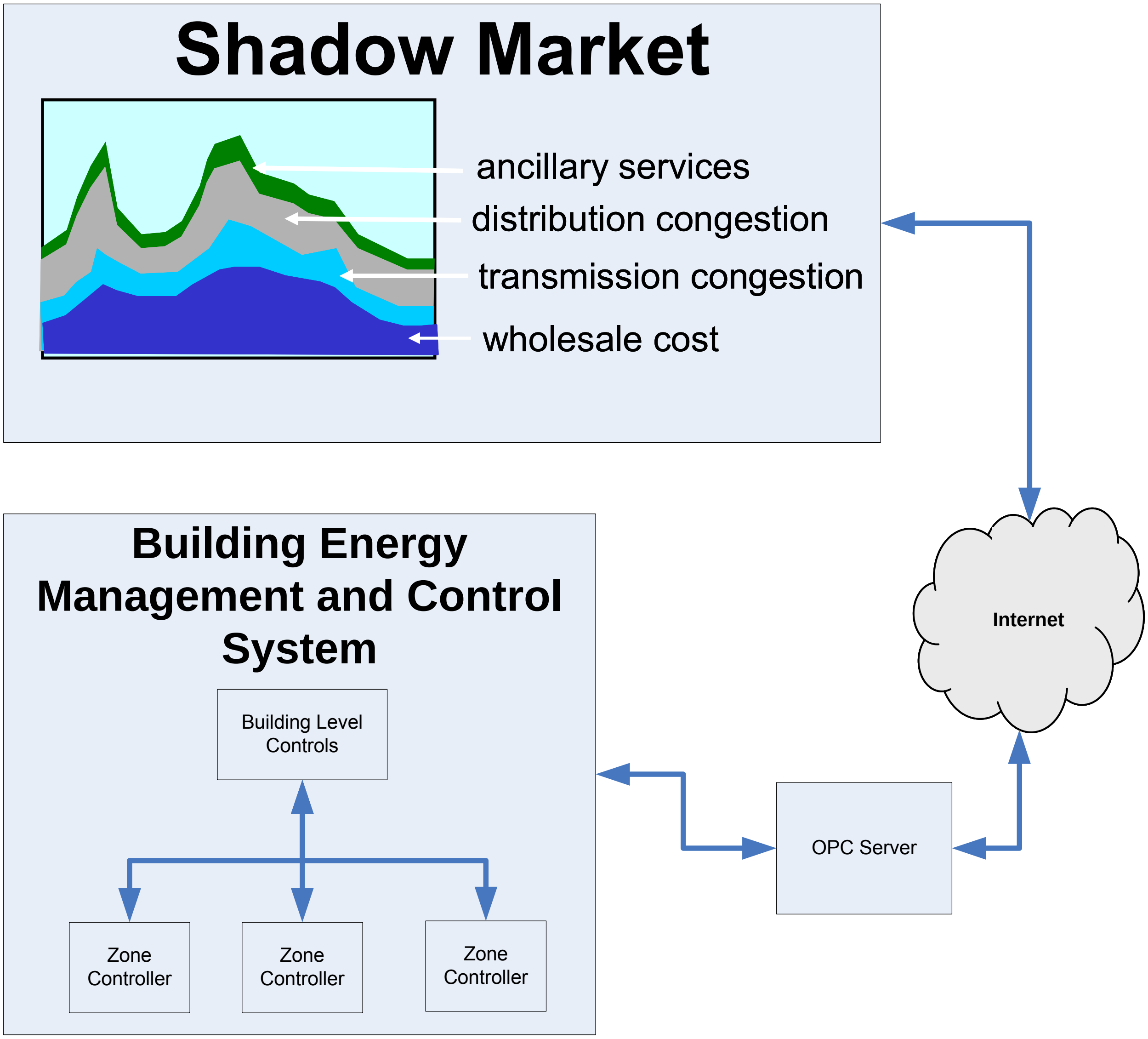
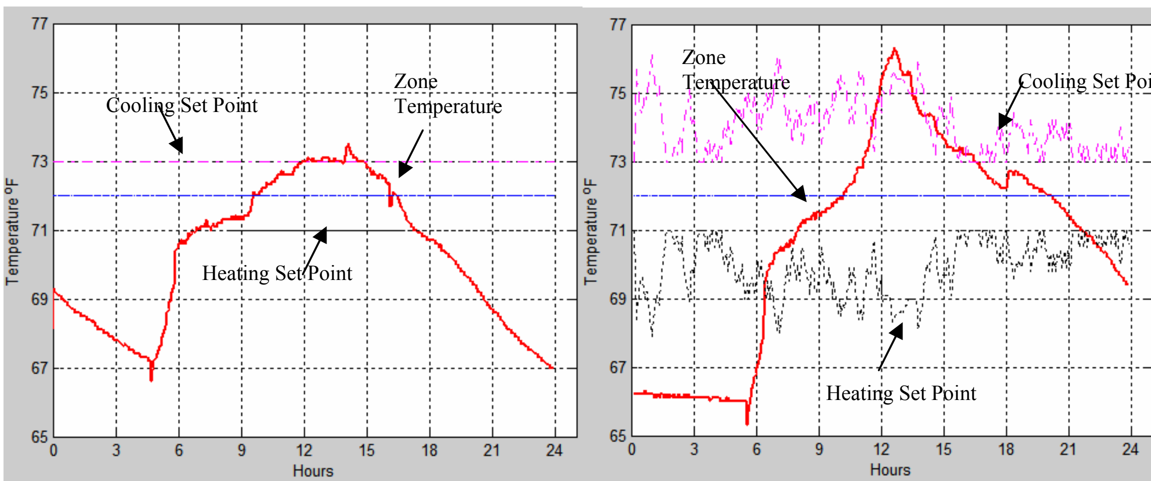


Figure 3 – Schematic of Transactive Controls Implementation in a Commercial Building

Figure 4 compares the response of a single zone on 2 consecutive days with conventional and transactive control. The heating and cooling set points during occupied hours (6:30 a.m. to 5:30 p.m.) for the zone with conventional control are 71°F and 73°F, respectively. As seen from Figure 4a, the zone temperature with conventional control is between the two set points (most of the time during occupied hours). Unlike the conventional control, on the day with transactive control, the heating and cooling set points are not constants but changing in response to the market price signal, as shown in Figure 4b. The corresponding bid price, market price and mean price are shown in Figure 5.

As seen from Figure 5, in this transactive control application, the zone bids are zero when the zone set point is satisfied (i.e., when the temperature are between 71°F and 73°F).



(a) (b)

Figure 4 – Comparison of Zone Temperatures without (a) and with (b) Transactive Control

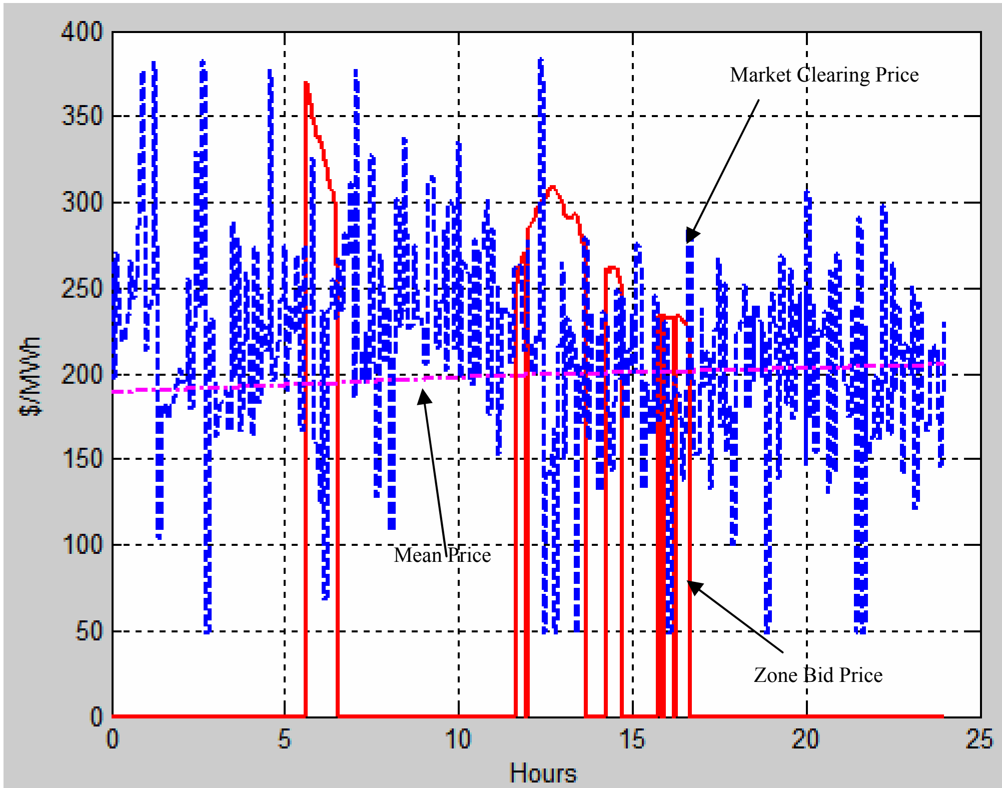


Figure 5 – Zone Bid, Market Clearing Price and Mean Price of the Electricity Corresponding to Figure 4 (b)

Future Work

One of the greatest obstacles for the penetration of demand response (DR) at the commercial building level is the lack of standardized, simple control interface hardware and software. The installation of DR systems tends to be unique to each building and, therefore, exhibits no economy of scale for later installations. Pacific Northwest National Laboratory (PNNL) is proposing to work with a number of major BAS manufacturers to facilitate the development of approaches for more rapid deployment of one successful building DR installation to another in commercial buildings.

Another important theme during implementation should be flexibility. DR will be accepted better if it can be flexibly tailored to the needs and capabilities of each building, the building owner, and the building's occupants.

A number of utilities over the years have used DR and load curtailment technologies. Some projects have even demonstrated the use of BASs in large commercial buildings to perform pre-specified control actions based on a price signal. Most of these demonstrations use a building-level gateway to communicate price signals and control actions to the BASs. Hardware gateways may be necessary to communicate with some legacy systems, but are not essential with most modern BASs (systems installed over the past 10 years).

The case study showed that market-based controls or transactive controls are possible. In addition, the case study also showed that such controls can be implemented with existing BASs without significant capital investment. However, there are many practical issues yet to be resolved, and additional test beds are needed to quantify the benefits and implementation of transactive controls in the commercial building sector. PNNL will deploy this technology in a number of buildings without the need for additional hardware gateways and, we hope, thereby reduce the cost of the control implementation.

Benefits from DR technologies, including the transactive control technology, have been widely published. However, the cost of implementing these technologies varies widely and is not fully understood. Planned demonstrations like the one being proposed will provide some answers to the implementation cost. Because our approach relies on development of automated control strategies that are flexible and portable across various BASs, the cost of implementation should be significantly lower than conventional approaches. This approach, however, only applies to a small fraction of buildings (less than 15%) because many commercial buildings lack BASs. For those buildings we are exploring other delivery options, including using inexpensive gateways.

The commercial building customer should benefit from successful development and deployment of the proposed GridWise control technologies because these technologies would make the building more demand responsive with no or very little capital investment.

The control manufacturers and energy service providers will benefit from having access to GridWise technologies for use with other customers. The utility partners will benefit from knowing how GridWise technologies can help alleviate transmission and distribution reliability problems.