Model Predictive Control Technique for Energy Optimization in Residential Sector

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***Abstract*—Over the years the energy needs have increased dramatically and we have become aware that our needs were and are having implications on the environment in which we live. Increasingly people are aware to saving electricity by turning off the equipment that is not been used, or connect electrical loads just outside the on-peak hours. However, these few efforts are not enough to reduce the global energy consumption, which is increasing. Regarding the field of optimization, researchers throughout the world have been making an effort in introducing better control schemes, both in industry and domestic sectors, for all types of loads from small lamps to large motors. Much of the reduction was due to mechanical improvements; however, with the advancing of the years' new types of control arise. All these factors provide a motive in this paper for introducing a new consumption reduction method in some residential loads via the implementation of Model Predictive Control (MPC). A single cost function is required to set the reference output near the goal, and consequently through the variation of this cost function by changing the weights, thus specific control actions have priority over the remaining actions. Therefore, it is possible to have different goals during the day, determining the possible savings for each appliance that can be made during on-peak, mid-peak, off-peak and by providing simulations upon 24 hours in the household.**

Keywords—Model predictive control; Energy management; Residential building; Variable Cost Function Weights.

I. INTRODUCTION

The energetic status of the world has been intensely altered during the last 40 years, not only by the increase in demand for all of the energy sources but also the role of each source at a global level. With a growing interest in using alternative energy sources for generating electricity, the main developed countries have put in place investment plans and incentive policies for implementing them. Consequently, given any type of scenario, the energetic efficiency optimization of any sort of system is a strategic factor in sustainable energy management for all types of energy buildings, and thus has been a major focus for researchers, stakeholders and policy makers [1].

Facing a constant growing demand for energy, out of the box strategies have to be applied at various stages of human activity. All the sectors have to endorse efficient use of energy, sectors such as the industrial and the residential sectors, in which studies stated that the last has been accountable for 31% of the global energy requirements that includes domestic consumers [2]. This signifies that a growing amount of electronic appliances and devices in a typical dwelling create space for efficiency increases on energy consumption and combined operations can be made to tackle energy waste in dwellings [3]. A possibility is implementing new tariff policies related to demand response programs that assist the customer with the alteration of their electricity consuming behaviors [4]. An alternative method consists in modernizing the control equipment specifically the domestic appliances working with regulating temperature.

The space heating to improve thermal comfort in dwellings and workplaces seems to be particularly relevant. For instance, as of 2008, circa 50% of the total energy demand for heat generation was utilized with the purpose of space heating [5]. Conventionally, in a usual dwelling, the equipment with the greater energy consumption is the one that offers heating and cooling (i.e. water heater (WH), air conditioning (AC), and less significantly the refrigerator (RF)) [6]. By adopting energy efficiency measures there is room for real and tangible potential for energy savings that can reach up to 30% [7]. Consequently, one of the methods towards the goal of reducing the energetic demand is by modernizing the control technology that runs such types of home appliances. With the purpose of regulating the temperature the cooling and heating equipment utilize typical ON-OFF solutions. Given its low production price and that is so common the ON-OFF devices have proven to be the first choice by appliance manufacturers.

Many researchers have been investigating diverse control methods to cope with energy efficient utilization of electric loads of appliances in dwellings. Types of control such as employing fuzzy logic [8], PID control, artificial neural networks, MPC, and so on [3].

The MPC is an advanced feedback strategy targeting control systems with input, output and state constraints [9]. The objective of MPC is to find the control input applied to a system by calculating an optimal control problem solution. That is, a control law which maintains system response within known limits through the specification of constrained operative conditions. A key aspect of MPC based control problem formulation requires an explicit use of a mathematical model of the system, i.e. the control algorithm estimates system states variable over a future time horizon in order to generate the optimal control sequence. The MPC has the capacity to control nonlinearities while simultaneously satisfying the constraints of the system. This method has been subject of increasing popularity in different fields of application [10].

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In the literature, various different MPC schemes have been developed aimed at the residential sector such as those that are utilized with the intention to improve the dwelling thermal comfort, decrease the peak load, and reduce the energetic expenses [11]. Generally, the MPC tool is intended for ventilation, heating, cooling and air conditioning (HVAC) equipment with the intention of minimizing the energetic expenses for more than just a simple reduction of the consumed energy [12]. Another implementation was the application of a MPC based thermal dynamics for office building energy management purposes [13] while in [14] a MPC strategy for energy efficient buildings with demand-response is proposed.

As a part of MPC controller design process there is a need to set up the control objectives as a singular cost function. To satisfy all the control objectives at the same time is not possible since usually the particular control actions have an increased significance over other actions. Consequently, performance compromises must to be reached among the contending control objectives. Thus, to the input and output variables of the process are associated specific weight factors, and as a result, enhancing the prioritization of the individual performance in order to carry out the control restricted by process constraints. Thus, MPC utilizes distinct weights on tracing errors [15] and the attribution of control variables weight is called MPC tuning.

Overall the MPC presents several significant advantages such as the process model integration on controller facilitates the detection of the static and dynamic interplay among the system variables, the capability to impose constraints on input and outputs within specified ranges while for several output variables the control estimations allow the selection of optimal set points, and a detailed and accurate system model maximizes MPC performance. However, a main drawbacks stand out. To solve an open-loop optimal problem a large amount of calculations is executed at every sampling instant. Thus, the controller implementation requires high computational capabilities to support optimization problem solution at every sampling instant [9].

The aim of this paper is to focus on the MPC weight tuning influence on domestic cooling and heating appliances with the aim to reduce the energetic consumption and cost. Three domestic appliances are utilized for MPC tuning evaluation: the room temperature control by AC, WH, and RF. This study follows the path initiated in previous works [16] [17] [18].

The paper is organised as follows. The MPC theory is described in Section II. Section III presents the domestic appliances under study and the testing methodology for MPC performance evaluation. Section IV contains the simulations and provides results discussion. Finally, the conclusions are summarized in Section V.

II. OPERATION PRINCIPLES OF THE MODEL PREDICTIVE CONTROL

Controller design methodology lies on time horizon prediction calculations. That is, the controller plays with future outputs and future control signals to keep to a feasible extent the system close to the set point reference.

Finite control horizon for the future outputs is called prediction horizon *N*. The time frame implies that the set of future outputs are estimated at every sampling instant *k*. The estimated outputs are formulated as $y(k+i|k)$. Thus, *k* represents the current control interval and $k+i$ denotes the time instant associated to the future state prediction for $i=1...N$. Future control signals $u(k+i|k)$, $i=0...P-1$, in which *P* is the control horizon, are estimated by a satisfying performance criterion or cost function. In other words, the input set calculated consist of the current input $u(k)$ and $P-1$ future inputs. These inputs are estimated in such way that calculated future outputs $y(k+i)$ allow the system to reach the set-point in an optimal form.

It should be noticed that despite a set of *P* inputs are determined at each sampling instant, just the first element is actually used for generating the control move. The performance index is built using a quadratic function that takes into account the error value between the estimated future output signal $y(k+i)$ and set point reference $r(k+i)$ for obtaining the control law $u(k)$. From a control system point of view, the cost function consists of three standard terms, each one with a weight factor that penalizes the prediction variable effort. In other words, it establishes control objectives with an output penalty, an input penalty and an input rate penalty. Thus, the general expression for an objective function is:

$$\min_{U} \ \varphi(P,N) = \varphi_y + \varphi_u + \varphi_{\Delta u} + \varphi_\varepsilon \tag{1}$$

where φ_y optimizes the error due to the output reference trajectory, φ_u is the control signal tracking error, φ_u minimizes control signal increments and φ_ε is associated to constraint violations. Since the cost function has a quadratic form, a quadratic programming *(QP)* solver generates an input vector Ψ solution as:

$$\Psi = \left[u(k|k)^T \ u(k+1\,|\,k)^T \ldots u(k+P-1\,|\,k)^T \right] \tag{2}$$

In case of domestic appliances, a single-input and single-output (SISO) model is only necessary. Therefore, output variables number is limited to one. Then, the performance index for minimizing the tracking error is as follows:

$$\varphi_y = \sum_{i=1}^{N} \left\{ \omega_i^y \left[r(k+i\,|\,k) - y(k+i\,|\,k) \right] \right\}^2 \tag{3}$$

where $r(k+i|k)$ defines the set-point reference, $y(k+i|k)$ is the estimated output scaled by a weighting factor ω_i^y that allocates more relevance to the term.

Input signal tracking control objective is:

$$\varphi_u = \sum_{i=1}^{P} \left\{ \omega_i^u \left[u(k+i\,|\,k) - u_t(k+i\,|\,k) \right] \right\}^2 \tag{4}$$

where $u(k+i|k)$ is the control signal, $u_t(k+i-1|k)$ is the goal to be reached by the control signal. The difference error is multiplied by a weighting coefficient ω_i^u that gives more importance to this term.

Input signals wide variations are penalized to no allow abrupt changes on input variables. The equivalent cost function term is defined as:

$$\varphi_{\Delta u} = \sum_{i=1}^{P} \left\{ \omega_i^{\Delta u} \left[u(k+i\,|\,k) - u_k(k+i-1\,|\,k) \right] \right\}^2 \tag{5}$$

where $u(k+i-1|k)$ is the input signal from the previous sampling instant $k-1$ and $\omega^{\Delta u}$ penalizes high differences between successive estimated input signals u_k.

Constraint violation performance index is formulated as:

$$\varphi_\varepsilon = \rho_\varepsilon \, \varepsilon_k^2 \tag{6}$$

where ρ_ε is a constraint violation penalty weight and ε_k is a slack variable at control interval k.

Weights ω_i^y and ω_i^u must be tuned to guarantee the system performance desired. For instance, giving more importance to weight ω_i^y in preference to the weight ω_i^u, the controller goal is to estimate successive sets of future outputs that minimizes the predicted divergences from the set point reference. On contrary, if ω_i^y is reduced, then the gap between the reference tracking to the plant output is going to rise.

MPC can be implemented considering constraints in the minimization problem. That is, fixing bounds in the amplitude and in the slew rate of the variables, the controller forces the system operation to respect physical operational limits.

Therefore, the formulation of a quadratic programming based constrained MPC is given by the Eq. 1 and the following constraint expressions:

$$\begin{aligned} & y_{min}(i) - \varepsilon_k \zeta^y_{min}(i) \le y(k+i\,|\,k) \le \\ & \le y_{max}(i) + \varepsilon_k \zeta^y_{max}(i), i = 1:N \end{aligned} \tag{7}$$

$$\begin{aligned} & u_{min}(i) - \varepsilon_k \zeta^u_{min}(i) \le u(k+i-1\,|\,k) \le \\ & \le u_{max}(i) + \varepsilon_k \zeta^u_{max}(i), i = 1:P \end{aligned} \tag{8}$$

where y_{min} and y_{max} are the minimum and maximum limits of future outputs, the parameter ζ is a dimensionless controller constant and the lower and upper bounds for the control signal are represented by u_{min} and u_{max}, respectively.

III. METHODOLOGY AND CASE STUDIES

A. Methodology

The testing framework consists of three domestic appliances commonly found in residences whose function is to provide heating and cooling services: WH, RF and AC. This set of loads where chosen due to their energy intensive usage and consequently their significant contribution to home electricity bill.

The conventional thermostatic control serves as a reference to the MPC. As a consequence, the energy required to operate the appliances, the cost of using energy spread during off-peak, mid-peak, and on-peak along in conjunction with the temperature variation designed as function of weight selection associated to the manipulated variable and process output as an element of the cost function. The assessment of the energy cost is based on the prices practiced in the Canadian residential market and is utilized throughout a period of 24 hours. The MPC controller is explored with two different weighting sets in order to evaluate the impact on electric bill reduction goal. As the calculation time horizon, P control moves number is set to 4 and 12 is the set of N predicted outputs.

B. Case Studies

i) Household

The acclimatization of the room is provided by AC system having a cooling capacity of 8900 BTUs (2.608kW). Heat exchange with the external environment through the external wall of the room, it is the main factor of disturbance to maintain the internal temperature in thermal comfort level desired. In order to test both control strategies, the rate of heat loss/generation through the external wall of the room is modelled using a temperature based time series with significant wide thermal amplitude variation upon 24 hours. The TH device is configured with a setting of +/1° referred to a temperature of 23ºC. MPC cost function is instructed to limit the temperature variations on the same range. That is, between 22.5ºC and 23.5ºC. The greatness of the physical parameters is obtained from [19]. The transient thermal model of the room equations is represented as [20]:

$$\frac{dT_w}{dt} = \frac{Q_s}{C_w} + \frac{T_{out}}{R_w C_w} + \frac{T_{in}}{R_w C_w} - \frac{2T_w}{R_w C_w} \tag{9}$$

$$\frac{dT_{in}}{dt} = \frac{(Q_{in} - Q_{ac\_ht})S(t)}{C_{in}} - \frac{T_{in}}{C_{in}}\left(\frac{1}{R_w} + \frac{1}{R_c}\right) - \frac{T_w}{R_w C_{in}} \tag{10}$$

where Q_{ac_ht} is the thermal source due to AC, Q_{in} is the heat to be removed from the room, T_{out} is the ambient temperature, T_{in} is the room's temperature, T_w is the wall temperature, C_w is the thermal capacitance of the wall, R_w is the thermal resistance of the wall, R_c is the thermal resistance of windows, C_{in} is the thermal capacitance of the indoor air and $S(t)$ is a binary variable that emulate the turn-on and turn-off of the thermostat. The AC operation is a power switch block without internal loss.

ii) Water heater

The WH unit heats the water to be used on personal hygiene activities by the house habitants. Hot water consumption has a peak-hour at early on the morning and at evening before the sleeping period. Thus, temperature regulation system must maintain the water enough hot during those peak-periods.

The heating element inside of WH is rated at 4.5kW and 184 L is the reservoir capacity of the unit. TH set point (SP) is set to 55ºC with a hysteric range of +/-1.5 ºC. The same temperate fluctuation band is adopted for MPC configuration. WH external wall temperature is fixed at 23 ºC.

Modelling of WH follows the method presented in [21]:

$$\frac{dT_w}{dt} = \frac{mC_p}{C_w} T_{inlet} + \frac{UA}{C_w} T_{amb} - \frac{UA + mC_p}{C_w} + Q_{eg}\eta \tag{11}$$

where m is the water mass, C_p is the water specific heat, C_w is the thermal capacitance of the wall and UA is the fibre glass characteristic, Q_{eg} is the heating element electric rated power and η the WH global efficiency.

iii) Refrigerator

The temperature of the interior is normally regulated by thermostatic relay. Opening the RF's door increases the energy consumption to recover the previous internal temperature setting. The thermal dynamic behaviour is approximated with the Eq. 9 and Eq. 10. The conventional control is compared to MPC alternative considering a RF simulated with a power rating of 0.23kW (RF's compressor motor nominal power rating).

The MPC system is set up to preserve the internal temperature between 3.9ºC and 5.1ºC. Disturbing events are recreated with two door opening closing sequences, which are simulated at 10-11 pm and at 14-15pm respectively.

IV. RESULTS AND DISCUSSION

This section presents the essential outcomes by comparing two sets of MPC weights on controller performance versus the thermostatic relay response.

A. Transient response characterization of controllers

i) Case 1: Air conditioner controlled residential building temperature

The performance of the MPC technique is presented in Fig. 1, where two different weights set are employed to tune the controller and compared to the thermostatic approach. Data shown is related to the AC energy consumption, room internal temperature and environment temperature.

As expected the room temperature when regulated by the thermostat shows a maximum and minimum deviation about the set-point, dictated by thermostatic hysteric characteristic. On the other hand, room temperature profile is more erratic with the AC unit actuated by a MPC type controller.

By applying different weighting set to the MPC controller, it can be seen that one of MPC weight set overpass the higher limit of the temperature regulation range, although the deviation is very small. In terms of temperature variation, the MPC shows lower amplitude.

ii. Case 2: Water heater

In Fig. 2 one of the MPC weight set clearly worse the MPC performance since the temperature evolution does not respect the input constraint. In fact, temperature constraint violation can surpass 1ºC. In another period of the day, the same weight set denotes again some visible deviation.

iii. Case 3: Refrigerator

The simulation in Fig. 3 points out that the TH controller confines easily the successive disturbances impact, due to its hysteric nature. That is, in the first disturbance event which consists of opening the fridge's door several times in a short amount of time, the controller performs a sequence of opening and closing of the switch associated to the TH. As for the next disturbance with the door kept open for a longer time, the refrigerator consumes additional energy to overcome internal cold air loss.

In this simulation scenario both MPC weight sets lead to similar regulation responses. In addition, in both tuning sets when the second disturbance arrives, the performance response is insufficient, allowing the temperature rise observed in Fig. 3.

B. Energy consumption and electric bill savings

Tables I, II and III gather economic and electric nature data to characterize energy usage efficiency as function of the controller type employed. The energy costs associated to each time frame tariff of the day are also illustrated. One can see at Table I and Table II that MPC weight set 2 enables higher energy consumption reduction in relation to MPC weight set 1, despite its poorer performance in regulating the temperature according to the output constraint. Consequently, the second controller tuning set presents the lowest energy bill.

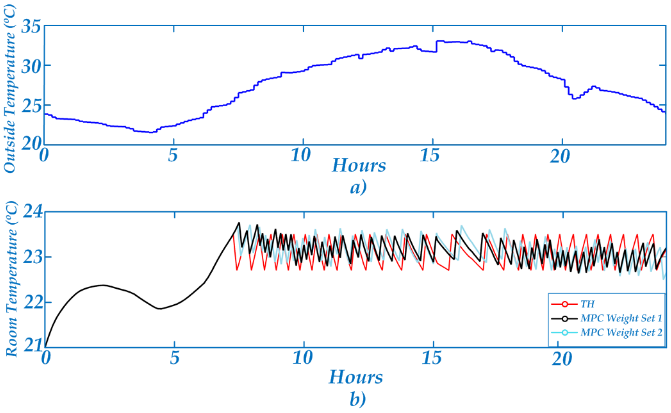

Fig. 1. Air conditioner operation: a) Ambient temperature b) TH and MPC responses

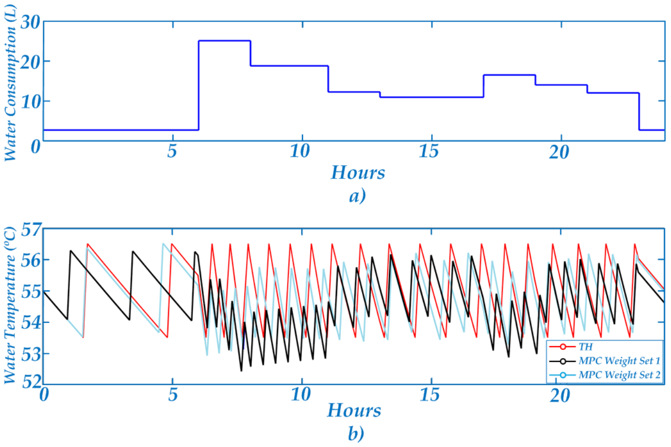

Fig. 2. Water heater operation: a) Water consumption b) TH and MPC responses

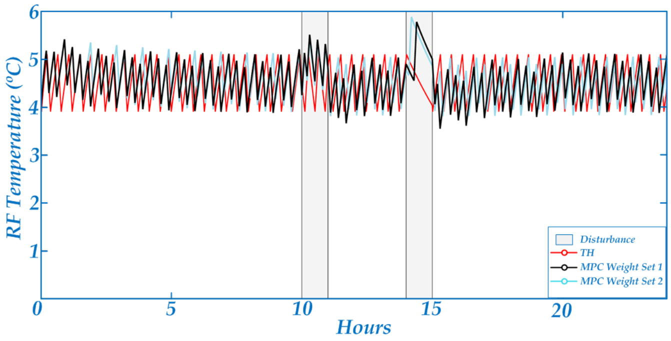

Fig. 3. Refrigerator operation: TH and MPC responses.

TABLE I. AIR CONDITIONER

	Thermostat		MPC Weight Set 1		MPC Weight Set 2	
	Energy (kWh)	*Cost ($)*	*Energy (kWh)*	*Cost ($)*	*Energy (kWh)*	*Cost ($)*
Off-Peak	5.005	0.310	5.065	0.314	5.012	0.311
Mid-Peak	8.417	0.774	8.546	0.786	8.441	0.777
On-Peak	12.934	1.397	12.661	1.367	12.661	1.367
Total	26.356	2.482	26.272	2.468	26.114	2.455

TABLE II. WATER HEATER

	Thermostat		MPC Weight Set 1		MPC Weight Set 2	
	Energy (kWh)	*Cost ($)*	*Energy (kWh)*	*Cost ($)*	*Energy (kWh)*	*Cost ($)*
Off-Peak	5.919	0.367	6.278	0.389	6.480	0.402
Mid-Peak	6.740	0.620	6.975	0.642	6.480	0.596
On-Peak	4.939	0.533	4.185	0.452	4.320	0.467
Total	17.598	1.521	17.437	1.483	17.280	1.465

TABLE III. REFRIGERATOR

	Thermostat		MPC Weight Set 1		MPC Weight Set 2	
	Energy (kWh)	*Cost ($)*	*Energy (kWh)*	*Cost ($)*	*Energy (kWh)*	*Cost ($)*
Off-Peak	0.824	0.051	0.828	0.051	0.840	0.057
Mid-Peak	0.504	0.046	0.483	0.044	0.473	0.045
On-Peak	0.549	0.059	0.552	0.060	0.550	0.064
Total	1.878	0.157	1.863	0.155	1.863	0.156

For these two domestic appliances, in both tuning sets loaded on the MPC controller, the cost of the energy consumed is lower than the appliance controlled TH. As there are three distinct tariffs during the 24h time frame, the goal is to diminish the energy cost for the period of ON peak hours. This is true to AC and TH appliances. On the other hand, the same tuning set 2 in the case of the refrigerator the electricity bill is slightly higher, as can be verified in Table III. Anyway, the energy cost computed continues to be lower than the conventional solution based on TH control. It is now evident that to reduce the energy consumption using a MPC scheme type, the controller parameters values choice must be selected through a tuning procedure to achieve a good performance. However, to achieve this goal a penalizing effect may prevent to fulfil the constraint conditions.

Finally, in Fig. 4, Fig. 5 and Fig. 6 total energy costs relationship to energy consumption profile are shown for each appliance. For AC and WH equipment electricity bill reduction is aligned with the energy usage linearly. On a contrary, for the refrigerator is not the case.

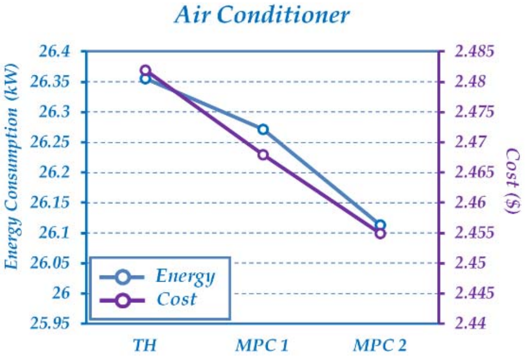

Fig. 4. AC: Energy consumption vs energy costs.

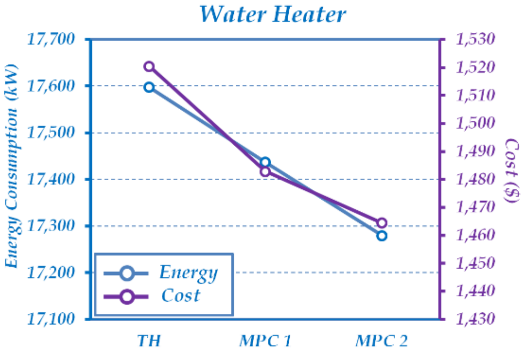

Fig. 5. WH: Energy consumption vs energy costs.

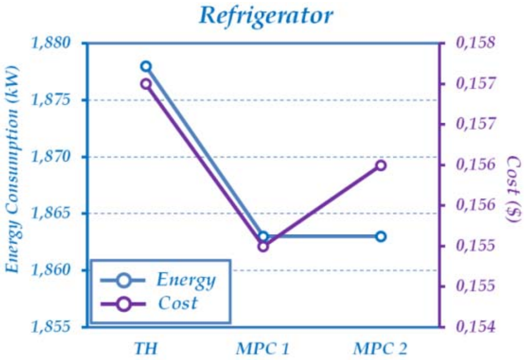

Fig. 6. RF: Energy consumption vs energy costs.

V. CONCLUSION

This paper presented a study concerning the adoption of an alternative control strategy in cooling and heating domestic equipment, normally the highest energy consumers at residential households. Consequently, a MPC technique was investigated to assess its capability to improve energy consumption efficiency with the goal of reducing electric bill. The MPC performance was further explored tuning the controller with two different weight sets and compared to a thermostat control. Three typical domestic loads were utilized as case studies. The simulation results made clear that there was a reduction on the energy billed when the thermostatic regulation was replaced by the MPC. In short, the MPC based thermal regulation had a positive impact circa 2% on the energy bill reduction. However, the two MPC weight sets have proven that it is necessary to adjust the controller weights in order to maximize the potential of energy cost saving.

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