AN APPROACH TO EVALUATION OF ADVANCED CONTROL STRATEGIES FOR THE PROCESS INDUSTRY

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Abstract: In the last decades, the area of process control was focused on the development of new and more efficient control systems. The large number of advanced control strategies and the lack of a practical selection methodology makes the choice of an appropriate strategy for a given plant challenging. In order to support the process industry in the choice of proper control strategies (software products), a set of corresponding criteria is developed. An expandable test environment is created aiming at the controller evaluation considering these criteria. In this paper the structure of the workbench is explained and the evaluation approach is demonstrated by means of an example. *Copyright ©2000 IFAC*

Keywords: Benchmark examples, Performance indices, Multi-input/multi-output systems

1. INTRODUCTION

In the last decades, more sophisticated control strategies have been developed (e.g. model predictive control, neuronal network or fuzzy control), in the area of process control. With the number of advanced control algorithms increasing the need for a selection methodology arises inspiring this project. Since the evaluation criteria are developed to assist the process industry issues such as practical relevance and easy applicability are important. To meet the practical relevance many aspects of the controller design are considered, i.e. the standard set of criteria describing the controlled variable performance is extended by:

- Engineering effort
- Robustness and integrity
- Ability to operate at constraints
- ....

The method for the evaluation of controllers can be applied to compare representative controllers belonging to strategies like PID, fuzzy control, model predictive control etc.. In section 5 the method is illustrated by means of an example.

The approach assumes that detailed rigorous models of typical process plants can be used instead of real plants. The simulations necessary for the comparative controller assessment are performed on the test environment. The workbench is utilized to identify controller design models as well as implement and evaluate the controllers. To achieve an industrially relevant assessment of the above-mentioned criteria a distributed control system (DCS) and representative commercial advanced controllers are required. The DCS collects and checks process data and transfers them from the simulated plant to the advanced controller (figure 1). In addition, it provides an easy implementation of conventional control strategies

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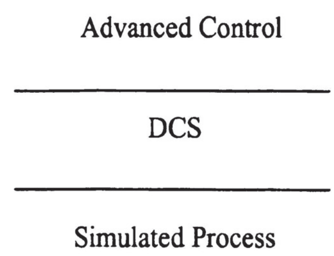

Fig. 1. Structure of the workbench

(e.g. PID and decoupling control). Detailed information about the technical requirements for the workbench are described in section 2. Currently, three process models (rigorous) of different complexities and four control strategies are integrated into the workbench (section 3).

2. TECHNICAL REQUIREMENTS FOR THE WORKBENCH

The workbench is supposed to be utilized from several users after a short training period, thus it is implemented on an easy to use Windows NT platform. The possibility to include additional controllers and process models is obtained because of a DCS which offers widely spread interfaces like DDE (Dynamic Data Exchange) and OPC (Object Linking Embedding for Process Control). In order to minimize the cost and maximize the portability of the workbench a DCS with the capability to emulate the "process station" is selected. The entire workbench, therefore might be realized even on a laptop. The real time control software (e.g. DCS, MPC) and the simulated processes have to be synchronized. To compare the control strategies a great number of simulations must be run. Consequently the acceleration of the time consuming "real time" simulation was investigated and an acceleration between 10 and 20 is typically applied.

3. PROCESS MODELS AND CONTROLLERS IN THE WORKBENCH

The workbench contains PID control, adaptive control, linear MPC and nonlinear MPC. The status quo shall be expanded by neuronal network control and fuzzy control. The three process models usable for evaluation are the Wood Berry Column (Bequette, 1998), the Tennessee Eastman Challenge Process (Downs and Vogel, 1993) and a dynamic simulator of a complex distillation process. All models contain unit operations relevant for process industry like distillation, heat exchanger or reactor. They are selected to meet the following demands:

- Wood Berry column: A simple distillation process suitable to gather initial experience in controller implementation and evaluation
- Tennessee Eastman process: A complex and academically acknowledged process
- Dynamic simulator: A detailed process which can be utilized not only for normal operating but also for start-up and shut down transients.

Since the first evaluation example is performed using the Wood Berry column the plant is described in more detail.

3.1 *Wood Berry Column*

The Wood Berry column (figure 2) has 41 stages and separates a binary mixture. The model is based on the assumptions below:

- Constant relative volatility
- Constant holdup
- Perfect level control.

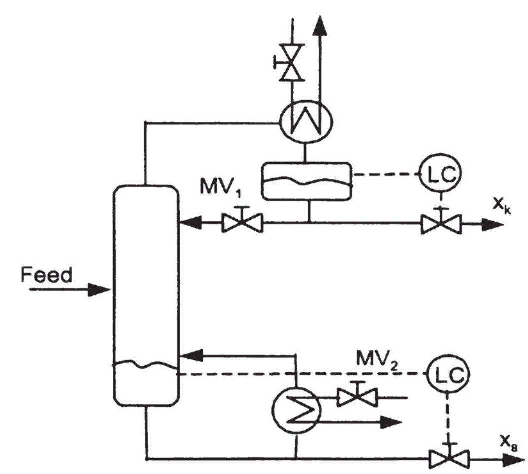

Fig. 2. Wood Berry column

The model of the distillation column considers only the material balance and the phase equilibrium on each stage. As both levels are controlled the remaining manipulated variables reflux and heating steam serve to adjust the concentrations of the light component x_K and x_S. The control objective is to ensure tight control during operating point changes and in the presence of disturbances.

4. EVALUATION CRITERIA

The choice of advanced control strategies is influenced by several issues. The demands on the APC strategy, the qualification of the user as well as the financial situation can significantly differ. Due to interviews with engineers (chemical and petrochemical industry) and literature recherche the criteria below were collected. [2]

4.1 *Control aspects*

Controlled variable performance: The well known ISE, IAE and an extended criteria (1) considering the moves of the manipulated variables, are applied at representative scenarios.

$$J_1 = \sum_i^N \left(w_1 e_i^2 + w_2 \Delta MV_i^2 \right) \qquad (1)$$

In order to avoid the impact of the weighting factors the integral of the squared errors and movements of the manipulated variable are shown separately. Furthermore the closed-loop time and maximal overshoot are calculated, and the transient for a setpoint change is also depicted.

Robustness to model errors: The robustness index *(RI)* (2) see (Page *et al.*, 1986) has the advantage of being independent on control strategies and models. For example: The methods which are based on frequency domain can not be utilized directly for MPC. The method proposed here increases critical process model parameters until the process reaches the stability margin. Therefore *RI* is defined as:

$$RI_{KP} = \frac{\Delta KP}{KP} \quad RI_{TP} = \frac{\Delta TP}{TP} \qquad (2)$$

ΔKP and ΔTP are the minimal change of the process gain and process deadtime inducing unstable operation of the closed-loop. Since the dynamic models are not represented as transfer functions, the uncertainty of the gain and deadtime is introduced into the measurement output. To compare robustness of several controllers, the relative robustness index is applied. For instance, equation (3) compares an MPC and a PID controller at the same plant.

$$RRI_{KP} = \frac{\Delta KP_{MPC}}{KP_{PID}} \quad RRI_{TP} = \frac{\Delta TP_{MPC}}{TP_{PID}} \qquad (3)$$

Integrity to controller status changes: Each controller should retain reasonable performance for its basic objective even if performance is somewhat degraded, as changes occur in the automatic /manual status of interaction loops(Marlin, 1995). Although this issue is very important for MIMO systems (process industry) only few articles are published. The simulation environment described in section 3 enables an engineer to obtain experimental information. The information might be helpful to verify features of APC strategies. For instance: Some controllers claim that they can compensate defective measurements by using a prediction as well as defective manipulated variables by rearranging the control problem.

Consideration of constraints: Manipulated and controlled variables hit frequently constraints in process industry. Therefore the techniques to cope with this problem are investigated. (low: use of selector or override blocks; medium: use of weighting factors; high: explicit targets).

Stiff systems: Plants of the process industry may include fast and slow dynamics. This can complicate the model identification as well as the controller design. It might even force a decomposition of the system. (irrelevant; partial for modelling and controller design; complete)

4.2 *Aspects of industrial usability*

This section describes properties of control strategies, which may depend on both the control strategy and its implementation into a product.

Education requirements for the engineering: (low: basic knowledge of control; medium: basic knowledge of control and the process; high: very good knowledge of control, the process and the product)

Implementation and installation effort: (low: no programming; medium: controller configuration applying the available tools; high: programming to adjust tuning parameters)

Tools for modelling and controller design: (low: no tools available; medium: widely spread tools like Matlab can be used; high: tools for modelling and closed-loop simulation are available)

Support of operation mode changes (Man/Auto): (low: no support; medium: only for SISO systems; high: no programming even for MIMO systems)

User friendly interfaces for MIMO systems: (low: no support ; medium: support of MIMO control interfaces; high: like medium & data access from other interfaces)

5. APPLICATION OF THE EVALUATION APPROACH

The proposed evaluation methodology can be applied on several APC strategies. In order to exam the method and the workbench just three controllers of different complexity are assessed at the Wood Berry column.

[2] If quantitative assessments are not possible, then the qualitative statements/definitions are given in brackets

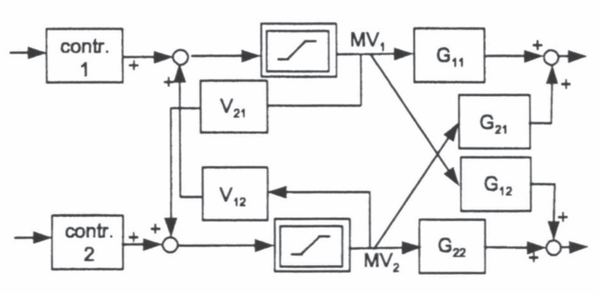

Fig. 3. V-decoupling network

The three controllers implemented are described below:

Decentralized PID controller (IMC-Tuning): The main paths of the linear process model (figure 4) without the coupling paths are considered for the controller design. Since the models are second order utmost the IMC tuning can be utilized straightforwardly. This leads to PID controllers, where the parameters are obtained on the basis of the model structures and the IMC filter constants (Rivera *et al.*, 1986). The filter constants of the two controllers are tuned to meet predefined criteria at the linear model.

Decoupled PID controller (IMC-Tuning): In order to minimize the coupling a PID controller with a decoupling network is applied (figure 3). Due to the decoupling network added the input-output model is changed, thus a new model of second order is approximated. Afterwards the IMC tuning is applied as described before. In comparison with alternative decoupling networks the used one can easily be implemented by standard blocks of the DCS.

Model predictive controller (MPC#1): The MPC#1 utilizes a step response model derived from a linear transfer function to determine the control solution. The new manipulated variables are calculated by a nonlinear optimization at every cycle. Through the prediction of the manipulated and controlled variables constraint violations of those variables can be accounted for directly. The tuning parameters are the closed-loop settling time of each controlled variable and the weighting factors of the manipulated variables to determine a ranking when more than one variable can meet the objective. A special feature of this controller is the possibility of setpoint and range control.

In order to "reconstruct" the industrial control engineering procedure the following approach is considered.

- Determination of the process model, (identification applying step tests). The identified model of the Wood Berry Column is depicted in figure 4.
- Controller design and verification using an off-line simulator.

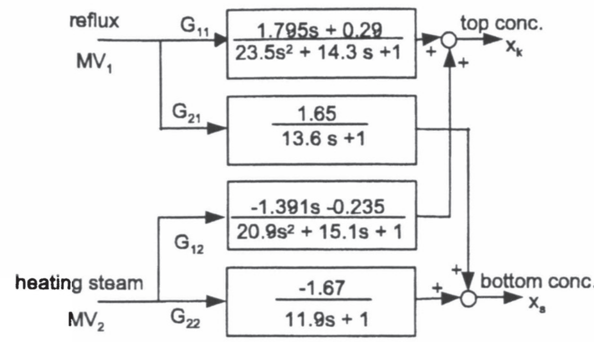

Fig. 4. Linear model used for controller design

The tuning parameters of the three controllers are determined to minimize the moves in the manipulated variables under consideration of certain criteria: In this case the closed-loop settling time of x_k should be smaller than 18 min within a maximal overshoot range of $x_s = 1.2^{-3}$ for a step change from 0.9812 to 0.99 of x_k (see figure 5). The tuning parameters of all controllers are determined using the same coupled linear model (see figure 4).

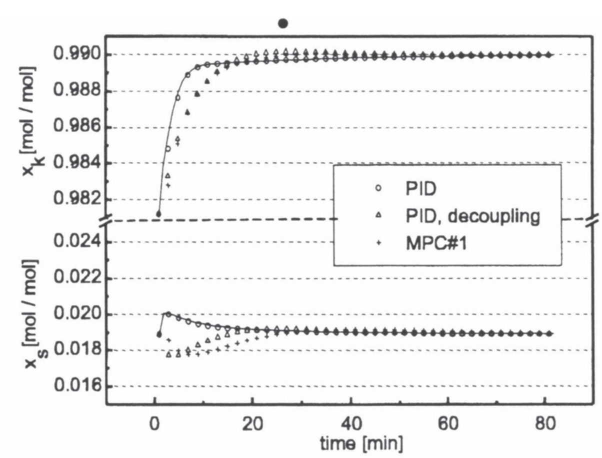

Fig. 5. Dynamic response of a step change in x_k, using the linear model

- Implementation of the controllers on the DCS or the on-line computer.
- A step change x_k from 0.9812 to 0.99 (see figure 6) and a disturbance in the feed concentration are investigated using the dynamic nonlinear model.

Further simulations are executed to evaluate the criteria of the above mentioned catalog (see figure 7).

6. CONCLUSION

An approach was proposed to evaluate and select advanced process control strategies for the process industry. By utilizing the workbench created an engineer is able to emulate the industrial application engineering and to reveal the information

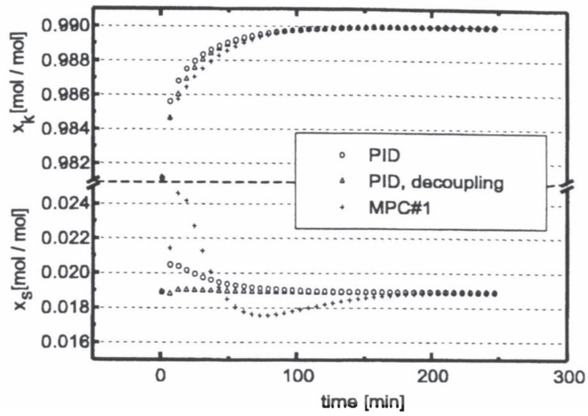

Fig. 6. Dynamic response of a step change in x_k, using the nonlinear model

necessary answering the comprehensive criteria catalog. It is supposed that the evaluation of control strategies for a process unit like a distillation column can be extended to other process units with similar properties. For the time being the method can only be applied to controllers for continuous plants. The gained experience lead to the following assessment:

- It is possible to evaluate APC strategies for certain process units and demands using the proposed approach.
- Due to the consideration of certain assumptions like model uncertainty, disturbances and setpoint changes it may be necessary to have an accurate rigorous model of the process unit for detailed investigation.
- Up to now, the application engineering effort depends strongly on the qualification and experience of the engineer.
- The comparative assessment of the controlled variable performance is rather difficult, since the control products have different inherent performance criteria. Thus an equal base for the tuning procedure has to be defined. In this example all controllers must meet the predefined response time and a minimum degree of decoupling.
- Although all APC controllers are commercially available, only few of them are ready for external use. The raised difficulties during the installation and implementation revealed that a close contact to the supplier is still very important.
- The standard interfaces like OPC and DDE in the workbench decrease the implementation effort significantly and facilitate the use of diverse model formats (Matlab, Fortran, etc.).
- In case a proper control strategy is selected it can be effortlessly and quickly migrated to the real plant. Thus the "time to market" is reduced by using the workbench.

The method and the workbench shall be utilized for further investigations including other models and controllers.

7. REFERENCES

Bequette, B.E. (1998). *Process Dynamics Modeling, Analysis and Simulation.* Prentical Hall PTR. ISBN 0-13-206889-3.

Downs, J.J. and E.F. Vogel (1993). A plant-wide industrial process control problem. *Chemical Engng.* **17**, 245–255.

Marlin, T.E. (1995). *Process Control.* McGraw-Hill. ISBN 0-07-113816-1.

Page, G.P. Le, M.O. Tade and R.J Stone (1986). Comparative evaluation of advanced process control techniques for alumina flash calciners. Vol. 8. pp. 287–298.

Rivera, D.E., M. Morari and S. Skogestad (1986). Internal model control. 4. pid controller design. Vol. 25. pp. 252–265.

Group	Criteria	PID	PID with decoupling	MPC#1
Auxiliary control objectives	Closed-loop time x_K	18 min	18 min	18 min
	Max. overshoot x_S	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$
Controlled variable performance at the linear model	IAE x_K	0.046	0.057	0.059
	IAE x_S	0.017	0.018	0.025
	$J_1 = \sum_i^N \left(w_1 e_i^2 + w_2 \Delta MV_i^2\right)$			
	$J_{11} = [\ \Sigma e(x_k)^2 \mid \Sigma(\Delta MV_1)^2\ ]$	$[\ 1.85 \cdot 10^{-4} \mid 20.6 \cdot 10^{-3}\ ]$	$[\ 2.85 \cdot 10^{-4} \mid 7.7 \cdot 10^{-3}\ ]$	$[\ 3.06 \cdot 10^{-4} \mid 3.5\ 10^{-3}\ ]$
	$J_{12} = [\ \Sigma e(x_S)^2 \mid \Sigma(\Delta MV_2)^2\ ]$	$[\ 0.09 \cdot 10^{-4} \mid 15.8 \cdot 10^{-3}\ ]$	$[\ 0.10 \cdot 10^{-4} \mid 6.8 \cdot 10^{-3}\ ]$	$[\ 0.15 \cdot 10^{-4} \mid 2.9\ 10^{-3}\ ]$
Controlled variable performance at the nonlinear model	Closed-loop time x_K	76 min	79 min	85 min
	Max. overshoot x_S	$1.6 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$	$5.8 \cdot 10^{-3}$
	IAE x_K	0.16	0.19	0.21
	IAE x_S	0.065	0.008	0.23
	$J_1 = \sum_i^N \left(w_1 e_i^2 + w_2 \Delta MV_i^2\right)$			
	$J_{11} = [\ \Sigma e(x_k)^2 \mid \Sigma(\Delta MV_1)^2\ ]$	$[\ 5.13 \cdot 10^{-4} \mid 16.0 \cdot 10^{-3}\ ]$	$[\ 6.64 \cdot 10^{-4} \mid 13.0 \cdot 10^{-3}\ ]$	$[\ 6.90 \cdot 10^{-4} \mid 7.6 \cdot 10^{-3}\ ]$
	$J_{12} = [\ \Sigma e(x_S)^2 \mid \Sigma(\Delta MV_2)^2\ ]$	$[\ 0.61 \cdot 10^{-4} \mid 23.3 \cdot 10^{-3}\ ]$	$[\ 0.02 \cdot 10^{-4} \mid 12.4 \cdot 10^{-3}\ ]$	$[\ 6.29 \cdot 10^{-4} \mid 6.9 \cdot 10^{-3}\ ]$
Robustness at the nonlinear model	$RI_{KP} = \dfrac{\Delta KP}{\Delta KP_{PID}}$	1	8	2
	$RI_{TP} = \dfrac{\Delta TP}{\Delta TP_{PID}}$	1	1.75	2.25
Integrity		Yes, depending on tuning	Yes, depending on tuning	Yes (explicit by consideration of constraints, substitution of the prediction for the measurements temporarily possible)
Consideration of constraints	Controlled variable	No	No	Direct
	Manipulated variable	No	No	Direct
Stiff systems		Irrelevant	Irrelevant	Subsystem necessary
Anti-reset windup		Yes	Yes	Yes

Criteria	PID	PID with decoupling	MPC#1
Education requirements for the engineering	Medium	Medium–High	Medium–High
Implementation and Installation effort	Low	Medium–High	High
Tools for modeling and controller design	Medium	Medium	High
Support of operation mode changes (Man/Auto)	Medium	Medium	High
User friendly interface for MIMO-System	Low	Low	Medium

Fig. 7. Evaluation results