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Domestic appliances energy optimization with model predictive control

E.M.G. Rodrigues [a], R. Godina [a], E. Pouresmaeil [b,c], J.R. Ferreira [d], J.P.S. Catalão [a,b,d,*]

[a] C-MAST, University of Beira Interior, R. Fonte do Lameiro, 6201-001 Covilhã, Portugal
[b] INESC-ID, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal
[c] ESTIA Institute of Technology, ESTIA, F-64210 Bidart, France
[d] INESC TEC and Faculty of Engineering of the University of Porto, R. Dr. Roberto Frias, 4200-465 Porto, Portugal

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ABSTRACT

A vital element in making a sustainable world is correctly managing the energy in the domestic sector. Thus, this sector evidently stands as a key one for to be addressed in terms of climate change goals. Increasingly, people are aware of electricity savings 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. Much of the reduction was due to technological improvements, however with the advancing of the years new types of control arise. Domestic appliances with the purpose of heating and cooling rely on thermostatic regulation technique. The study in this paper is focused on the subject of an alternative power management control for home appliances that require thermal regulation. In this paper a Model Predictive Control scheme is assessed and its performance studied and compared to the thermostat with the aim of minimizing the cooling energy consumption through the minimization of the energy cost while satisfying the adequate temperature range for the human comfort. In addition, the Model Predictive Control problem formulation is explored through tuning weights with the aim of reducing energetic consumption and cost. For this purpose, the typical consumption of a 24 h period of a summer day was simulated a three-level tariff scheme was used. The new contribution of the proposal is a modulation scheme of a two-level Model Predictive Control's control signal as an interface block between the Model Predictive Control output and the domestic appliance that functions as a two-state power switch, thus reducing the Model Predictive Control implementation costs in home appliances with thermal regulation requirements.

1. Introduction

The energy consumption in buildings is accountable for roughly 33% of the entire energy use, thus, contributing to the global CO_2 emissions [1]. The present environmental circumstances require firm investigation concerning the energy efficiency and possible energy savings in the building sector. Consequently, many new projects are supported by policy makers and researchers in order to improve the energy efficiency [2], to intensify the energy production from renewable resources and reduce the greenhouse gas emissions [3]. In the residential sector the energy efficiency and savings is gaining more and more importance, enthused either by economic concerns or environmental reasons [4].

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]. Until now most of the efforts to lower the energy in buildings have been concentrated on studying alternative materials that could reduce heat loss in the construction itself or by improving the operation of the domestic appliances. In this sense, a good example to have is the paradigm shift from classical incandescent light bulb to led technology with significant energy savings since the energy conversion efficiency is much higher. Also, over the years the manufacture of appliances has been modernizing different aspects of the domestic devices operation. At the moment, variable speed drives are common in vacuum cleaners, washing machines or air conditioning units (HVAC). Moreover, Modern HVAC systems are introducing variable speed compressors which set a new level of efficiency

Abbreviations: AC, Air Conditioner; BTU, British Thermal Units; HVAC, Heating, Ventilation and Air Conditioning; MPC, Model Predictive Control; TH, Thermostat; WH, water heater; QP, quadratic programming; RF, refrigerator; SISO, single-input and single-output.

* Corresponding author at: The Faculty of Engineering of the University of Porto, R. Dr. Roberto Frias, 4200-465 Porto, Portugal.
E-mail address: catalao@ubi.pt (J.P.S. Catalão).

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Nomenclature

A_w	the wall area
A_t	the surface area of the tank
$\boldsymbol{A}$	the state (or system) matrix
$\boldsymbol{B}$	the input matrix
$\boldsymbol{C}$	the output matrix
C_{in}	the thermal capacitance of the indoor air
C_{RFi}	the heat storage capacity of the refrigerator
C_{wa}	the thermal capacitance of the water
C_{wl}	the thermal capacitance of the wall
h_o	the combined convection and radiation heat transfer coefficient
k	sampling instant and the current control interval
$k+i$	the time instant associated to the future state prediction for $i = 1 \ldots N$
m	the water mass
N	the prediction horizon
P	the control horizon
Q_{wa}	the water specific heat
Q_{ac}	the cooling power input to the room
Q_{eg}	the heating element electric rated power
Q_s	the heat flow into an exterior surface of the house subjected to solar radiation
T_{in}	the temperature of the room
T_{RF}	the fridge internal temperature
T_{RFe}	the inlet temperature of the evaporator's refrigerant
T_{out}	the ambient temperature
T_s	the wall surface temperature
T_{wa}	the water temperature variable
T_{wa_inlet}	the incoming water temperature
T_{wl}	the wall temperature
$r(k+i)$	the set point reference
R_{wd}	the thermal resistance of the windows
R_{RFw}	the thermal resistance of the wall insulation
R_{RFwe}	the thermal resistance of the wall between the cabinet and the evaporator
R_{wl}	the thermal resistance of the wall
$S(t)$	a binary variable that emulates the turn-on and turn-off of the thermostat
U	the overall heat transfer coefficient for the WH wall
$u(k)$	the present input
$u(k+i\|k)$	future control signals for $i = 0 \ldots P-1$
U_{min}	the lower limit of the control signal
U_{max}	the upper limit of the control signal
$x(k)$	the state vector
$y(k)$	the system output
$y(k+i\|k)$	the estimated outputs
Y_{min}	the minimum limit of future outputs
Y_{max}	the maximum limit of future outputs
$\Lambda(k)$	the two level input vector
φ_u	the control signal tracking error
$\varphi_{\Delta u}$	the equivalent cost function term that minimizes control signal increments
φ_y	optimization of the error due to the output reference trajectory
φ_ε	the constraint violation performance index
Ψ	input vector
ω_i^y	weighting factor that allocates more relevance to the term
ω_i^u	weighting factor that allocates more relevance to the term
$\omega^{\Delta u}$	weighting factor that penalizes high differences between successive estimated input signals u_k
ρ_ε	a constraint violation penalty weight
ε_k	a slack variable at control interval k
ζ	a dimensionless controller constant
η	the electrical resistance heating element efficiency

and comfort [6]. Despite these continuous improvements, most of domestic applications for regulating temperature are still based on conventional control techniques as is the case of the bang-bang control that has been around for decades. The thermostatic technique, extensively used in home HVAC system, space heater, water heater or washing machines, has shown several drawbacks [7]. The thermostat maintenance limits are the same which does not take into account the house thermal characteristics, the weather where the house is located or the HVAC system efficiency rating level. In addition, for example, there is no method to assess the rise in outdoor temperature that could prevent a continuous injection of heat inside the room by the thermostat in order to avoid the overheating of the house. In sum, the conventional thermostatic technology is built with standard rules that may be adequate to some houses and HVAC systems but not to others.

In the past, any usage of computational power was prohibitive. But now, low power and powerful microcontroller units (MCUs) at derisory prices are revolutionizing the embedded systems market [8]. Plenty resources for floating point operations based mathematical calculations opens new possibilities to implement advanced energy management techniques from appliances point of view. This means that for optimizing temperature regulation in terms of energy savings at maximum comfort, a dedicated thermal model can be acquired and personalized according to the house, weather, HVAC systems and area occupancy rates. Such amount of computational capacity could also enable the inclusion of novel energy usage related user behaviour prediction tools to precise load matching without compromising the comfort of the user [9].

This signifies that a growing number 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 [10]. A possibility is implementing new tariff policies related to demand response programs that assist the customer with the alteration of their electricity consuming behaviours [11]. An alternative method consists in modernizing the control equipment specifically the domestic appliances with controlled temperature.

Normally, in a usual dwelling, the equipment with the greater energy consumption and that tends to be the one that are constantly in operation throughout the day is the one that offers heating and cooling (i.e. water heater (WH), air conditioning (AC), and less significantly the refrigerator (RF)) [12]. By adopting energy efficiency measures there is room for real and tangible potential for energy savings that can reach up to 30% [13]. 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 are so common the ON-OFF devices have proven to be the first choice by appliance manufacturers.

Currently, the Model Predictive Control (MPC) has been accepted by academics and industry as a very compelling method with solid theoretical foundations and proven capability to deal with a large number of control challenges [14]. This method is considered to be a broadly spread technology in industry intended for