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MODEL PREDICTIVE CONTROL (LINEAR AND NONLINEAR) OF A COMPLEX FCCU

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ABSTRACT. Model Predictive Control (MPC) is standard multivariable control solution in the continuous process industries and it is becoming increasingly popular in the petrochemical industry due to the large economical benefits. The paper present the most important modern process control strategies using industrial relevant complex Fluid Catalytic Cracking process as the subject of control performance studies. The nonlinear and linear MPC methods have been investigated and the results demonstrate that modern MPC approached can be successfully applied for complex chemical processes.

1. INTRODUCTION

Petroleum refineries are complex plants, where the combination and sequence of processes is usually specific to the characteristics of the crude oil (raw material) and the products to be produced. A number of different catalytic cracking processes have evolved in order to increase the degree of conversion and improve product quality. The most important are hydrocracking and fluid catalytic cracking. Fluid Catalytic Cracking Unit (FCCU) is one of the most important conversion processes in a petroleum refinery; during the process, high-boiling petroleum fractions (gasoil) are converted in valuable products: gasoline and diesel and valuable gases (ethylene, propylene, isobutylene) are also produced [1].

The process is presented in Figure 1.

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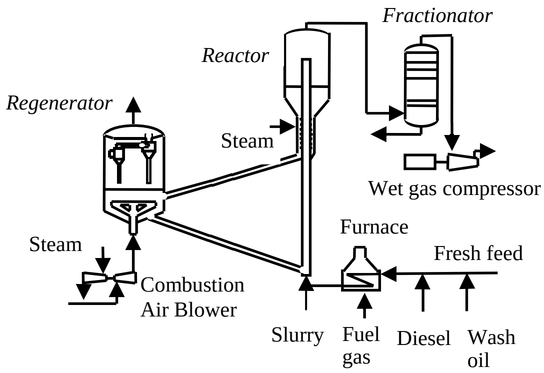

Figure 1. Fluid Catalytic Cracking Unit

The process consists in the following: pre-heated feed is mixed with the hot slurry recycle (from the bottom of the main fractionator) and injected into the reactor riser, where it mixes with hot regenerated catalyst and totally vaporizes. A carbonaceous material (coke) is deposited on the surface of the catalyst and poisons the catalyst, continuous regeneration is made in regenerator. Spent catalyst is transported from the reactor to the regenerator. Catalyst in the regenerator is fluidized, carbon and hydrogen on the catalyst react with oxygen to produce gases such as CO, CO_2, H_2O. Gas travels up in the regenerator into the cyclones where the entrained catalyst is removed and returned into the bed Reactor products (gas, gasoline, diesel, slurry) are passed to the main fractionator for separation [2].

A control system is used to maintain the stable operation of a process, to reduce variability in the product specification, to protect the physical and operational constraints or to maintain a maximum operating efficiency. The development in process control is influenced by the improvement of the performance of computers suitable for on-line control. The process computer having high speed and storage capacity can be easily needed in controlling the processes due to its low capitol costs [3]. The petroleum refining industry is one of the world leaders in application of advanced control methods and the FCCU became in the last decades the testing bench for every modern refinery control system. Researchers, but also people from industry, are interested in developing control algorithms and their efficient FCC implementation due to the large economic benefits.

2. MODEL PREDICTIVE CONTROL ALGORITHM

Model Predictive Control (MPC) algorithm has become a standard multivariable control solution in the continuous process industries, and it is becoming increasingly popular in the petrochemical industry. The main reasons for this preference include the ability to handle constraints in an optimal way and the flexible formulation in the time domain. Linear MPC schemes, (MPC schemes for which the prediction is based on a linear description of the plant) and nonlinear MPC schemes (MPC based on a nonlinear plant description) has been studied intensely in the past decade and the number of reported industrial applications is continuously growing.

Model Predictive Control (MPC) is a form of control in which the current control action is obtained by solving on-line, at each sampling instant, a finite horizon open loop optimal control problem, using the current state of the plant as the initial state; the optimization yields an optimal control sequence and the first control in this sequence is applied to the plant- this is its main difference from conventional control which uses a pre-computed control law. The optimization problem is solved on-line based on prediction obtained from a nonlinear or linear model of the plant [4].

The algorithm is presented in Figure 2.

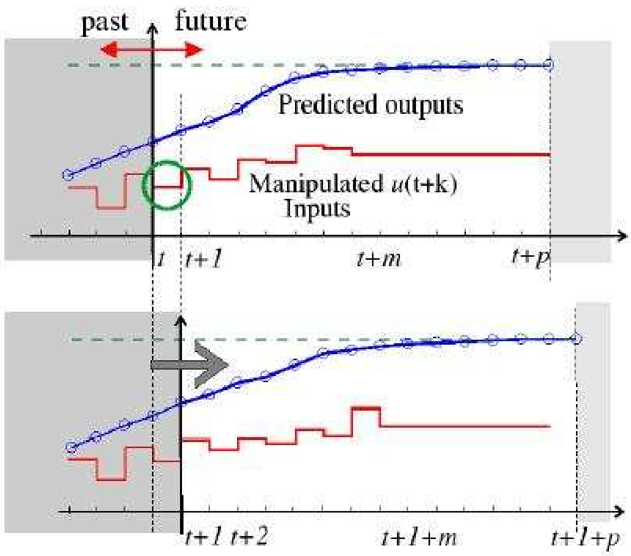

Figure 2. MPC algorithm

At the present time *k* the behavior of the process over a horizon *p* is considered. Using the model, the response of the process output to changes in the manipulated variable is predicted. Current and future moves of the manipulated variables are selected such that the predicted response has certain desirable (or optimal) characteristics. The first control action is implemented, new measurements are obtained which are used for the compensation of plant/model mismatch and the estimation of unmeasured state variables. Finally the prediction horizon is shifted by one sampling time into the future and the optimization is performed again

The mathematical formulation of the model predictive control problem is [5,6]:

- *objective function*:

$$\min_{u(.),P,M}\{J(x(t),u(.),P,M)\} \tag{1}$$

- *constraints:*

$$\frac{\partial x}{\partial t}=f(f,u,q,d) \tag{2}$$

$$x(k)=x_{est}(k) \tag{3}$$

$$0=g_1(x) \tag{4}$$

$$y_p=g_2(x) \tag{5}$$

$$u_{\min}(k+i)\le u(k+i)\le u_{\max}(k+i) \tag{6}$$

$$u(k+i)=u(k+M-1) \tag{7}$$

$$x_{min}(k+i)\le x(k+i)\le x_{max}(k+i) \tag{8}$$

$$y_{\min}(k+i)\le y_P(k+i)\le y_{\max}(k+i) \tag{9}$$

where *x* are state variables, *u* are manipulated variables, *q* are parameters, *d* are measured and unmeasured disturbances and *y* are output variables.

The objective function is the sum of the squares of the differences between the predicted outputs and the setpoint values over the prediction horizon of *P* time steps and it has a second term, which is the square sum of manipulated variable changes over the control horizon (*M*)::

$$\begin{aligned}\min_{u(k)\ldots u(k+M-1)}\{&\sum_{i=1}^{P}\|Q_i(r(k+i)-y_P(k+1))\|^2+\sum_{i=1}^{M}\|R_i\Delta u(k+i-1)\|^2\\&+\sum_{i=1}^{M}\|R_{uss}\Delta u(k+i-1)-u^{ref}(k+i-1))\|^2\}\end{aligned} \tag{10}$$

3. FCCU control results

Traditional control theory is no longer suitable for the FCCU increasingly sophisticated operating conditions and product specifications. There is now a strong demand for advanced control strategies with higher control quality to meet the challenges imposed by the growing technological and market competition.

The FCCU dynamic model for which MPC studies has been done was developed on the basis of reference construction and operation data from an industrial unit (ROMPETROL Company) and consists of detailed models of the feed and preheat system, reactor stripper, riser, regenerator, air blower, wet gas compressor, catalyst circulation lines and main fractionator. The model captures the major dynamic effects that can occur in an actual FCCU system. It is multivariable, strongly interacting and highly nonlinear (it consist of 933 differential algebraic equatios (ODEs) and more than 100 algebraic equations).

Linear Model Predictive Control (LMPC) and Nonlinear Model Predictive Control (NMPC) algorithms based on the global reactor-regenerator-main fractionator FCCU are presented in a complex 5x7 structure control; it was investigated the most important process variables: reactor temperature (T_r), fractionator pressure (P_5), reactor catalyst inventory (W_r) and gasoline and diesel composition in the top and bottom of the main fractionator. The control of those variables is important in the efficient and safe operation of the unit and also influences the products quality and plant productivity. As manipulated variables where chose form a practical point of view: the spent and regenerated catalyst circulation lines valve positions (*svsc* and *svrgc*), stack valve position (V_{14}), condenser's liquid flow *(LT)* and reboiler's liquid flow *(VB)*.

Comparisons of the MPC based nonlinear model (NMPC) with the MPC based linear FCCU model (LMPC) in the presence of coking rate disturbance (1% increase at t=8 min) are presented in the Figure 3 and Figure 4. This disturbance shows the effect of changes in raw material properties on the process variables.

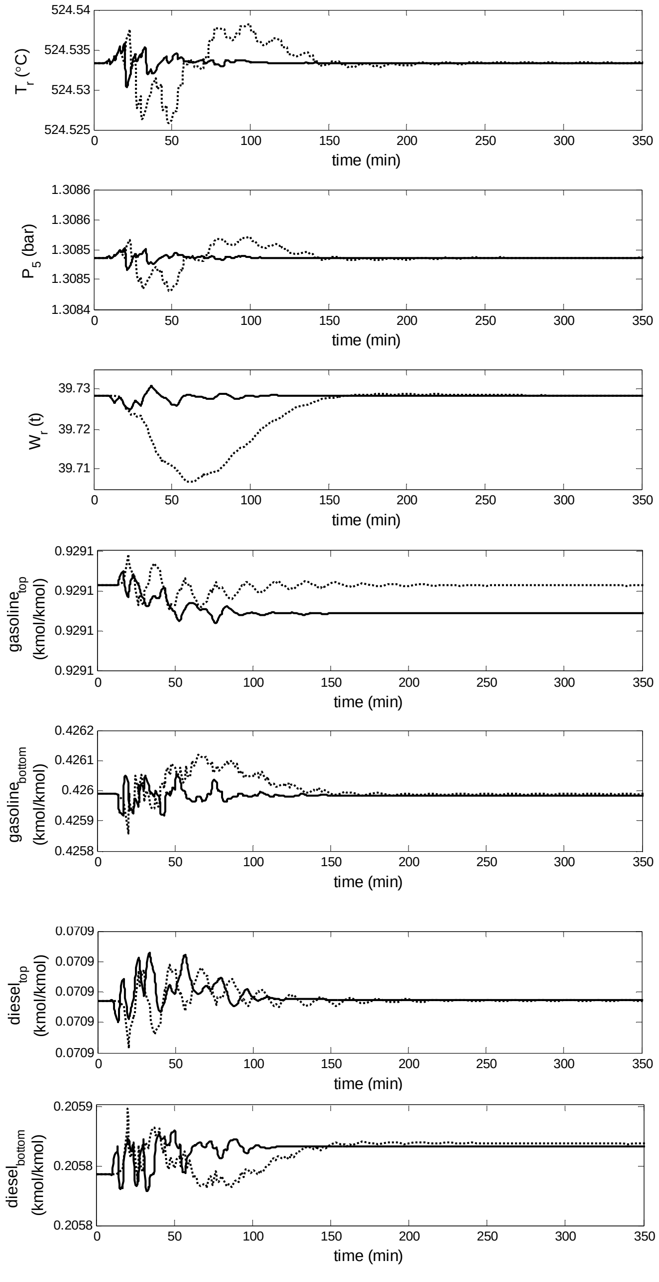

Figure 3. Simulation of FCCU dynamic behavior-controlled variables (LMPC - dotted line; NMPC - solid line)

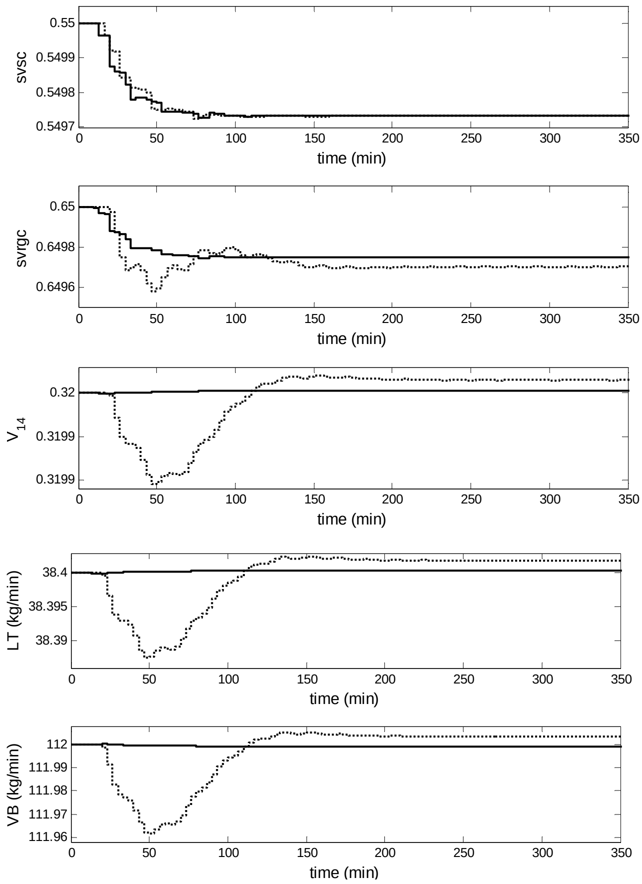

Figure 4. Simulation of FCCU dynamic behavior-manipulated variables (LMPC - dotted line; NMPC - solid line)

4. CONCLUSIONS

Modern control studies have been done for a complex petrochemical process: Fluid Catalytic Cracking Unit. It is shown that complex MPC structures based linear and nonlinear model can successfully be applied for a very height dimensional FCC system. MPC it was successfully applied and present good control performance for complex FCCU based on its multivariable feature, inherent prediction ability and capacity to direct handle the constraints and this fact has made it an important tool for the control engineer. NMPC algorithms performs better than LMPC algorithm in tracking the setpoints and rejecting disturbances The results of the proposed complex control structures encourage the application of the advanced control algorithms to the industrial FCCU.

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