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Optimal residential model predictive control energy management performance with PV microgeneration

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ABSTRACT

The energy demand of the residential sector and the adjacent option for fossil fuels has negative consequences by both greenhouse gases (GHG) and other air pollutants emissions. Since home energy demand consists mainly of energy requirements for space and water heating along with the energy dedicated for appliances, different strategies that aim to stimulate an efficient use of energy need to be reinforced at all levels of human activity. In this paper, a comprehensive comparison is made between the thermostat (ON/OFF), proportional-integral-derivative (PID) and Model Predictive Control (MPC) control models of a domestic heating, ventilation and air conditioning (HVAC) system controlling the temperature of a room. A power interface that adjusts the MPC dynamic range of the output command signal into a discrete two level control signal is proposed, as a new contribution to earlier studies. The model of the house with local solar microgeneration is assumed to be located in a Portuguese city. The household of the case study is subject to the local solar irradiance, temperature and 5 Time-of-Use (ToU) electricity rates applied on an entire week of August 2016. The purpose of the optimisation is to achieve the best compromise between temperature comfort levels and energy costs and also to assess which is the best electricity ToU rate option provided by the electricity retailer for the residential sector. Also, for each electrical load of the HVAC system, the energy and cost are calculated and the results are presented by varying the different MPC weight combination in order to obtain the best possible solution and increase the quality of the model. Finally, after the best tariff and controller are determined, the impact of the solar generation is assessed.

1. Introduction

Concerns regarding climate change tend to grow when confronted with the damaging consequences of rapid and uncontrolled urbanisation. To cope with the current energy consumption growing rate several efforts are necessary to oppose environmental threats (Nishant et al., 2014; Georgiou, 2016). Results published by the Intergovernmental Panel on Climate Change (IPCC) emphasised the requirement to preserve the GHG below 450 ppm CO_2 equivalence by 2050 in order to maintain the increase of the temperature of the planet under 2 °C (Matsumoto et al., 2016; Han et al., 2014).

Countries gradually concentrate their initiatives and environmental policies on reducing the negative environmental repercussions of careless energy consumption (Bigerna et al., 2016). The energy sector is experiencing substantial transformation driven by legislation with the purpose to reduce energy consumption and the consequently related environmental impacts (Udaeta et al., 2015; Wanjiru et al., 2016).

Presently, the consumption of energy in buildings is responsible for circa 33% of the final energy consumption on the planet (Tan et al., 2016; Mei and Xia, 2017). In the case of primary energy consumption, the building sector embodies about 40% in most of the IEA (International Energy Agency) nations and is accountable for 36% of the European Union (EU) CO_2 emissions (Missaoui et al., 2014). Also, the same sector absorbs 40% of EU final consumption and 60% of electricity consumption (Louis et al., 2016).

As part of the building sector, the residential sector is accountable for 60% of the final energy consumption and presents the highest prospective to decrease the peak demand which is described by the volatility of energy utilisation (Heinen et al., 2011).

The tendency of the electricity production and supply system, still deeply rooted in electricity generated by centralised fossil fuel

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and nuclear power plants, is to change into the direction of a distributed electricity generation system comprising small scale renewable energy producers such as edifices and houses equipped with photovoltaic panels (PV) and even storage systems. The enormous structural change that is being witnessed during the last decade and complemented by the recent regulatory policies unveils new challenges concerning how the energy is consumed (Velik and Nicolay, 2016).

Even though the flexibility related with home appliances and distinct electricity ToU rate options can accomplish palpable positive results for consumers, the present residential load control operations are still operated manually, thus signifying demanding challenges to consumers in planning the activity of their appliances in an optimal manner. Several clients might not have enough time to plan such type of scheduling operations and at times when the price variation is quick and recurrent the scheduling might be perceived as significantly complex. Therefore, an energy management system (EMS) could be a solution to optimise the operation of appliances (Chen et al., 2013).

As a whole, two methodologies currently exist aiming to achieve energy savings: the inclusion of more energy efficient equipment in buildings, or the efficient management of the energy consumption through an EMS (Ma et al., 2014). In the last ten years, the price of storage, data processing, and communication diminished while the incorporation of EMS has become increasingly effective. Such types of solutions offer additional possibilities for the project and implementation of forefront control methods (Liang et al., 2015).

However, it is not enough. As soon as the communications and distributed capabilities will be easily available, new ways to involve and control different utility-owned and third-party assets in a reliable and sustainable mean will be required (Khodayar et al., 2016). Transactive energy could pave the way for the accomplishment of such a goal by utilising value as a common ground with the purpose to integrate control and economic methods and to adjust value streams for every party involved by stimulating actively managed systems that can coordinate their behaviour with the requirements of the rest of the elements of the system (Pratt et al., 2016; Melton and Fuller, 2016).

The development of numerous control techniques have been proposed for HVAC systems and are classified into classical control, soft control, hard control, hybrid control, and other control methods. Yet, due to their simplicity, ON/OFF and PID controls are still utilised in several HVAC systems even though such settings might not be adequate for the entirety of the house. Thus, through the definition of set points for local controllers, the regulatory control is utilised to enhance the global system performance such as costs or energy consumption (Afram and Janabi-Sharifi, 2014).

Driven by the recent improvements in data storage, communication devices, and computing, it is currently possible to materialise a suitable control technique to surmount the characteristic weaknesses in HVAC control. The implementation of EMS control strategies could be an auspicious solution for reaching improved results in HVAC systems when compared to other common control methods. By utilizing embedded EMS control units in HVAC systems, several improvements in energy efficiency could be obtained without the changes affecting the heating and cooling systems. Such types of controllers are found to be a reliable improvement for dwellings and can be without much effort installed, ran and replaced (Allen et al., 2016).

Several methods based on the MPC have been created and tested with the purpose to optimise the operation of HVAC systems. The MPC is, in essence, an optimisation based approach in which a clear model is used to predict the performance of the controlled plants over a receding horizon. The popularity of the MPC ascended ever since its first application in the process industry in 1970s (Godina et al., 2016).

Presently, MPC is broadly utilised in numerous applications that range from railway traffic management (Caimi et al., 2012), improving energy efficiency of hybrid and electric vehicles (Guo et al., 2017; Gomozov et al., 2017), to supply chain systems (Sarimveis et al., 2008) and switching frequency regulation in power converters (Aguirre et al., 2017). The common research of MPC is mostly dedicated to a centralised implementation. On the other hand, with the accelerated improvement of energy efficiency technology and the required improvement for the economic behaviour, large scale systems, such as EMS, are becoming more complex (Forbes et al., 2015). Thus, new means are required to engage and control various utility-owned and third-party assets in a reliable and sustainable way (Oliveira et al., 2015b).

The MPC is considered to be superior to the classical control techniques such as ON/OFF and PID controllers. PID controllers are inferior due to the reason that they offer low accuracy in processes which are either non-linear or have a large time delay. For instance, PID controllers only manage efficiently single input single output (SISO) systems. On the other hand, the MPC is able to manage multiple input-multiple output (MIMO) systems, to show a greater accuracy, to operate with constraints, is robust when facing disturbances and has the capacity to predict the performance of the controlled plants over a receding horizon. However, such advantages are counterweighted with greater computational requirements (Wanjiru et al., 2016; Silva et al., 2017; Godina et al., 2017a, b).

Academics have been researching a vast range of control techniques with the goal to achieve an efficient energy utilisation of HVAC systems and other domestic appliances (Afram and Janabi-Sharifi, 2014).

In (Wallace et al., 2012) is showed the application of MPC to HVAC units and demonstrated that the closed-loop performance and energy efficiency can be improved over conventional methods, but the authors focus only on the comparison between the MPC and the proportional-integral controller (PI) without addressing the costs. A model predictive and genetic algorithm-based optimisation of residential temperature control of a HVAC unit and an electric heater in the presence of time-varying electricity prices was presented in (Molina et al., 2013). However, in this case the pricing scheme is not specified. In (Liang et al., 2015) the authors develop a MPC model with the purpose to minimise the energy consumption of the air temperature and flow rate of an air-handling-unit for multi-zone variable air volumes. Yet, this study lacks of a proper economic analysis since no costs reflecting the energy that was saved are given in this study. In (Široký et al., 2011) the MPC was combined with conventional local loop PID controllers in a hierarchical structure in order to minimise the energy consumption using current energy sources and minimal retrofitting and using weather predictions. This study, however, also does not support the obtained results with an economic analysis. A MPC architecture design for the optimal temperature control of a real commercial building was presented in (Mantovani and Ferrarini, 2015). However, the pricing scheme was not specified in this study.

In (Aswani et al., 2012) a retrofitted and inexpensive HVAC testbed was built with the purpose to reduce the transient and steady state electricity consumption in HVAC systems using learning-based MPC. Still, a more flexible approach was made since within the objective of this study the upper and lower limits of the room temperature were moderately disrupted. An economic MPC to a commercial building HVAC system in Milwaukee WI that described the effectiveness of the method in closed-loop load shifting and demand reduction was applied in (Ma et al., 2014), but the authors use only one price scheme. In (Mai and Chung, 2015) an economic MPC operated building aggregator was proposed and