Application of Predictive Control Strategies in a Net Zero Energy Solar House

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ABSTRACT: The current availability of online weather forecasts, with increasingly abundant and detailed information, facilitates the implementation of predictive control strategies in buildings, a measure that can help in reducing energy consumption and peak loads, and in improving comfort. These forecasts are even more useful in the case of solar-optimized buildings, where the estimation of future conditions (especially solar radiation availability) is essential for planning a sequence of control actions. This paper presents methods to incorporated weather forecasts into the control system of a solar house, focusing on applications for a cold climate. Simulation results employing Simulink (a MATLAB® based tool) are presented for the particular case of a solar house under Montréal weather conditions. It has been found that predictive control, by helping to manage stored thermal energy, becomes essential to enhance the performance of a building integrated photovoltaic thermal (BIPV/T) system. The use of predictive control permits cutting down the utilization of the backup heat source, and the reducing the total electric energy consumption of the heat pump by 23.4%. Simulations indicate that a BIPV/T roof can supply 70% of the auxiliary heating needed by a house in Montréal during the month of February.
Keywords: predictive control, passive solar design, solar-optimized building, weather forecast

INTRODUCTION

The estimation of future weather variables has long been recognized as a powerful tool for improving building control strategies [1, 2]. Before the advent of widely available online weather forecasts, however, alternative approaches were used with limited success. For example, mathematical models based on based on past and present measurements have been used to estimate the likelihood of future weather conditions [1]. Another example is the manual introduction of limited quantitative and qualitative weather forecast information presented in newspapers [3], complementing historical records and current trends, with the aim of developing curves of solar radiation and temperature. Today, in contrast, the Internet makes possible the distribution of very complete, frequently updated, accurate weather forecasts, with very high spatial resolution, and describing many relevant variables: beam and diffuse solar irradiance, temperature, humidity, wind speed, among many others [4]. This paper presents an approach for using weather forecasts to optimize the performance of a solar home. Preliminary results of simulation carried out in Simulink are presented.

SOLAR-OPTIMIZED BUILDINGS

Solar-optimized buildings (often called simply "solar buildings") go one step beyond the concept of passive solar building. Apart from exploiting the potential of passive solar design (e.g., improved building envelope, orientation, fenestration, thermal mass and enhanced natural ventilation), solar-optimized buildings also make use of "active" technologies, such as photovoltaic panels, solar thermal collectors, thermal energy storage (TES) systems, ground source heat pumps and motorized blinds. When correctly designed, these active technologies are integrated in a global, coherent approach with the passive solar aspects. Devices often play more than one function, or play complementary roles. Solar buildings often have a renewable electric generation system connected to the local electric utility, which acts as a storage device. The use of the aforementioned technologies may enable solar-optimized buildings to reach or approach a net-zero energy balance over the course of a year in a more cost effective manner. In other words, the building satisfies its own energy needs.

PREDICTIVE CONTROL

Predictive strategies are useful at two clearly distinct, but very closely related, building control levels [5]:

Supervisory control level concerned with the decision between modes of operation and set-points (usually temperature set-points). This control level is usually associated with relatively long time scales, of several hours or even days. Well-known examples of conventional (non predictive) supervisory control strategies are: having a fixed set-point (constant temperature), "night set-back" (lower nocturnal set-point in winter), or 3 or more set-points during a day. In summer, commercial buildings sometimes use a "night set-up" (let the temperature rise at night, when the building is unoccupied).

At the supervisory level, knowledge −or a good estimate− of future loads permits establishing a sequence of temperature set-points to achieve reductions in energy consumption or peak loads. A method to accomplish this objective consists of using analytical or numerical techniques to define the sequence of set-points while optimizing a desired objective function (cost, energy, peak loads). This approach, called *optimal control*, has been used to actively incorporate the thermal mass of conventional building [6, 7] as a passive thermal storage device. It has been experimentally found [7] that an optimal control strategy can outperform a "night set-up" strategy during the cooling season by cooling the building at night.

An extension of the optimal control strategy has been the use of thermal energy storage (TES) devices (active storage) as a complement to the thermal storage capacity of the building itself. Most optimal control studies have dealt with the control of commercial buildings, which are cooling dominated, and where the reduction of electricity peak loads is an important issue due to the associated cost. These studies have often focused on the utilization of ice storage systems, either optimizing only the use of the TES [8]; or optimizing the coordinated operation of the TES (active storage) and the building's thermal inertia (passive storage) [2, 9], as shown in Figure 1.

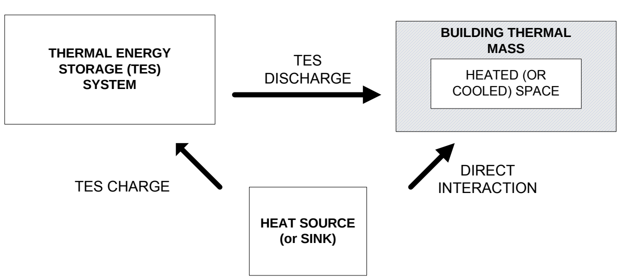

Figure 1: Typical configuration of a TES System and its interaction with the mechanical system and the building's thermal mass. Adapted from [5].

Local control level deals with the operation of specific systems to match the set-points prescribed by the supervisory control. This level is associated with smaller time scales, ranging from a few minutes to a couple of hours. The final objective is the determination of the position of the actuators (valves, dampers, pumps, blinds, etc.) at every time step.

Many methods exist for managing local-control loops in HVAC systems [10], ranging from traditional on-off controls and PID, to advanced techniques such as adaptive control. Optimal control has been applied to supply temperatures and flow rates [11]. Forecasted loads have also been incorporated in the local-control loops [12].

PREDICTIVE CONTROL IN SOLAR BUILDINGS

Comparatively less work has been done in the implementation of predictive control in solar-optimized buildings. However, although solar-optimized buildings can be designed in many different ways, they share features which make them especially suitable for the implementation of predictive control:

- Control of storage, collection and delivery of the solar energy resource is essential.
- The operation of some active technologies (heat pumps, heat recovery fans, etc.) requires significant amounts of energy. Therefore, criteria such as efficiency, cost, and peak load charges (when applicable) should be considered.
- Large thermal mass implies long time delays, which should be taken into account by the local control loops.
- Solar heat gains, whose effect on the room air temperature is only perceived several hours later, can be partially controlled by the use of motorized blinds or curtains to contribute to the prevention of overheating.
- Better management of the energy storage capacity could help in load management, thus reducing the required rating of costly equipment.
- Predictive energy management could help extend the autonomy of the building in case of an emergency.

ALSTONVALE NET ZERO HOUSE

The Alstonvale Net Zero House (ANZH) is presented as a case study for the development of predictive control strategies in solar buildings. Details of the ANZH, an advanced solar-optimized 2-storey house, have been described elsewhere [13]. This house is currently under construction (see Fig. 2) in Hudson (Québec). Its main energy supply will consist of a 7.35 kW building-integrated photovoltaic/thermal (BIPV/T) roof. As its name indicates, this roof will produce both electricity and heat. A variable speed drive fan draws exterior air under the PV panels, thus recovering a large fraction of the solar radiation not used for electricity generation. The heated air from the BIPV/T roof passes through an air-to-water heat exchanger which permits using it as the heat source for two small heat pumps. These heat pumps

Figure 2: Alstonvale Net Zero House (under construction)

operate in parallel (or one at a time) to charge a 4000 L water tank playing the function of an active thermal energy storage system (TES). When the BIPV/T air temperatures are high enough, the TES tank can be charged directly from the heat exchanger. If the tank needs charging, and the BIPV/T air temperatures are not satisfactory, one of the heat pumps extracts heat from a ground source loop. There are 4 modes of operation: (a) direct operation between the heat exchanger and the tank; (b) BIPV/T air with 2 heat pumps; (c) BIPV/T air with one heat pump; and (d) one heat pump using the ground as a heat source (Fig. 3).

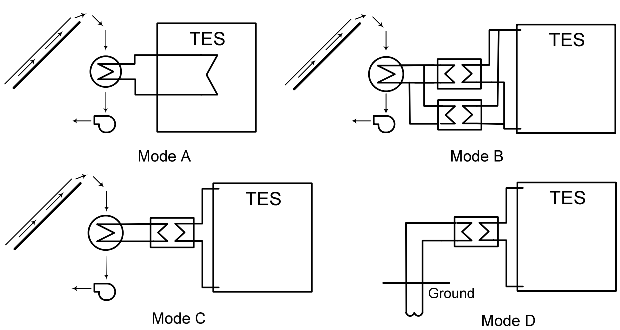

Figure 3: Modes of charging the TES tank.

The heat is delivered to the house through a radiant floor heating system installed in the concrete floors. A masonry wall (forming a small atrium that communicates the lower and upper floors) also adds to the total thermal mass. The floors and the masonry wall receive solar heat gains passing through the large south-facing windows (covering about 40%) of the south façade. Properly sized overhangs and internal motorized theatre curtains help to prevent overheating. A “solar chimney” on the roof of the house enhances natural ventilation during the summer. The thermal mass of the house, especially the concrete floor, acts as a passive storage system (provided that some degree of temperature fluctuation is tolerated). Since the radiant heating system communicates the TES tank and the concrete floor, heat transfer is possible between these two storage media.

The predictive control strategies developed for the ANZH have focused on the supervisory control loop, by using the possibilities of heat exchange and thermal storage offered by the active and passive TES (Figure 4) based on estimates of expected solar radiation. However, refinement of local control remains a necessity especially because of the time constants associated with radiant floor heating.

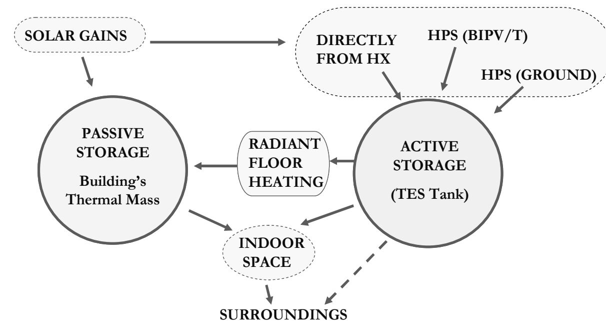

Figure 4: Heat exchange possibilities in the ANZH.

TESTING OF CONTROL STRATEGIES

Simulink is a well-known component of MATLAB® developed for the simulation of dynamic systems [14]. It has become a popular tool for building simulation [15]. One of its advantages is the ease of implementation of different control strategies, a relative weakness of many simulation packages. Simulink® also permits the use of ready made PID control blocks, dead-bands, transfer functions, noise generators, and other useful mathematical functions. Control strategies for the ANZH were first simulated using M-files (MATLAB’s programming language) [16]. However, although Simulink runs in a MATLAB® environment, its graphical interface is a good illustration of the connection between different systems, and facilitates “debugging” and the development of subroutines (Figures 5 and 6).

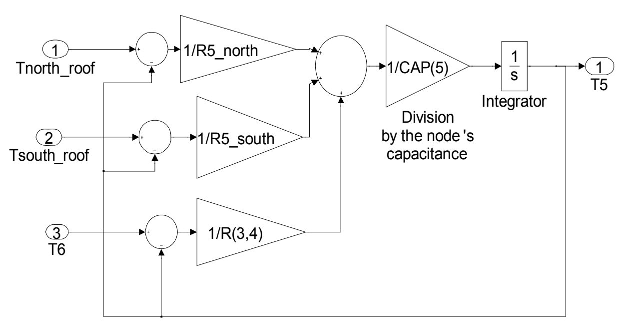

Figure 5: Representation of a heat balance equation in Simulink

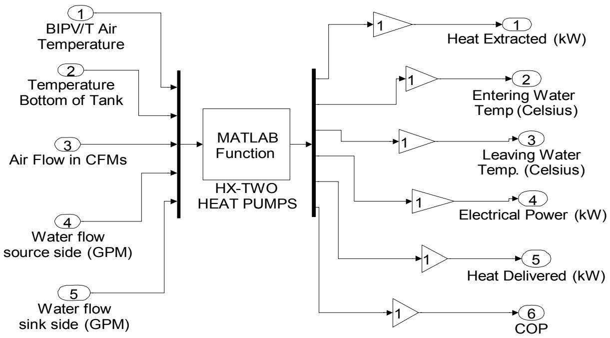

Figure 6. Inputs and Outputs linked to the heat exchanger in Simulink (Two Heat Pumps Model).

Previously developed M-files for the TES tank, BIPV/T roof, heat exchanger and heat pump(s) interaction have been adapted into Simulink. A typical meteorological weather file (TMY) file for Montreal was adapted as a set of Simulink signals.

The following control strategies have been implemented:

Strategy 1 – **No predictive control**. The tank set-point is fixed at 48 °C and the room air set-point is fixed at 23 °C. The BIPV/T fan flow rate is kept constant at 1600 CFM. If the exit air is at least 3 °C higher than the bottom of the TES tank, then direct exchange between the heat exchanger and the tank (mode A) takes place; if the exit air is below 48.9 °C (the operation limit of the heat pump) but above 10 °C, then two heat pumps are used (mode B); if the air is between 3.5 °C and 10 °C (mode C); finally, if the air is temperature is below 3.5 °C and *the tank top temperature is below 35 °C*, then mode D (ground source operation) is activated. In this latter mode, the ground source is operated until the tank temperature is 2 °C above that limit (i.e., 37 °C).

Strategy 2 – **Predictive control with fixed BIPV/T fan speeds**. Same as above, but the control system decides on tank and room air set-points according to the solar radiation expected for the current day and for the following day. For instance, if the current day is expected to be sunny and the next day overcast, then the tank set-point is increased to 48 °C. For two consecutive sunny days, then the tank set-point is only 40 °C, as it is not likely that much heat will be needed.

Strategy 3 – Predictive control with variable fan speeds. Same as Strategy 2, but in this case the fan speed is allowed to vary between 800 and 1600 CFM according to the measured solar radiation.

Strategy 4. Similar to Strategy 3, but in this case mode B is activated when the air temperature is between 20 °C and 48.9°C, mode C is activated between 3.5 °C and 20 °C, and mode D for T < 3.5 °C.

Strategy 5. Similar to strategy 3, but in this case the ground source loop is only used if the tank temperature drops under 30°C (instead of 35°C).

Strategy 6. Similar to strategy 3, but the ground source is only used if the TES temperature drops below 28 °C.

Table 1 summarizes the characteristics of the analyzed control strategies.

Table 1: Summary of control strategies (relevant features of each strategy are highlighted). Te *is the exit temperature of the BIPV/T air, and* Tb *is the temperature of the bottom of the TES*

	Strategy 1	Strategy 2	Strategy 3
Mode A	Te > Tb + 3°C	Te > Tb + 3°C	Te > Tb + 3°C
Mode B	10 °C ≤ Te < 48.9 °C	10 °C ≤ Te < 48.9 °C	10 °C ≤ Te < 48.9 °C
Mode C	3.5 °C ≤ Te < 10 °C	3.5 °C ≤ Te < 10 °C	3.5 °C ≤ Te < 10 °C
Mode D	Tb < 35 °C	Tb < 35 °C	Tb < 35 °C
Fan Speed	Fixed	Fixed	Variable
Comment	Reference case (no predictive control)	Predictive control (variable set-points)	Predictive control (variable set-points)

	Strategy 4	Strategy 5	Strategy 6
Mode A	Te > Tb + 3°C	Te > Tb + 3°C	Te > Tb + 3°C
Mode B	20 °C ≤ Te < 48.9 °C	10 °C ≤ Te < 48.9 °C	10 °C ≤ Te < 48.9 °C
Mode C	3.5 °C ≤ Te < 20 °C	3.5 °C ≤ Te < 10 °C	3.5 °C ≤ Te < 10 °C
Mode D	Tb < 35 °C	Tb < 30 °C	Tb < 28 °C
Fan Speed	Variable	Variable	Variable
Comment	Predictive control (variable set-points)	Predictive control (variable set-points)	Predictive control (variable set-points)

RESULTS

The aforementioned control strategies were applied for the month of February. The energy delivered to the TES tank for each mode of operation, and the power consumption of the heat pump(s) is presented in Table 2.

Table 2: Heat delivery and heat pump power consumption for the 6 control strategies (S1 to S6) in kWh

	S1	S2	S3	S4	S5	S6
Mode A	0.0	0.0	0.0	0.0	2.8	7.68
Mode B	1670.0	1089.0	1394.0	987.0	1757.0	1806
Mode C	345.2	296.4	80.0	473.0	84.0	86.87
Mode D	1055.0	1400.0	1313.0	1327.0	916.9	835.6
Heat Pump Consumption	820.7	699.8	699.6	682.5	645.2	628.1

Operation mode A is practically never used in the month of February, as it is rather unlikely to obtain BIPV/T at temperatures considerably higher than those of the tank. There is a noticeable improvement if the predictive control is used to change the temperature set-points of the house and the TES tank (Strategy 2). Changing the fan speed depending on the solar radiation (Strategy 3) did not improve the overall consumption of the heat pump versus Strategy 2, but the percentage of the heat provided by the ground source loop was slightly reduced. Changing the temperature intervals for the operation of one or two heat pumps (Strategy 4) did not alter the performance of the system.

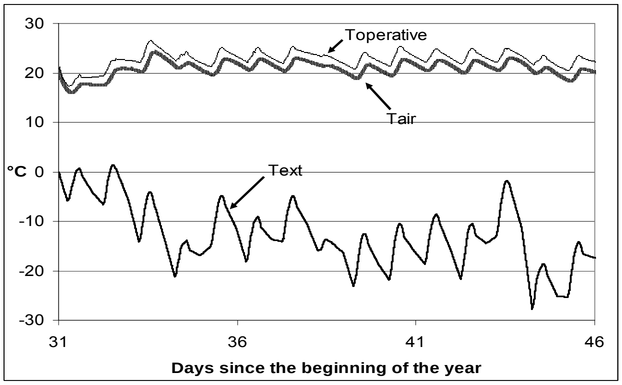

Figure 7: Exterior temperature, indoor air temperature and operative temperature for the first February 1-15 (Strategy 6).

An adjustment that had a significant effect was the reduction of the temperature required for the use of the ground loop (Strategy 5) from 35 °C to 30 °C. Although, the heat pump electrical consumption was only reduced by 5.5%, the fraction of thermal energy provided by the ground loop was reduced from 47.6% to 33.2%. Interestingly, this control strategy also permitted the direct use of the heat exchanger (mode A) during a brief period of time. The last control strategy (Strategy 6), with a further reduction in the coldest temperature tolerated without using the heat pump, showed again some improvement: the electric consumption of the heat pump is the smallest of all the strategies, the ground source loop only provides 30% of the required energy, and the use of Mode A is slightly increased. Results observed in strategies 5 and 6 are to be expected, since it is easier to supply heat with the BIPV/T to a colder water tank. Satisfactory temperature results were obtained (Figure 7).

Figures 8 and 9 compare the results in tank temperature variation obtained for Strategies 3 and 6. Strategy 3 guarantees higher temperatures for the TES tank. However, Strategy 6 makes it easier for the BIPV/T to raise the temperature of the tank.

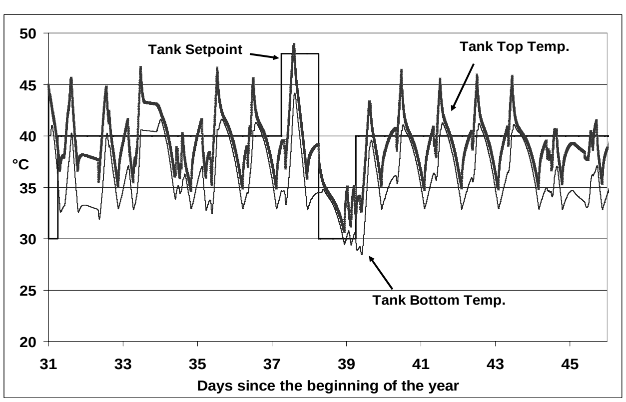

Figure 8: Tank set-points, and simulated tank top and bottom temperatures (Control Strategy 3).

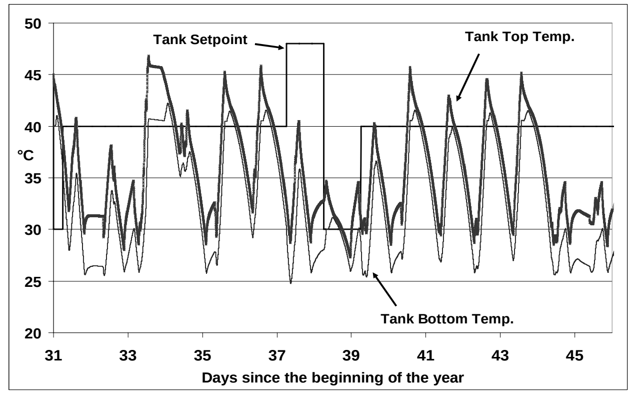

Figure 9: Tank set-points, and simulated tank top and bottom temperatures (Control Strategy 6)

Figure 10 shows the variation of the fan speed for the control Strategies from 3 through 6. The fan speed tracks closely daily fluctuations of solar radiation. An improvement on this control strategy would be to also use exterior temperature together with the solar radiation to determine the optimal operating point for the fan. Since the exit temperature of the BIPV/T air also depends on the wind speed, this parameter should be considered in the determination of the optimum operating point for the fan.

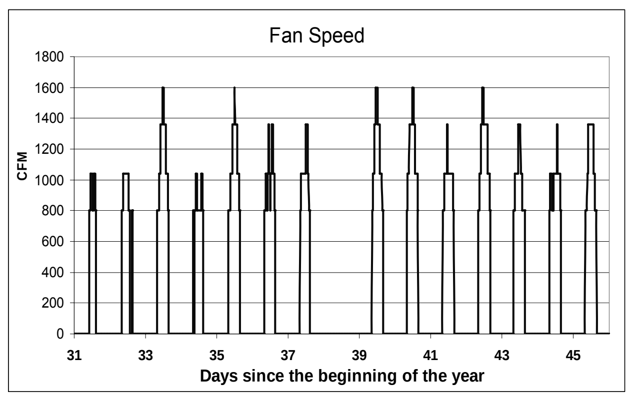

Figure 10: Fan speed variation (Control Strategy 6).

WEATHER FORECASTS

These strategies will be experimentally tested in the ANZH when its construction is completed during this year. In preparation of this implementation, a MATLAB program has been written to parse and analyze forecasts published by Environment Canada every 12 hours for specific Canadian locations [17]. The information provided includes temperature, wind speed, wind direction, humidity, probability of precipitation, precipitation and cloud cover. From the expected irradiance on a horizontal surface, calculations can be made to estimate the expected irradiance on any surface of interest, such as a plane where a photovoltaic system is installed (such as the roof) and the corresponding electricity output for a given air flow rate (Figure 11). As a preliminary test, a DOS script has been written to execute this MATLAB program every twelve hours, and

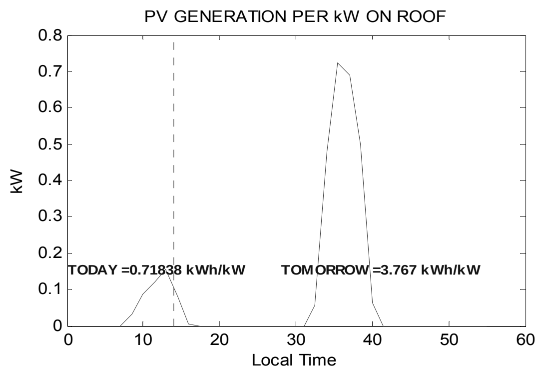

Figure 11: Forecasted photovoltaic production for two days (January 19th to 20th, 2009)

email a plot of relevant variables to interested recipients.

CONCLUSION

This paper has presented predictive control strategies for supervisory control of solar-optimized buildings, with applied to a case study: a net-zero energy demonstration house in Hudson (Québec), in the vicinity of Montréal.

It was found that by anticipating weather conditions over a 48 hour horizon, the solar fraction utilization can be significantly increased, and the need for a backup energy source can be substantially reduced. It is often advisable to let the temperature of the active TES system fall below the set-point in order to prevent the unnecessary use of the backup heat source (ground source). These actions reduced the electrical energy consumption of the heat pumps by 23.4% (Strategy 6 versus Strategy 1). Strategy 6 shows it is possible to provide nearly 70% of the required auxiliary heating energy with the BIPV/T roof in the month of February in Montréal.

Future work will focus on the development of local-level control strategies for the control of different radiant floor heating zones in the building.

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