Modern Method of Generating the Best Control Structure for Binary Distillation Columns

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Abstract: The proposed method is situated within the actual trend of integrated process control design. The paper deals with a modern research theme in plantwide control field. Within this framework, it tries to solve the problems concerning the operation of distillation columns, many of these problems deriving from design errors of control structure. Analyzing from plantwide control point of view the place of distillation column within the plant, the result will be the best control configuration. The proposed method will supplement and enrich the plantwide control field, which is at beginning stage of its development.

Key-words: plantwide control, composition control, dynamic simulations.

1 Introduction[1]

In the last years it is emphasized a new research direction in chemical process control field the so called integrated design and control of chemical processes ([1], [2], [3], [4]). For new plants the simulations done with state of the art dynamic simulators are crucial in establishing the best control configuration. The already designed plants can be improved choosing the best control configuration using plantwide control procedures ([5], [6], [7], [8]). The goal of plantwide control studies is to design a control system that can achieve the operating requirements of the complete plant optimal conditions [9]. The problem focuses on the whole plant and not only on individual units. The size of plantwide control problems is larger than that for individual units, making the solution much more difficult. The main problem is the presence of recycle streams that provide interactions between different equipments. Disturbances that occur in a process can propagate not only downstream from one unit operation to the next, but upstream through material and energy recycle loops [10].

Plantwide control does not mean the tuning and studying the behavior of each of these loops; it corresponds to the control philosophy of the overall plant with emphasis on the structural decisions [5]. The use of an effective plantwide control structure may lead to a significant reduction in the size of these intermediate inventories or possibly their elimination from plant design ([11], [12]). Luyben and his coworkers [6] have provided a set of guidelines that enable the user to develop a plantwide structure that provides tight and effective control for some chemical processes. This is very important in a system, which includes large recycle streams that often propagate and amplify process variation and the effect of disturbances [13]. Arkun and Stephanopoulos have dealt with the problem of how one can systematically synthesize plantwide control architectures from steady-state process models with use of optimization. Results for the application of the synthesis procedure to the TEC process are presented ([14], [11], [8]). Stephanopoulos and Ng [8] provided a comparative analysis of various approaches emphasizing some practical issues associated with the design of plantwide control. Vasbinder and Hoo [9] described a modular decomposition of plant flowsheets that is assessed according to a decision-based approach to plantwide control structure synthesis.

Many works in the open literature present studies on modeling and control of the separation task from process unit approach ([15], [16], [17], [18], [19], [20], [21]), but relatively few publications are found out concerning the plantwide control approach for a complex separation unit (formed by interconnected distillation columns). The objectives of this paper are the presentation of the proposed method of generating the best control structure for binary distillation columns and simulating it on the separation part of the FCCU (also called GPU – Gas Processing Unit). By its topics, this paper is situated in the framework of

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general effort to develop modern techniques of plantwide control design for distillation plants, representing a good premise for the next development of the researches in this field.

2 Proposed method

The main objective accomplished is implementing at a minimum functional level of working framework to develop the application of generating the best structure. This means the design of these basic components: simulation module of binary distillation columns, the simulation module of decoupling control composition loops, and the composition control modules.

In order to develop such an application there were acquired licenses for two state of the art dynamic simulators Dynsim® and Aspen Hysys®. At this stage of the project after a thoroughgoing study on mathematical formalism used for distillation columns the result is a distillation model suited for control purposes. This model is resulted after studying the dynamic behavior of distillation columns with different control configuration using Dynsim® and Aspen Hysys® environments [22].

This paper also deals with the design issues (detailing the requirements for the proposed application and the evaluation methods of the results, detailing the initial project specifying the new implementation requirements) and determining a simple way to describe the requirements of such application so that it can represent a useful guide for the process engineer designer. As already known, in the last years it is emphasized a new research direction in chemical process control field the so called *integrated design and control of chemical processes*. Achieving this high importance objective implies increasing efforts both in modernizing and varying of control and calculus means, and also in designing good control structures effectively implemented in industrial processes. The already designed plants can be improved choosing the best control configuration, choice that it is done using plantwide control criteria. The validation of the proposed structure is done by simulation. Distillation plants are from economical point of view, one of high energy consumption units from a refinery. The developing of chemical industry is tightly linked with the emerging of advanced chemical process control systems, while the energy consumptions are considerably reduced. The complexity of the distillation process leads to an increase effort in finding the best control configuration.

In plantwide control context, the problem of control structure design is made in 5 steps:

1. selecting controlled variables;
2. selecting manipulated variables;
3. selecting measured variables;
4. selecting control configuration;
5. selecting and tuning the controller type.

The primary controlled variables are selected based on steady state economic criteria. The accomplishment of the first step makes the link between the steady state optimization level and the inferior control level, and the *self optimizing control* concept introduced by Skogestad provides a useful framework for taking the best decisions in hierarchical control of processes.

On the other side, it appears as viable alternative, the principle of *feedback optimizing control structures*, proposed by Stephanopoulos and Ng as formal framework for identifying the controlled variables. The hierarchical approach is an efficient mechanism of treating the complexity of the control problem by:

(i) specifying the control objectives with different time scales;
(ii) modeling from abstract to detailed level;
(iii) selecting the control variables and manipulated variables;
(iv) facilitating the configuring of control structures.

The ideas presented in this chapter, based both on studying references and our own experience in hierarchical control systems lead to the next conclusions:

• Plantwide control field is in an early stage of its development. In the last years there were made some progresses both in case studies and general theoretic approach. Plantwide control issue has a bigger dimension than unit base approach. In spite of this, there are still many case studies associated with process units, considered to belong to plantwide control field. Generally, the case studies made by now refer to low complexity chemical plants. Although the distillation process is well known and deeply theoretically investigated, its complexity and the magnitude of associated material and energetic fluxes justify the need of ongoing efforts to build mathematical models as efficient as possible from control perspective. That is why, for the distillation process is needed the efficient solving of the modeling issues of this process from plantwide control point of view.

• In order to find plantwide control solutions, the process descriptions hierarchies enable control problem decomposition into a series of sub problems with reduced complexity. Another plantwide control solution, namely decentralized control structure represents an alternative to the use of centralize multivariable controller with very large dimension.

Some solutions took into account the hierarchical treatment of control objectives. In order to find the structural decisions there were used empirical laws, based on the experience from operating the process. For emphasizing the modeling needs there were used temporal hierarchical decompositions, process based and control objectives oriented. Most of the papers of the last decades treats the plantwide control structure synthesis as being synonym to the pairing loops (choosing the pair manipulated variable – control variable) in order to form monovariabile control loops.

Binary distillation columns are high energy consumers, so any improvement in their operation being very important for a refinery.

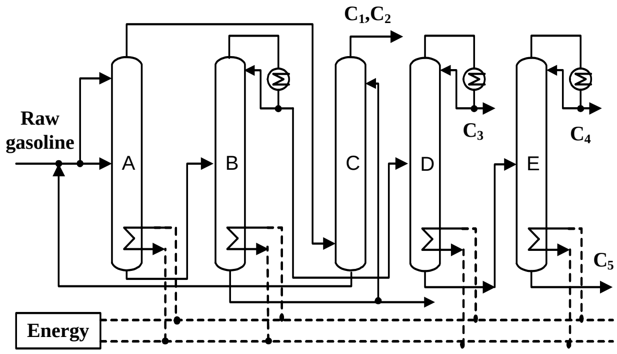

Fig.1. Concentration unit.

The proposed method takes into account the place of the studied distillation column. Distillation columns usually take part into a large complex formed by other process units. From this point of view we can characterize a distillation column as the first process unit, intermediate or final distillation columns. An intermediate column influences downstream units if there are no recycle streams; otherwise it has effects on both downstream and upstream units, Fig.1 (B, D, E – distillation columns, A, C - absorption – desorption columns). Final columns do not disturb any upstream or downstream unit. From plantwide control strategy, there is no restriction imposed to this final column, the best control structure for it being generated by steady state criteria (e.g. RGA) usually combined with dynamic simulations with rigorous simulation tools.

The first distillation column is usually forced to refine the main flux formed by a mixture from which the final products of the unit will be recovered. The throughput manipulator place also influences the control decisions to be taken. The control structure chosen must have good features regarding the effect of the main disturbances that affect a distillation column, namely feed flowrate F and its composition x_F (Fig.2).

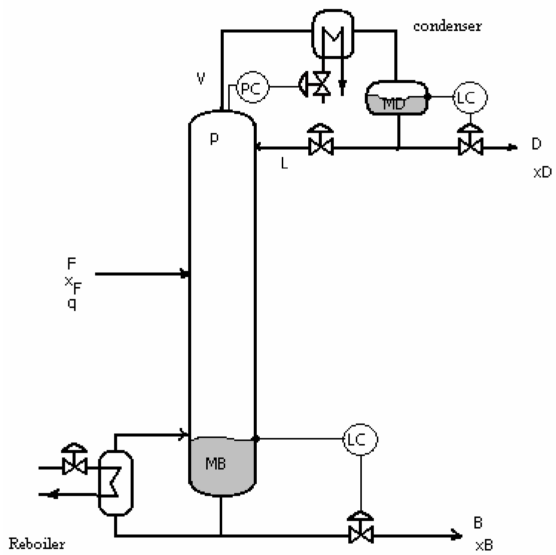

Fig.2. Manual LV configuration for a binary distillation column

Also, the proposed structure for the first distillation column must avoid the use of the ends as manipulating variables, because the final products of the first column represent feed streams for downstream units. Usually distillate is the most important product of the columns, so the main flux of the plant will be directed to the tops of distillation columns. The structure of an intermediate distillation column will depend on the existence of the recycle streams. After studying various processes units from Romanian refineries, in the absence of recycle streams we recommend a control structure with minimum influence for downstream units. The presence of recycle streams is solved by fixing flowrates in recycle streams, as dynamic simulations proved ([1], [23], [24]).

In Fig.2 it is considered a binary distillation column with one feed. From systemic perspective it has five manipulated variables $u = (L, V, D, B, Q_c)^T$ representing the reflux flowrate, the boilup flowrate, distillate flowrate, bottom product flowrate and cooling agent flowrate. The system outputs are also five $y = (x_D, x_B, M_D, M_B, p)^T$ represented by light component composition in distillate and bottom product, the holdups on reflux drum and in the bottom of the column, and the column pressure. In the case of a distillation column the first thing to be done is stabilizing the column by its inventory control loops (three decentralized monovariabile control loops: one for pressure and two for level) with the outputs:

$$y_2 = (M_D \ M_B \ p)^T . \quad (1)$$

The non-controlled variables are the compositions:

$$y_1 = (x_D \ x_B)^T . \quad (2)$$

The three monovariabile control loops associated to y_2 weakly interact between them and can be considered independents. There are more possibilities to choose the u_2 manipulated variables (therefore for u_1, too). These control configurations are named from u_1 inputs remained for composition control loops. The LV configuration from Fig.2 refers to control system with

$$\begin{cases} u_1 = (L\ V)^T \\ u_2 = (D\ B\ Q_c)^T \end{cases} \tag{3}$$

The most known control configurations for distillation columns are LV, DV, LB or double ratio configurations etc. [25]. Although distillation control has been largely applied in industry and many efficient control structures were established [17], the frequent use of plants with recycles, the heat recovery and regeneration lead to conflicts between process unit control structures, making the unit-based approach ineffective.

3 Case Study

The concentration and separation plant belong to catalytic cracking unit and their aims are the recovery and distillation of gas flux resulted from catalytic cracking process of vacuum distillate. In concentration and separation plant there are integrated Merox gasoline and Merox LPG plants which must eliminate the sulphur components. A more detailed representation of hydrocarbon distillation plant emphasized the presence of recycle streams in concentration subsystem. In the other two subsystems (treatment and gas separation units) the connections are only in a serial branch sequence, which will make less difficult the control system design. Its structure is more complicated compared to the plantwide control test problems from literature. For gas separation unit (Fig.3), the production programme consists in establishing:

- the quantity of raw material for processing;
- the quantity of valuable products expressed in mass % from raw material;
- quality specification of products;
- constraints in energy consumption programme.

Due to the fact that this process follows the FCC unit, the raw material cannot be controlled, this flow being one of the most important disturbances.

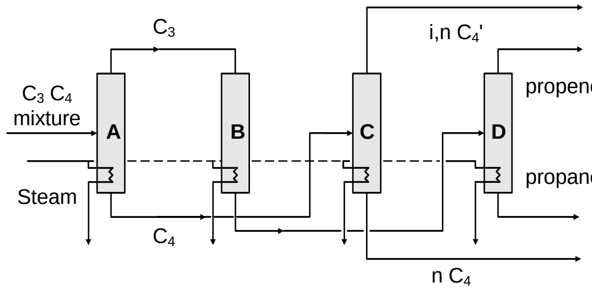

Fig.3. Gas separation unit.

Evaluating the raw material flow, the functions of the control system at this representation are:

- the most advanced recovery of the valuable products (propylene, propane);
- minimizing energy consumption.

GPU consists of three distillation columns A, C, D and dehydrating column B that works out only if the raw material has important changes. The data associated with these three columns are taken from a Romanian refinery and are briefly presented in Table 1. The simulations of the separation unit were done using Aspen Hysys® simulator. The transient times associated to these columns are about 600-700 min. For A (depropanizer), C (butane-butylene distillation column, BBDC) and D (propylene-propane distillation column, PPDC) the best control configurations were established taking into account their influences in the plant (plantwide control criteria).

Table 1

Column data	A	C	D
NT total stages	21	75	70
NF feed stage	10	38	23
F [kmol/min]	9.77	5.91	3.85
x_F [mole fr.]	0.42	0.62	0.67
q_F	1.0	1.0	1.0
L [kmol/min]	7.71	36.53	31.53
V [kmol/min]	11.57	40.36	34.26
M0_i [kmol]	1.13	1.7	1.5
M0_1 [kmol]	16.77	10	51.8
M0_NT [kmol]	98.72	32	71.6
Taul [min.]	0.063	0.063	0.063
lambda	0	0	0
Relative volatility	2.7	1.23	1.14

The serial branch sequence of gas separation unit lead to the following control structures:

- for depropanizer column – LV structure with one point bottom composition control;
- for BBDC - SV/B structure;
- for PPDC - SV/B structure.

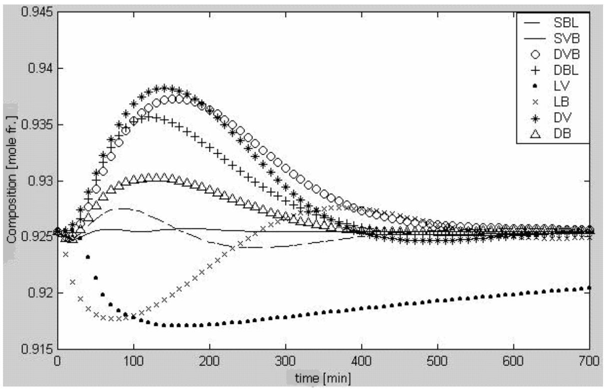

Fig.4. Dynamic responses to flowrate changes of PPDC.

The BBDC and PPDC are final distillation columns that process the most important products of FCCU. The SV/B structures associated to these columns do not influence any downstream units. The depropanizer column has as ends the distillate D that represents the feed for PPDC, and the bottom product B, that represents the feed for BBDC. Consequently, these two streams cannot vary too much in order not to upset downstream columns BB splitter and PP splitter that proved to be very sensitive to feed changes (in flowrate and composition). The external flows D and B will be used to inventory control loops. D is manipulated variable for depropanizer reflux drum level control and B is the manipulated variable for the depropanizer bottom level control. The level control loops uses PI controllers with weak integral component ($k_P = 1$ and $T_i = 200$ min), in order to minimize the effect on downstream units. This choice leads to the LV structure for depropanizer column, the available manipulated variables being the reflux flowrate L and boilup flowrate V . The resulted structure is LV with one point bottom composition control, based on dynamic simulations for the depropanizer. The simulation results concluded that the depropanizer distillate is less influenced than the bottom product at changes in feed flowrate and composition.

The PPDC that was studied has proven to be sensitive to any disturbance, especially to changes of the feed quality (x_F). The specifications for this column were stiff concerning the composition for the top product (90% vol. propylene) while the specification for bottom product is flexible. The results concerning the RGA [24] proved that the best structure for the studied column is represented by ratio control schemes naming SV/B and DV/B configurations. The specifications for this column and the current x_B range (0.01…0.05% mole fr.) lead to RGA closest to 1. The most important parameter taken into account is the dynamic response of the structure. The SV/B structure has a faster dynamic response than DV/B structure, as a result of dynamic simulations. More important for SV/B structure is the feature that rejects the effect of feed flowrate changes even in open loop mode (Fig.4). For butane-butylene distillation column (BBDC), the best control configuration is also SV/B, from steady state and dynamic criteria [24]. Simulation results lead to an enhanced response of the GPU to changes in feed flowrate, especially for PPDC column (Fig.5) that has the most valuable products of the plant.

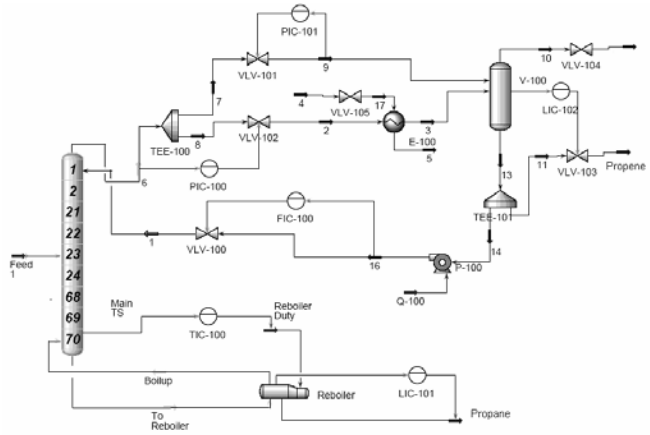

Fig.5. Propylene propane distillation column.

The continuous improvement trend of industrial plant performance lead to the design of more integrated plants, and that is why the plantwide control strategy represents the key factor in improving economical performance of a factory.

4 Conclusions

In plantwide control researches, the main results are obtained in arguing the reasons for which are measured and controlled the parameters of a plant. The plantwide control concept reflects the control strategy/control philosophy of a chemical plant (Stephanopoulos and Ng, Larsson and Skogestad, respectively).In an explicit manner, the formal framework is granted by the *Feedback Optimizing Control Structure* and its alternatives *Self-optimizing Control Structure* and *Partial Control*.

The paper presents a plantwide control approach concerning the structure, functions and control of hierarchical system for a gas processing plant from a catalytic cracking unit and some practical results in implementing it to the process. The main features of the proposed method are: good performances, robustness according to model parameters uncertainties, easy guide to process engineer designer. The proposed method will supplement and enrich the plantwide control field, which is at beginning stage of its development.The paper insists on those problems that are likely to become a starting-point for the future research in the main aspects of the proposed method. This method will be tested for more complex units, the first step indicating the entire FCC complex.

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