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Robust model predictive control of an industrial partial combustion fluidized-bed catalytic cracking converter

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ABSTRACT

It is presented here in the study of the application of a robust model predictive control to an industrial partial combustion fluidized-bed catalytic cracking (FCC) converter. This particular type of FCC converter shows an interesting dynamics in which most of the system outputs are integrating with respect to the manipulated inputs. Time delays are also present and the model parameters can change depending on the operating point. Then, the system model should be represented by a set of possible plants, which can stand for different operating conditions of this process system. Moreover, one needs to include a comprehensive model formulation in order to accommodate time-delays for both stable and integrating outputs. The proposed control strategy was tested through simulation for the disturbances commonly found in the FCC converter unit, taking into consideration the plant/model mismatch. Results obtained from the simulated scenarios point out a fine prospective method. The robust controller shows a good potential to be implemented in the real process.

Keywords: FCC converter; Model predictive control; Zone control; Multi-model control.

1. Introduction

The fluidized-bed catalytic cracking (FCC) unit is one of the most profitable process units and perhaps the most complex and challenging operating process of any oil refinery. The major goal behind the cracking process is to transform catalytically low-value raw materials, such as gasoil and/or atmospheric residue, into lighter and more valuable products, of which the cracked naphtha (gasoline) and liquefied petroleum gas are the commercial products of highest aggregate value for the refinery considered here.

Mostly, this kind of industrial process exhibits complex dynamic behavior, strongly interacting variables as well as economic and operating constraints on the process system inputs and outputs. Because of these characteristics, it is rather unavoidable and justifiable to prefer the employment of advanced control strategies rather than the conventional PID-based decentralized control techniques, in order to extend the operating campaign, to preserve the mechanical integrity and mainly to reach economic objectives. Among these strategies, model predictive control (MPC) appears to be the standard approach for controlling industrial FCC units.

It is well known that MPC explicitly incorporates a linear or nonlinear process model to forecast the future behavior of the controlled outputs and to compute appropriate control actions through an optimization based formulation. In spite of the real model being nonlinear, MPC based on linear step response models has been thoroughly studied and implemented in FCC process systems (see e.g. Grosdidier et al., 1993; Moro and Odloak, 1995; Kalra and Georgakis, 1996; Yang et al., 1996; Abou-Jeyab and Gupta, 2001; Jia et al., 2003; De Souza et al., 2010). FCC units may be subject to frequent transitions in the operating conditions, caused by changes in the feed quality or due to the pursuit of economic goals, or both, so that the use of conventional linear MPC may result in poor control performance. A better performance seems to be achieved when one considers MPC strategies derived from first-principles nonlinear models (NMPC) (Khandalekar and Riggs, 1995; Ali and

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Elnashaie, 1997; Ansari and Tade, 2000; Harnischmacher and Marquardt, 2007; Roman et al., 2009).

The simulated applications of NMPC to FCC process systems can provide better results than the corresponding ones based on linear models, but these available solutions seem still far from the practical application stage, since they usually lead to unacceptable computational burdens. In order to circumvent this drawback, it has been considered the application of empirical nonlinear models such as artificial neural network (ANN) to represent the process system in the NMPC algorithm. Several research works that focused on the application of this modeling approach to FCC control strategies have been reported in several research works (Santos et al., 2000 and Vieira et al., 2005). The major disadvantage of the NMPC based on ANN is that it requires large training data sets, which is not usually available in the industrial environment. An excellent and detailed review on the MPC approaches mentioned earlier concerning the FCC system is available in a paper by Pinheiro et al. (2012).

Another class of advanced control algorithms that can deal with nonlinearities of the process model is the robust model predictive control where a linear model with varying parameters is considered to approximate the nonlinear process. Not withstanding the extensive research that has been done in robust MPC, the only strategy that seems already in an acceptable level of development for practical implementation is the one based on the cost-contraction formulation, proposed in the seminal work of Badgwell (1997). This is so done because in such an approach: the resulting NLP optimization problem is convex, the model uncertainty is easily represented by a discrete set of linear models (the so-called multi-model approach), and the control stability can be obtained when an infinite prediction horizon is considered. This control strategy has been successfully implemented in practice in distillation column systems (Porfírio et al., 2003; Martin et al., 2013), but its use in FCC process systems has not been evaluated yet. Then, the aim of this paper is to study the implementation of a cost-contracting robust MPC to the converter of an industrial FCC unit. Aiming at the practical case where a real-time optimizer (RTO) is integrated with the MPC layer, the controller studied here explicitly incorporates into the control optimization problem the tracking of economic targets for some inputs and/or outputs and zone control (or interval tracking) for the remaining outputs.

This work has been organized in the following way: Section 2 presents a brief description of the industrial FCC unit focusing on the control structure to be considered in this study. In Section 3, the robust MPC, which is based on the multi-model uncertainty description, is developed toward a general state-space model formulation to be included in the proposed method. Section 4 deals with the application of the proposed control strategy for different disturbance scenarios and plant/model mismatch of the FCC unit, and the results are compared to those from a conventional MPC existing in the real process. Finally, Section 5 concludes the paper.

2. The control structure of the FCC unit

The purpose of this work is to study the implementation of a robust model predictive controller at the FCC converter unit at the Cubatão (Brazil) refinery. A simplified schematic representation of this industrial unit is given in Fig. 1, as well as the main regulatory control loops (PID controllers). Summarily, this process unit comprises the feed pre-heating furnace, the reactor-regenerator system, the air blower and the main fractionating column. The feedstock for this process unit is mainly gasoil, which is pre-heated in the furnace to a temperature of about 230–300 °C. A small amount of raw naphtha is also fed to the system. Then, both gasoil and raw naphtha streams are fed to the riser where the cracking reactions take place in the presence of hot catalyst that comes from the regenerator-vessel (RG) and a regulatory PID controller of the riser outlet temperature adjusts the regenerated catalyst plug valve. The products of the cracking reaction are separated from the spent catalyst in the reactor-vessel (RX), and afterwards they are sent to the main fractionating column with the purpose of separating the products of the cracking process, such as fuel gas, liquefied petroleum gas (LPG), gasoline (main product) from the heavier products such as light cycle-oil (LCO) and clarified oil (CLO). At the bottom of the reactor RX the spent catalyst is held up in a fluidized-bed with steam, which aims to strip the hydrocarbons adsorbed on the catalyst particles. The level of catalyst in the reactor is controlled through the manipulation of the spent catalyst plug valve.

Simultaneously, we have the production of coke, which deposits on the catalyst surface, resulting in its deactivation. For this reason, the spent catalyst must be continuously regenerated in the regenerator (RG) by burning the coke with air. The regenerator system considered here operates in a partial-combustion mode (the conversion of coke to CO_2 is not complete), which implies that a large amount of CO is produced. The energy released from the coke combustion is used to supply the required heat to the endothermic catalytic cracking reactions, while the remaining energy is recovered in a heat recovery boiler to generate high-pressure steam, where the CO-rich regenerator flue gas is burned.

In the present study, the proposed MPC algorithm focuses on the control of the main processing section of this FCC unit, that is, the reactor-regenerator (converter) process system. For this purpose, the control structure considered here is the same as the FCC unit of Petrobras at Cubatão refinery, where the main controlled outputs are the following:

- y_1 – boiler flue gas velocity;
- y_2 – delta pressure on the spent catalyst valve;
- y_3 – average temperature of the regenerator dense phase;
- y_4 – average temperature of the regenerator dilute phase.

As highlighted in Fig. 1, the set of manipulated inputs for the proposed MPC controller are set-points to the following PID controllers:

- u_1 – gasoil feed flow rate;
- u_2 – temperature of the gasoil feed;
- u_3 – temperature at the outlet of the cracking riser;
- u_4 – raw naphtha feed flow rate;
- u_5 – total air flow rate to the regenerator.

With the proposed 4×5 control scheme, real plant test were performed and the system model was obtained at the most probable operating condition, which is denoted here as the nominal model (NM). The transfer functions corresponding to NM are given in Table 1. Such a model was found to best describe the dynamic behavior of the FCC at the nominal design conditions. As far as the authors' knowledge, all the MPC controllers implemented in industrial FCC systems are based on the nominal linear model. This means that the