ADCHEM 2006

International Symposium on Advanced Control of Chemical Processes
Gramado, Brazil – April 2-5, 2006

PARAMETRIC MODEL PREDICTIVE CONTROL OF AIR SEPARATION

Jorge A. Mandler*,
Nikolaos A. Bozinis, Vassilis Sakizlis**[1], Efstratios N. Pistikopoulos**,**
Alan L. Prentice*, Harish Ratna***, Richard Freeman*****

**Air Products and Chemicals, Inc., 7201 Hamilton Blvd, Allentown, PA, 18195 USA,*
mandleja@airproducts.com
***Centre for Process Systems Engineering, Department of Chemical Engineering,*
Imperial College London, London SW7 2AZ, United Kingdom and
Parametric Optimization Solutions (ParOS) Ltd, 90 Fetter Lane
London EC4A 1JP, United Kingdom
n.bozinis@parostech.com, e.pistikopoulos@imperial.ac.uk,
***[1] Currently with Bechtel, Hammersmith Road*
London W6 8DP,
vsakizli@bechtel.com
**** Air Products PLC, Hersham Place, Molesey Road, Hersham, Surrey, KT12 4RZ,*
United Kingdom

Abstract: This paper describes the application of Parametric Model Predictive Control to small processing units, in particular small Air Separation plants. Multiparametric optimization techniques are used to rigorously solve the MPC problem in two steps: an offline solution which generates a parametric mapping of the optimal control adjustments, and an online solution which reduces to a simple lookup operation. Because of the speed and simplicity of this lookup operation we are able to implement MPC in low-end computing devices such as PLCs, reaping the benefits of model-based control by implementing it at low cost in small plants where otherwise it would not be justified by the cost/benefit ratio. *Copyright © 2006 IFAC*

Keywords: parametric programming, parametric optimization, on-line optimization, predictive control, process control.

1. BACKGROUND

While Model Predictive Control (MPC) is the clear Advanced Control technology of choice in the Process Industries, it has found limited use to date for small processing units, despite its unquestionable superiority in terms of robustness, plant optimization and general control performance. One bottleneck is the complexity and relatively high cost of the controller compared to the unit cost in smaller size plants. This is partially due to the computing hardware and software required for executing on-line, real time optimization in order to determine the appropriate control action for the next time interval.

For the smaller Air Separation plants (single product plants, Nitrogen or Oxygen generators, cryogenic or non-cryogenic) Advanced Control of any kind was in the past an expensive proposition. As a result, the small plants would most often be operated in a conservative manner and suffer from the following operational drawbacks:

- They would consume more energy than required.
- They would be unable to load follow a varying customer demand.
- Venting of product or product backup would be required whenever the customer demand did not match the set production and single point of operation.

In the last few years, academic research on parametric programming has lead to a radically new approach to MPC (Pistikopoulos, *et al.*, 2002a; Pistikopoulos, *et al.*, 2002b; Dua, *et al.*, 2002; Bemporad, *et al.*, 2002). In this approach, the on-line control problem has been recast as a multi-parametric optimization problem where the system state variables act as "parameters". The original MPC problem can now be solved explicitly in an efficient manner, still generating the full control law in a mathematically rigorous fashion. In essence, most of the possible MPC scenarios that are encountered during the operation of a unit are solved a priori and off-line.

The implementation of the control law is transformed into a simple look-up function operation, where the current values of the state variables determine the control action. The control action taken by such a “parametric” controller is identical to traditional MPC for a given system state representation. The only difference and main advantage of the parametric approach lies in the manner the control action is decided: whereas traditional MPC requires on-line solution of dynamic optimization problems, the new approach just reads the current solution from a complete solution map drawn in advance. This is the concept of on-line control via off-line parametric optimization. Hence, a number of major advantages can be obtained:

1) Lower hardware costs - Simpler hardware, including PLCs and microchips, is completely adequate given the minimal on-line computational requirements;
2) Software costs are nearly eliminated;
3) Simple implementation is possible;
4) Increased control power is obtained, in part due to the very fast sampling now possible given the almost instantaneous solution.

The new parametric control concept has allowed us to extend the applicability of MPC to small Air Separation plants, for example small Nitrogen generators. We call our approach Parametric MPC (pMPC) of Air Separation. We have also called it “MPC on a chip”, since the pMPC controller, because of the ease of on-line implementation, can be readily commissioned on a microchip. We should stress at this point that the approach is not limited to small Air Separation plants. It can be equally applied in situations where, even though the Air Separation plant might be very large in terms of its production capacity, because of relative process simplicity there is still a small number of manipulated (MVs), controlled (CVs) and disturbance variables (DVs) in the process. This includes for example very large oxygen generators for GTL (gas-to-liquid) applications.

Parametric MPC is in fact a generic technology, with the only thing specific to a given application being the underlying process model and MPC problem formulation. ParOS Ltd has applied this technology in entirely different sectors, such as in the automotive industry where very fast and accurate control is required (e.g. sampling times of 0.1 millisecond).

2. PROCESS DESCRIPTION, BENEFITS SOUGHT AND CONTROL OBJECTIVES

Fig. 1 is a simplified diagram of a typical Nitrogen generator. Air is compressed, impurities such as CO_2 and water are eliminated in a Pressure Swing Adsorption unit (PSA, not shown), the clean air is then cooled to near its liquefaction temperature in the main heat exchanger and fed to a distillation column. In this distillation column the air is separated into a pure nitrogen fraction in the overhead, and an oxygen rich liquid fraction at the bottom. Part of the pure nitrogen is taken as GAN (gaseous nitrogen) product, and the rest is condensed and returned as reflux to the column. This is done in a reboiler/condenser by heat exchange against the enriched air from the bottom of the column, which boils at a lower pressure on the other side. A small amount of liquid nitrogen (LIN) is fed to the column to provide extra refrigeration. After heat exchange against the incoming feed, the GAN product is compressed and sent to the customer. The customer takes the product through a short pipeline and there may or may not be a buffer tank present.

In typical operation without advanced control, the plant produces GAN at a fixed production rate irrespective of the customer demand. Therefore if the customer demand increases, extra nitrogen may need to be provided by vaporizing LIN from a backup tank. If the customer demand drops, GAN product may need to be vented. While many customers have a constant take pattern that justifies this mode of operation, for other customers the product demand may vary quite frequently. For the latter cases, it is certainly a waste (mainly in terms of power usage) to produce pure gaseous nitrogen and then throw it to vent, and/or to vaporize significantly more expensive LIN when the demand exceeds what the plant is producing. This calls for an advanced control solution allowing the plant to quickly ramp up or down its production to match the customer demand, while maintaining the product purity within specifications. In our work this defined the first control and online optimization objective: To load follow the customer demand.

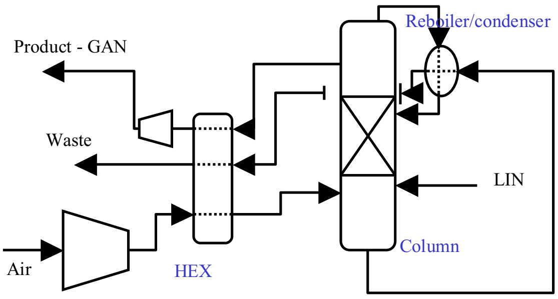


Fig 1. Simplified diagram of a Nitrogen generator.

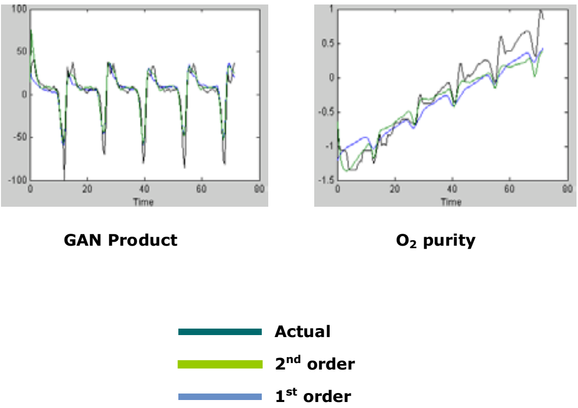
To run trouble-free and always meet the purity specifications in the face of disturbances, operations personnel may tend to run the plants “fat”, namely with extra air fed to the system and with the level of impurities (oxygen and argon in the case of a nitrogen generator) buried down. For example one particular plant had a specification of not more than 5 ppm impurities in the GAN product, but it was observed to be running as low as 0.1 ppm. Of course, this is another source of wasted power. An MPC controller, on the other hand, can be easily set up to run the plant against its true constraints in the face of disturbances. Our second control and optimization objective was thus defined: To operate against the upper impurity limit for the GAN product. This would lead to lower power use for the same production, or equivalently increased production at a given air rate. Although running against the upper impurity limit can be done with standard PID loops, the experience for this particular type of plants was that these loops were hard to tune and too much of an effort was required for the expected benefits.

All the standard benefits of MPC (the multivariable and optimal nature of the solution and the ability to handle constraints) were sought and were achieved, thanks to the parametric control formulation, without a need for expensive online computations.

3. CONTROLLER IMPLEMENTATION DETAILS

The feasibility of pMPC of small ASUs was first demonstrated on a detailed dynamic simulation of a Nitrogen generator. We next proceeded to design and implement a pMPC controller for an actual Nitrogen generator serving a customer. This plant was selected because the customer take pattern was such that it would help us demonstrate load following capabilities. The plant was also conveniently located and it had site personnel resources available as needed for our first prototype. Initially the controller was designed and implemented with only the load following objective, while still maintaining the product purity within constraints. Later a second optimization objective was added as an additional term in the objective function. The second objective led the pMPC controller to reduce air feed whenever possible to drive GAN purity against its upper limit (while not crossing it). Formally, the control and optimization objectives were implemented as follows: 1) Match GAN production to GAN demand (minimizing its difference); 2) Control GAN purity at a setpoint equal to the upper impurity limit. Note that in this plant the GAN demand (product taken by the customer) could not be directly measured but instead it was estimated using the customer valve position and pressure differences.

In order to attain the above control and optimization objectives we designed the following control structure. The pMPC controller was set up to operate as a supervisory controller, with inherently safe fallback mode to the underlying regulatory control loops in case of difficulties. As Manipulated Variables (MVs) we included the air flow setpoint, and the setpoint for the GAN/AIR ratio. There were two disturbance variables (DVs), the first one the deviation in air flow with respect to its setpoint (to account for each switch of the PSA unit), and the second one a measure of the LIN injection to the column. The controlled variables (CVs) were also two: the actual GAN product flow and the ppm O_2 in the GAN product. In summary, the controller had four inputs (2 MVs and 2 DVs) and two outputs.



GAN Product

O_2 purity

Fig. 2. Model Prediction for Each CV.

Data for system identification was obtained via step-change experiments. First and second order ARX models were identified both giving a good fit. Fig. 2 shows a validation set and the prediction by the first and second order models.

As indicated, the first control objective was to follow the customer demand without violating the purity constraints, and further subject to bounds on the MV values and on the maximum allowable rate of change for the MVs. The online MPC controller was obtained off-line via multi-parametric optimization. The techniques and the code employed to conduct this optimization are described elsewhere (Pistikopoulos, *et al.*, 2002a; Pistikopoulos, *et al.*, 2002b; Dua, *et al.*, 2002; Bemporad, *et al.*, 2002). The solution for this first pMPC controller involved 7 parameters, 2 control targets, and 209 piecewise affine control laws (regions of the parametric space). Just as an example, Fig. 3 shows the solution for one of the regions. Notice that the online solution (the value of each MV for the next control move) is obtained explicitly via a linear combination of the parameters. The values of the coefficients a_c and b_c are different for each solution region.

Because of the ease of online computation, we were able to implement the pMPC controller on the existing plant PLC. This PLC (programmable logic controller) was an older type model with very limited computing resources. The pMPC controller was implemented as a C function block and it worked together with the existing ladder logic. Timers ensured that the controller was called every 30 seconds precisely. Since the computation was very fast, the model-based control action could have been

Explicit Control Law:
$$\left| \begin{array}{l} u_0 = a_c\theta + b_c \\ \text{if } \; CR_c^1\theta + CR_c^2 \le 0 \\ c = 1, \ldots N_c \end{array} \right.$$

Region 117:

$$MAC(t+1)=5.8971\cdot X_{O2}(t) -4.2801\cdot GAN(t)-3.0664\cdot X_{O2}(t-1) +0.1304\cdot GAN(t-1) +0.0955\cdot MAC(t)+24.7965 \cdot(1/Ratio)+6.1678\cdot GAN^{set}$$

$$1/Ratio(t+1)=0.3063 \cdot X_{O2}(t)+0.2437\cdot GAN(t)-0.1488 \cdot X_{O2}(t-1)-0.1554 \cdot GAN(t-1)- +0.0072\cdot MAC(t)+0.8065\cdot(1/Ratio)-0.0766 \cdot GAN^{set}$$

$$-10.0<MAC(t)<10.0$$
$$-71.5< 42.38 \cdot X_{O2}(t)+33.72\cdot GAN(t) -20.5853\cdot X_{O2}(t-1) +\ldots -10.6 \cdot GAN^{set} <71.5$$

Fig . 3. Parametric control solution for Region 117.

done more frequently if this was needed for improved performance. The ability to implement model predictive control on a PLC became in itself a major accomplishment of our work.

Fig. 4 gives a schematic diagram of the function lookup operation constituting the online implementation of pMPC for the small ASU. At every sample the C code read the current plant state and formed a parameter vector consisting of 7 values based on the current and last sample conditions. A search was done to find the corresponding region in parametric space, and the coefficients of the explicit control law for that region were then applied to calculate the next control move for the MVs.

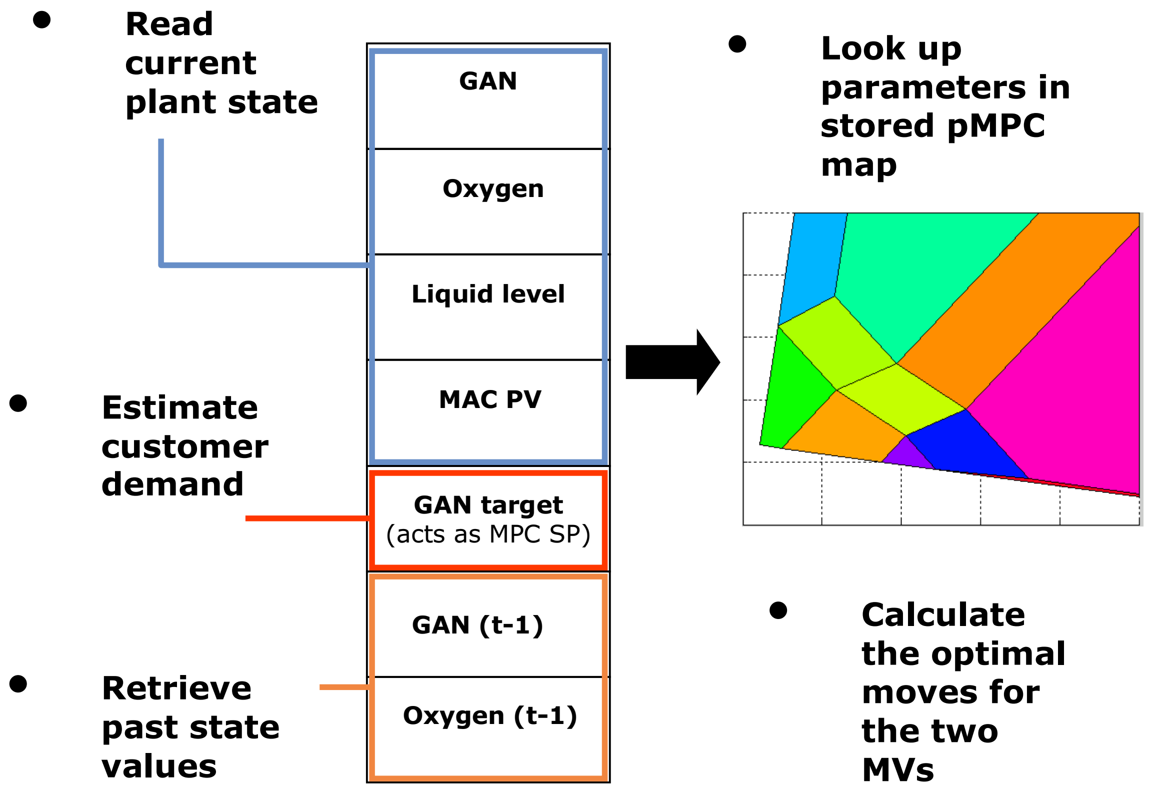


Fig. 4. Implementation of lookup operation of pMPC for a small Nitrogen generator. GAN: Gaseous Nitrogen; MAC PV: Measurement of air flowrate.

Fig. 5. Load following the customer demand, first controller implementation (left axis, MAC SP and customer demand; right axis: Ratio SP)

4. IMPLEMENTATION RESULTS AND ADDITIONAL STEPS

As mentioned earlier, the first pMPC controller was based on a single objective, i.e. load following. This controller was implemented at the selected Nitrogen plant serving a customer site. Significant benefits resulted from the ability to match the customer demand. The pMPC controller minimized liquid nitrogen (LIN) usage by ramping the plant up to maximum production when the customer demand was high, and it reduced power usage by ramping the plant down during low demand periods. While the speed of the ramp up was observed to be slightly slower than desired, overall the MPC controller was judged to be beneficial, and it was recommended that the operators turn it on every Monday morning after starting the plant up at the beginning of each week (this particular plant was shut down over weekends). The initial load following closed-loop behavior (single objective) is shown in Fig. 5.

The controller was next revised to include a purity control objective. As already mentioned, this second objective was to minimize power by operating against the upper impurity limit. The slow ramp up issue was also corrected. The new controller involved 8 parameters, and its solution 578 piecewise affine control laws. The new controller ramped the plant up or down at 3% of the design flow per minute. This is a significant ramp rate for this type of plants. Fig. 6 shows the load-following performance for this second controller. The plant layout included a buffer tank between the product compressor and the customer. By design, the controller was set up to load the buffer tank whenever possible, and the ramp down was not initiated unless the buffer tank pressure (which is shown in blue – buffer – in Fig. 6) exceeded 12 bar.

Before pMPC, the plant used to run at 0.01 ppm O_2 in the GAN product. By implementing the second optimization objective, the controller instead ran the plant at about 1 ppm, still being able to maintain the purity within specification in the face of disturbances. This led to a 1.5% reduction in air flow, with its consequent power savings. Fig. 7 shows the operation against the upper impurity limit, set at 1 ppm. At around sample 55 in the Figure, the controller started increasing the GAN/AIR ratio from 0.47 to its maximum limit of 0.499. This was effective while the plant was at maximum rates. At around sample 217 the customer suddenly started taking less product, and at that time both MVs, Air flow (not shown) and GAN/AIR ratio dropped to match the new customer demand.

The combined savings, namely from producing more product more efficiently when product was needed, and from ramping down the plant and saving power when less product was needed, were estimated to be in the order of £10000 per year. Without getting into the exact cost details for the controller, we are able to state that based on these results the controller would pay for itself in about half a year or less.

The same controller was duplicated, with almost no change, to a similar nitrogen generator in a different country. This served as an excellent test of the portability and robustness of the pMPC controller. The same model and same controller solution as in

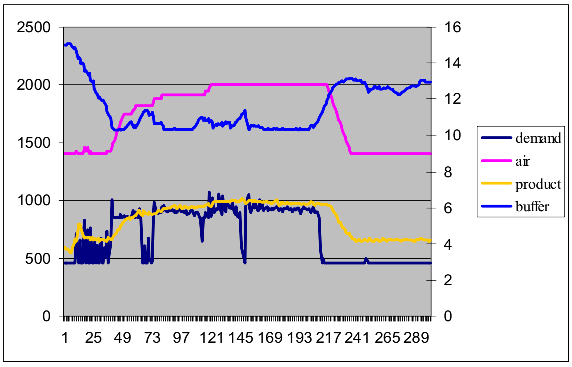


Fig. 6. Load following and operation with buffer tank, second controller implementation.

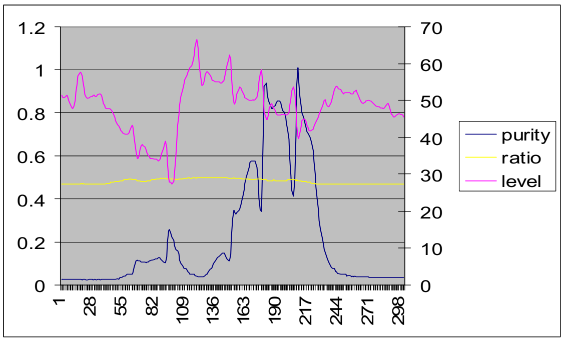


Fig. 7. Operation against upper impurity limit (Left axis, O_2 in GAN, ppm; left axis, GAN/AIR ratio; right axis, column sump level, %).

the previous site were used in spite of some differences in operating limits, customer requirements and customer take pattern. This controller was set up and loaded in just about a day, and ran well from the very beginning. Benefits were quickly obtained because of the increased production rates achievable at the plant with the help of the advanced controller. A third pMPC controller was later commissioned on a larger plant in the USA. Here a side-by-side comparison was done of pMPC operation versus standard operation at site, and the benefits of pMPC were thus demonstrated. Power savings from the use of pMPC were measured to be in the order of 3%. This corresponded well with the original savings estimated in our preliminary, simulation-based evaluation.

Our work also included initial research in the development of a robust parametric controller (Sakizlis, *et al.*, 2004). The idea is to do pMPC plant testing and controller development only once for a generic plant, in much the same way as demonstrated when we copied one controller from one site to another. Then, the robust controller can be simply duplicated to other similar plants, whether of the same size, larger or smaller, and have at most one or two tuning parameters for quick adjustment during commissioning.

CONCLUSION

By implementing MPC via multiparametric optimization (offline solution for online optimization) we can extend the realm and the benefits of model-based, optimizing control to small plants, devices and systems. Parametric MPC of small Nitrogen generators was implemented on existing PLCs and it has been running in several of our plants since 2003. Implementation on new plants is extremely rapid (can be as fast as 1 day). The controller has delivered:

1) Energy savings,
2) Product quality constraint satisfaction,
3) Accurate load following, and
4) Reduced venting of nitrogen.

At the present time, work proceeds for other types of Air Separation plants and in new areas beyond Air Separation.

REFERENCES

Bemporad, A., M. Morari, V. Dua and E.N. Pistikopoulos (2002). The explicit linear quadratic regulator for constrained systems. *Automatica,* **38**, 3-20.

Dua, V., N. A. Bozinis and E. N. Pistikopoulos (2002). A multiparametric programming approach for mixed integer and quadratic engineering problems. *Computers and Chemical Engineering,* **26**, 715-733.

Pistikopoulos, E. N., N. A. Bozinis, V. Dua, J. D. Perkins and V. Sakizlis (2002a). Improved process control. *World Patent Application WO 02/097540 A1.*

Pistikopoulos, E. N., V. Dua, N. A. Bozinis, A. Bemporad and M. Morari (2002b). On-line optimization via off-line parametric optimization tools. *Computers and Chemical Engineering,* **26**, 175-185.

Sakizlis, V., N. M. P. Kakalis, V. Dua, J. D. Perkins, E. N. Pistikopoulos (2004). Design of robust model-based controllers via parametric programming. *Automatica*, **40**, 189-201.