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Demand Response-A Process Architecture for Selection of HVAC Control Strategies for Varying Real Time Pricing Intervals

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Abstract
A methodology is presented to setup day-ahead Demand Response strategies for commercial office buildings for various Real Time Pricing (RTP) intervals. The electric utility is a summer peaking utility. The buildings deploy Building Automation Systems (BAS). The building owner undertakes commissioning for new buildings and recommissioning for existing buildings. During the commissioning process, in the operational phase with occupancy, real-time data for various HVAC control strategies both for on-peak and off-peak periods are uploaded from the BAS to the Cloud. The building has occupied and un-occupied periods .The data in the Cloud can then be analyzed to arrive at strategy duration times determined from the start time of the control strategy to the time the reduction in KW and kWh values occur say at the end of 5 minutes, 10 minutes, 15 minutes or 30 minutes to one hour. The corresponding outdoor air (OA) temperature is placed in 3^0C bin intervals. Shorter RTP intervals of the order of fifteen minutes or less is likely to become more prevalent to more closely match real time power generation to demand. The electric utility load forecast is based on OA temperature. The day-ahead RTP profile when coupled with day-ahead OA weather data results in the setting up of a time- of- day control strategy schedule by the building operator one day ahead for responding to the RTP. Integrating with a Fault Detection, Diagnosis and System Restoration feature and the new concept, Augmented RTP, should strengthen the reliability of the Smart Grid.

Keywords –Demand Responset; Real Time Pricing; HVAC; Office Buildings; Commissioning; BAS; Control Strategies; Smart Grid

1. Introduction

The need to match power generation to demand is critical to ensure reliability of the Power Grid. Demand Response in conjunction with RTP is a tool employed by many utilities to address this issue. Day-ahead notification of RTP at one hour intervals for commercial buildings and industrial facilities is often utilized. However, shorter intervals of the order of fifteen minutes or less is likely to become more prevalent to more closely match real time power generation to demand for non-residential buildings. The commercial sector in the USA accounted for 36% of the total electric energy consumption in 2015 [1]. According to the CBECS and EIA 2012 survey of commercial office buildings [2], the total floor space of all office buildings with floor space area > 9,000 m^2 is about 0.58 billion m^2. There are 24,000 buildings in this group and the annual energy consumption per building is 309 kWh/m^2. The total annual energy consumption for this group of buildings is 180 billion kWh. Large office buildings, though just 2% of the total building stock, account for 35% of all office floor area. This clearly indicates, that given the start and end times of occupancy in office buildings, most of the occupancy hours and the associated energy consumption occur during the electric utilities' on-peak periods. All the 24,000 buildings are served by central chillers and have Building Automation Systems (BAS). These statistics clearly demonstrate the importance of Demand Response (DR) programs for legacy electric utilities serving commercial office buildings in the USA. One type of DR program called, price responsive, where the utility sends an hour by hour Real Time Pricing (RTP) signal one day ahead directly to the building operator or via a BAS. The RTP can be either based on wholesale energy prices or through the use of real-time retail rates. The 24 hour RTP provides the operator to shed loads during on-peak periods or move loads to favorable on-peak periods or move loads to off-peak periods where the RTP is most favorable.

In [3], the author makes use of modeling and an emulator to come up with control strategies for on-day RTP. These are subject to comfort constraints based on Predicted Mean Vote (PMV). They consider in their study only chilled water reset, ChWR, and control of lighting power density. Depending on the RTP intervals, strategies are grouped under quick responding and those appropriate for longer intervals. It's not apparent as to how accurately they model the building thermal characteristics, control loop performance and interactions among several sub-systems in the HVAC system. Also, the computing time needed with the emulator becomes critical since they propose to accomplish this in real time. The authors of reference [4] focus on developing a model for the centrifugal chiller at one of their campus buildings. They also concentrate on calculating response time for ChWR. Their assumption of chiller motor input varying proportionally with the leaving chilled water temperature is not borne by the performance characteristics for a centrifugal chiller. In this paper, a novel methodology is presented for the building operator to implement HVAC and other control strategies in the BAS a day-ahead to respond to the RTP for an office building.

2. Methodology Development

Consider a large office building with a floor area greater than 9,000 m^2. The building HVAC consists of variable volume systems (VAV) and with a central plant consisting of centrifugal chillers. The building also has an ice storage system. The occupancy is from 7 AM to 5 PM. The building owner undertakes commissioning for new buildings and re-commissioning for existing buildings. During the commissioning process, in the operational phase with occupancy, the correctness of operation of the HVAC system including controls and control strategies and performance of the cooling equipment, backup power system (BPS), Electric Vehicle (EV) battery system and operator interface features are evaluated for each day of each month of the cooling season (May to September). These actions are performed on an hourly basis. The process schematic is shown in Figure 1.

The commissioning is performed according to ASHRAE Guidelines [5], [6], [7]. The process is repeated for un-occupied periods as well. These result in obtaining 24 hour profiles for; building load, chiller load, air-handling-unit (AHU) fan, pump, ice storage charge and discharge, energy conservation measures' impact, lighting, occupancy, outdoor air temperature (T_{OA}), energy consumption, BPS start/stop and EV battery charge/discharge. It must be mentioned that the BAS performs local loop control, daylighting control, condenser water reset, chiller sequencing, zone CO_2 control, integrated economizer control, optimal static pressure reset and Automatic Fault Detection and Diagnosis (AFDD). The rest of the control strategies are initiated by the operator.

For each of the operator initiated control strategies, the corresponding T_{OA} are arranged in 3^0C bin intervals. The building owner after the commissioning period, signs-up with the electric utility for the RTP program. The electric utility is a summer peaking utility. The RTP is sent by email to the building operator or posted on their website one-day ahead. These could be hourly or shorter time intervals of the order of 5, 10, 15 or 30 minutes. For illustrative purposes, 24-hour RTP profiles generated in this paper are shown for each of the summer months for a week day (May through September) in Figure 2 [8]. The on-peak period is from 9AM to 9PM. It can be seen that the off-peak energy cost/kWh is at least 50% lower than that for the peak hour. Figure 3 shows on-peak profile trends for T_{OA} for a hot and a mild day [9] and RTP for a September weekday. Further, comparing RTP for July/August in Figure 2 and with those in Figure 3, it can be seen that both T_{OA} and RTP exhibit similar trends as a function of time- of-day. From the weather station link to the BAS, day-ahead hourly data for T_{OA} is available to the operator. For intervals less than one hour, interpolation is used to calculate $T_{OA.}$ The outdoor air temperature is setup as bin data at 3^0C intervals.

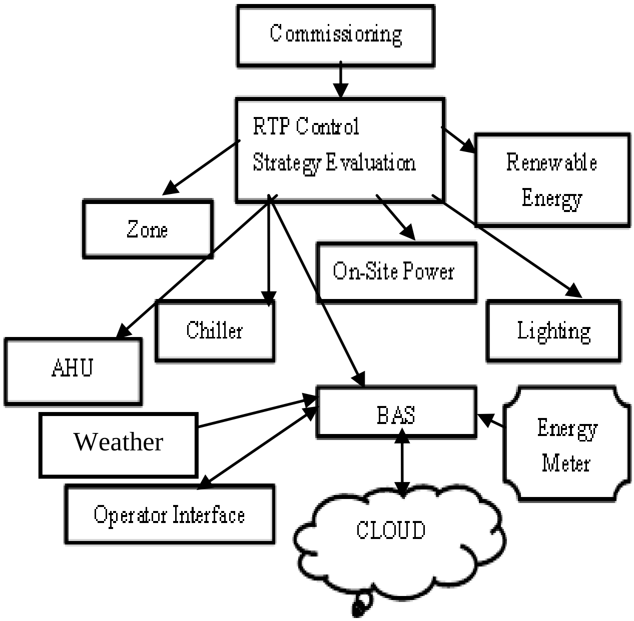

Fig.1 Process architecture for control strategy evaluation

Thus, it is reasonable to assume that the operator can program DR control strategies one-day ahead based on 24 hour T_{OA} profile for the next day. Figure 4 shows the process schematic for operator initiated time-of-day DR strategy implementation to RTP. If there is no response to any DR strategy at any given time, AFDD is activated in the BAS. The corrective action based on the diagnosis is fed back to the operator. The operator then restores the system so that the expected benefits of the DR strategy are realized. The algorithm development and analysis for the AFDD and system restoration feature will be covered in a future work. The operator can intervene to modify the DR control strategies should the measured T_{OA} bin-interval be different from the predicted day-ahead data for the 24 hour period. The methodology developed in this paper appears to be an easier approach than trying to model the HVAC system and equipment and identifying an optimization technique to minimize the energy consumption in real time [10], [11], and [12]. The control strategies used in this paper are available in the literature [13], [14], [15], [16]. Table 1 shows T_{OA} bins as a function of on-peak time-of-day. The RTP interval could, as an example, vary from 5 minutes to 1 hour depending on the RTP structure dictated by the market pricing for the electric utility.

Table1. Control strategy data collection

Bin	Time	RTP Interval	Control Strategy	Strategy Duration	KWh Reduction
13-16^{0}F	7-8 AM				
	.				
	8-9 PM				
16-19 ^{0}C	7-8 AM				
.	..				

For each RTP interval starting from 9 AM, the corresponding control strategy, strategy duration, KW reduction and kWh reduction are identified. The selection of control strategy and its impact on duration time and kWh reduction depends on what time of day the bin temperature occurs. An average value for kWh reduction is calculated to account for variation in its value for any bin temperature as a function of time of day.

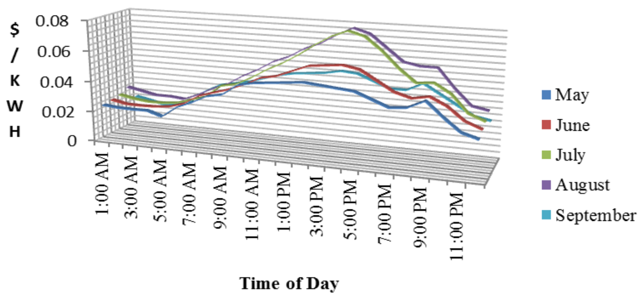

Fig. 2 Example summer months RTP profiles

On a hot or warm day, where one or more zone VAV dampers may be fully open calling for full flow to meet the zone cooling load say from 11AM onwards. This will result in SAR and ChWR being effective strategies only from say 8 AM until 11AM, since the same bin interval temperature occurs for a shorter duration on a hot day compared to a cool day.

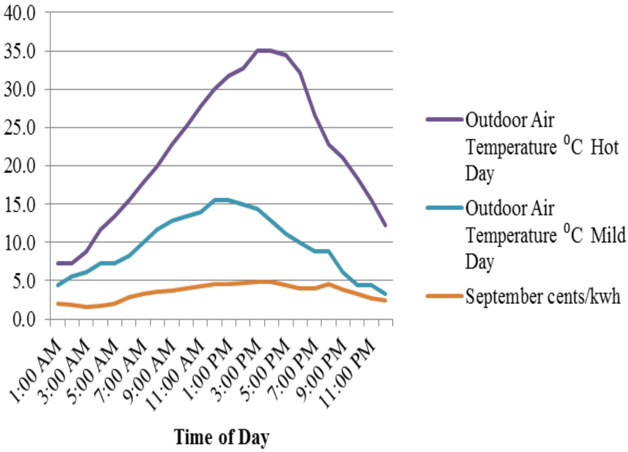

Fig. 3 Comparison of RTP profile and outdoor air temperature profile

Strategy duration is defined as the time from the initiation of the control strategy to the time at which the strategy is terminated. The termination could be due to comfort constraint, equipment constraint, fault detection or operator initiated. The kWh reduction that occurs during the strategy duration time are obtained from the energy meter readings facilitated by the BAS. In optimal start cooling, chillers are used prior to occupancy in the off-peak period till the space temperature reaches the lower end of the comfort dry-bulb temperature range. This temperature is maintained till the start of the on-peak period (9AM). Floating Control is employed without operating the chiller from 9AM till the upper limit of the comfort temperature is reached. Lighting control is achieved by turning off or dimming a bank of lights in the corridors or unoccupied spaces for an hour in the morning say 9-10AM and 3-4PM in the afternoon. In the morning, after the occupancy start time the corridors and hallways maybe busy till the occupants settle in their offices by 9AM. A similar argument can be made for the afternoon lighting schedule when people are likely on the move one hour before the end of occupancy.

In ice storage, charging takes place during the off-peak period. Ice use takes place during the on-peak period. These are functions of outdoor air conditions in the on-peak and off-peak periods and energy cost for chiller use and ice charge capacity. BPS strategy on a warm or hot day is achieved by turning it on one hour prior to the occurrence of maximum T_{OA} and turning it off one hour after the occurrence of maximum T_{OA}. In optimal stop feature, chillers are turned off prior to end of occupancy using the flywheel effect of the chilled water in the piping. Cooling energy potential of outdoor air is used for cooling building thermal mass in the off-peak period whenever T_{OA} is less than the space temperature plus a differential to prevent cycling. The AHU is shut and the outdoor air damper closed when outdoor air dew point is less than the space dew point to prevent condensation in the building space. Since the DR strategies to RTP in this paper is a function of T_{OA} only and not dew point, this feature will come as a part of the energy conservation package of the BAS.

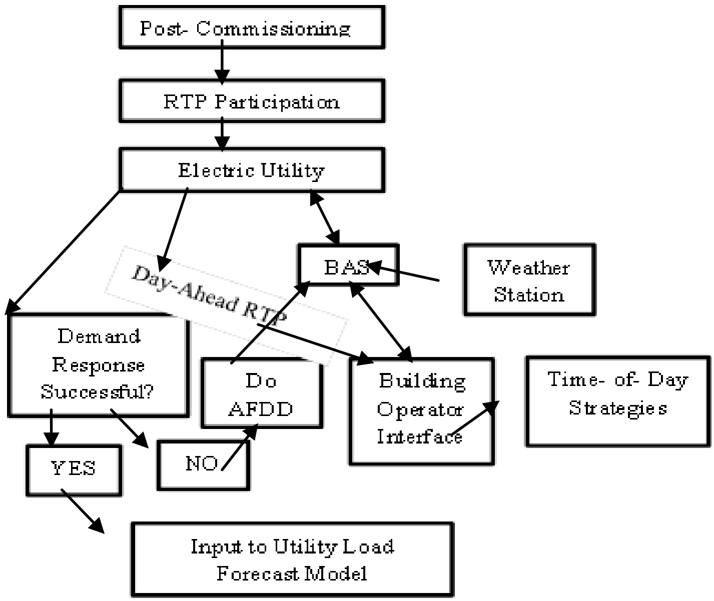

Fig. 4 Process architecture for building response to real time pricing

Figure 5 shows a hypothetical 24 hour load profile for a 500 ton chiller before RTP and after RTP participation on a warm day. It can be seen that for a given a chiller KW per ton, the kWh energy usage is less in the RTP case during the on-peak period and more in the off-peak period compared to the results prior to the RTP participation. The impact of the strategies is shown in Figure 6. The chiller profile above zero-the Y axis as a fraction of chiller full load-represents energy consumption in the on-peak period-9AM to 9PM- and the off-peak period-9PM to 9AM. The profile below zero represents energy savings in the on-peak period due to control strategies SAR, CHWR, ice use and optimal stop expressed as a fraction of chiller full load.

3. Augmented Real Time Pricing

A new concept called 'Augmented Real Time Pricing' (ARTP) is introduced and defined as a RTP offering by the utility where the utility pays the customers for kWh energy the customer generates and sends it back to the grid during the on-peak and off-peak periods.

The kWh energy could come from renewable energy sources such as wind and solar or from other sources including EV battery system during discharge from a fully charged state. The incentive could be based on the same conventional 24 hour RTP tariff that was used for the consumption of kWh. The adoption of ARTP by the electric utility enhances the reliability objectives of the Smart Grid by relieving the stress on the Generation side of the utility. This results in increased participation in the ARTP program by the customers and provides new opportunities for the customers to invest in renewable energy. It must be emphasized that the customer continues to pay for any kWh used during the on-peak and off-peak periods at the RTP tariff. Thus the methodology developed in this paper, to arrive at DR strategies to RTP, provides a practical architecture in meeting the goals of Smart Grid.

4. Conclusion and Future Work

A methodology is presented to address the issue of selecting HVAC control strategies to RTP for an office building. Unlike other methods published in the literature, the building operator programs 24-hour time-of-day schedule for the control strategies one day ahead as a function of $T_{OA.}$ Day-ahead 24 hour weather data for T_{OA} is available from the weather station at the location which is linked to the BAS. The operator schedules the control strategies developed during the commissioning process, by using Boolean operations. These Boolean features are standard in the BAS. The reason for using T_{OA} instead of instead of the 24 hour RTP is the similarity in their trend as a function of time of day. More importantly, when the control strategies are developed during the commissioning process, the customer is not a RTP customer of the electric utility. Under these circumstances, the customer does not receive the daily 24 hour RTP profiles. As discussed earlier, the procedure developed in this paper is far simpler than those based on the RTP real time energy cost minimization method. However, it must be emphasized that the methodology developed in this paper needs to be verified for an actual building. New concept called ARTP has been introduced in this paper.

The development of real time AFDD for RTP needs further study. Research opportunities exist for the electric utility should the customer permit access to his cloud data. In this scenario, it's conceivable the utility could execute on-day control action based on the day-ahead time-of-day control strategy set by the building operator in lieu of the BAS performing it. The AFDD algorithm will continue to reside in the BAS.

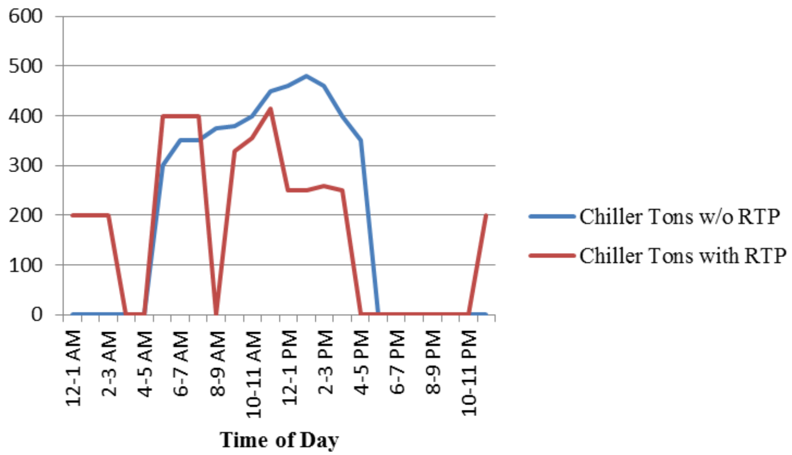

Fig. 5 Example chiller load profile before and after RTP participation

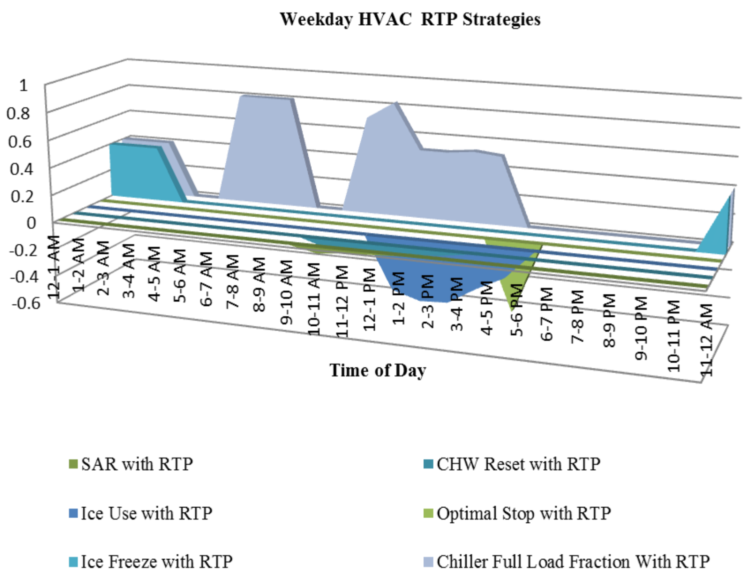

Fig. 6 Impact of HVAC control strategies to real time pricing

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