Computers and Chemical Engineering 106 (2017) 160–170

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Full Length Article

One-layer gradient-based MPC + RTO of a propylene/propane splitter

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ARTICLE INFO

Article history:
Received 5 June 2016
Received in revised form 23 May 2017
Accepted 3 June 2017
Available online 12 June 2017

Keywords:
Economic model predictive control
Real time optimization
Dynamic simulation
Propylene production unit

ABSTRACT

Here, the implementation of the gradient-based Economic MPC (Model Predictive Control) in an industrial distillation system is studied. The approach is an alternative to overcome the conflict between the MPC and RTO (Real Time Optimization) layers in the conventional control structure. The study is based on the rigorous dynamic simulation software (SimSciDynsim®) that reproduces the real system very closely and is able to communicate with Matlab. The gradient of the economic function, is obtained through the sensitivity tool of the real-time optimization package (SimSciROMeo®). In order to study the pros and cons of the new strategy, a propylene distillation system is simulated with both, the proposed approach (one-layer MPC + RTO) and the conventional two-layer hierarchical structure of control and optimization. The results show that, for this particular system, from the performance, stability and disturbance rejection viewpoint, the proposed gradient-based extended control method is equivalent or better than the conventional approach.

1. Introduction

In the conventional industrial practice, Model Predictive Controllers (MPC) and Real Time Optimization (RTO) are implemented in a hierarchical control structure (Engell, 2007; Qin and Badgwell, 2003; Rawlings et al., 2012; Tatjewski, 2008), as shown schematically in Fig. 1. The RTO is a model-based system, operated in closed loop, which implements the economic decision in real time, performing a static optimization, and providing the optimum operating point. It employs a stationary complex (nonlinear) model of the plant and, for this reason, it works on a timescale of hours or days. The optimization problem is a Nonlinear Programming(NLP), whose solution provides optimizing set-points to the dynamic layer of the controller, usually a MPC (Camacho and Bordons, 2004; Mayne et al., 2000; Rawlings and Mayne, 2009). The MPC calculates the optimal control action to be sent to the plant, in order to regulate it as close as possible to the optimum point, taking into account a dynamic model of the plant, constraints, and stability requirements.

The hierarchical control structure supposes a time-scale separation between the RTO and MPC layers. This separation represents a technical issue that may have serious consequences on the economic performance of the plant.

This technical issue is basically due to the fact that the RTO and the MPC implement two different optimizations, with different models, and very different time scales. A linear program (LP) or quadratic program (QP) optimizer is used in the MPC and a nonlinear optimizer is used in the RTO. The conflict between these optimizers may cause infeasibilities in the controller's optimization problem as well as unreachability of the economic set-point and poor economic performance (Cutler et al., 2014; Kadam and Marquardt, 2007). As a result, a proper strategy to unify these (probable competing) objectives becomes highly desirable from an operating point of view.

A first approach to avoid this problem was to add a new optimization level in between of RTO and MPC, referred as the steady-state target optimizer (SSTO). The SSTO calculates the steady-state to which the system has to be stabilized, solving a linear or quadratic programming, using the same model as the MPC and taking into account information from the RTO (Ferramosca et al., 2009; González and Odloak, 2009; Limon et al., 2008;

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http://dx.doi.org/10.1016/j.compchemeng.2017.06.006
0098-1354/

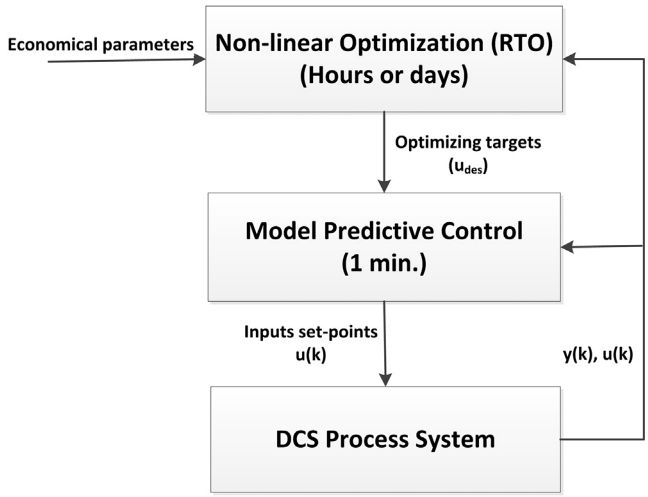

Fig. 1. Hierarchical two-layers control structure.

Marchetti et al., 2014; Muske, 1997; Rao and Rawlings, 1999; Würth et al., 2009).

Recently, economic optimizing MPC strategies have been proposed, with the aim to integrate the RTO optimization problem into the own MPC control problem. A first approach in this direction is represented by the Dynamic Real Time Optimizer (D-RTO) (Biegler, 2009; Kadam and Marquardt, 2007; Würth et al., 2009), which solves a dynamic economic optimization and delivers target trajectories (instead of target steady state) to the MPC layer. Also, Economic MPC controllers, which consider the nonlinear economic cost of the RTO, as the stage cost for the dynamic regulation problem, have been widely studied in the last few years, (Amrit, 2011; Amrit et al., 2011; Angeli et al., 2012; Biegler, 2009; Diehl et al., 2011; Ferramosca et al., 2014; Grüne, 2013; Heidarinejad et al., 2012; Rawlings et al., 2012).

Another interesting approach is represented by the one-layer MPC, which integrates the RTO economic cost function as part of the MPC cost function (Adetola and Guay, 2010).

First, (Zanin et al., 2002) proposed the inclusion of an economic function term (f_{eco}) in the advanced controller cost function, producing what was called as optimizing controller. This approach was tested by simulation and implemented in the Fluid Catalytic Cracking (FCC) process presented in (Moro and Odloak, 1995). The main disadvantage of this strategy is that the optimization problem is a nonlinear one, which becomes difficult to solve within the controller sampling time. It requires a high computational effort and does not guarantee a global optimum.

To circumvent the problem of dealing with a nonlinear optimizing problem (NLP), (De Souza et al., 2010) proposed a simplified version of the optimizing controller where the gradient or reduced gradient – depending on constraint violation – of the economic function was included in the controller's cost function instead of directly including the economic function. Therein, the control objective pushes to zero the reduced gradient of the economic objective while maintaining the system outputs inside their control zones. Because of the use of a finite prediction horizon for the controller outputs and the presence of the economic optimization component, there could be some constraint violation. Then, at each sampling time, the predicted values of the controlled variables were checked, in order to confirm that there were no violations of the constraints. Depending on the existence of any violation of the output bounds, additional constraints were included in the control problem or inputs were removed from the calculation of the economic gradient. With such approach, the integrated control/optimization problem became a quadratic programming (QP) that could be solved with any of the available QP solvers, instead of a NLP solver as in the previous approach. Simulations results with the FCC system presented in (Moro and Odloak, 1995) showed that this strategy produces almost the same economic benefit as the one with the full economic function inside the control cost, and could be implemented in the real system.

More recently, (Alamo et al., 2014, 2012) presented a MPC controller that also integrates RTO in the same control problem, in such a way that the controller cost function includes the gradient of the economic objective cost. However, instead of applying to the system the optimal solution of the approximated problem, they propose to apply the convex combination of a previously known feasible solution and an approximated solution. This way, a sub-optimal MPC strategy that only requires a QP solver was obtained, and it is shown that the strategy ensures recursive feasibility and convergence to the optimal steady-state in the economic sense. This approach was tested by simulation in a simplified version of the FCC unit, and the simulation results showed that the proposed algorithm has a good performance and can be tested using dynamic simulation in order to prove its applicability in real systems.

The main objective of this work is to show that the approach proposed in (Alamo et al., 2014) is effectively applicable on a real system. To this aim, a simulation based on a nonlinear simulator that perfectly represents the real plant, is proposed. The approach is implemented in a propylene/propane splitter and compared to the conventional multi-layer approach. The approach will be tested on the rigorous dynamic simulation software (Dynsim) that reproduces the system as a virtual plant and is able to communicate with the MPC algorithms (developed in Matlab) through an OLE for Process Control (OPC) interface (Hinojosa and Odloak, 2014, 2013). The gradient of the economic function, which is necessary to on-line execute the controller, is obtained through the use of the sensitivity tool of the real-time optimization package (ROMeo).

The paper is organized as follows. Section 2 presents and discusses the control problem and describes the propylene/propane splitter process. Then, in Section 3, it is presented the proposed one-layer gradient-based Economic MPC that integrates the RTO into the MPC and an algorithm is also provided. In Section 4, the economic function to be maximized is defined and the sensitivity tool for the gradient estimation is presented. Section 5 presents the simulation results that compare the application of the proposed method with the conventional two-layer MPC-RTO structure. Finally, in Section 6 the paper is concluded.

2. The control problem and process description of the propylene/propane splitter

The industrial process system considered here was designed to produce high-purity propylene polymer grade (99.5% molar). In the distillation column that is schematically represented in Fig. 2, propylene is separated from propane which also carries other hydrocarbons with four atoms of carbon. A typical composition of the feed stream of column T-03 is shown in Table 1. The propylene stream is produced as the top stream of the splitter and is sold to a nearby petrochemical plant, while the propane stream obtained as the bottom product is stored in propane spheres(Hinojosa and Odloak, 2014).

The distillation system studied here includes an energy recovery system through the integration of the top cooling system and the bottom heating system. As it can be observed from Fig. 2, there is a vapor recompression system where energy savings of about 50% have been reported when compared to the conventional steam reboiler system.

The high purity required for the products and the variable heat transfer area of the bottom reboilers justify the use of a multivari-