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PLANTWIDE CONTROL DESIGN USING AN EXPERT SYSTEM

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Abstract: The key objective of this paper is to show the application of an expert system to solve the plantwide control problem. The main advantage of this method is that only operation and design data about the plant are needed to obtain a valid control strategy for the process. The expert system is demonstrated generating automatically a plantwide control structure for the Tennessee Eastman challenge problem.

Keywords: Plantwide control, expert systems, control system design

1. INTRODUCTION

Plantwide control (PWC) refers to the structural and strategic decisions involved in the control system design of a complete plant, including the following tasks, see (Foss, 1973) (Skogestad *et al.*, 2000):

- Selection of controlled variables.
- Selection of measured variables.
- Selection of manipulated variables.
- Selection of control configuration (links between the previous variables).
- Selection of controller type.

The classical approach has focused on the control of single process units, considering the plant as the sum of the individual units. Nowadays, plants are highly integrated processes, mainly due to the effects of material recycle, the need of chemical component inventories, and the effects of energy integration. For example, recycle streams can alter the plant's dynamic and steady-state behavior because they propagate and amplify process variation and the effect of disturbances, leading to a significant influence on the performance of individual units. This means that it's necessary to design a control strategy for the overall plant.

In order to achieve the objectives of the plant (operability, profitability and stability) some procedures have been suggested for the development of a control system since the pioneering work of (Buckley, 1964): (Luyben *et al.*, 1999) use control heuristics, (McAvoy, 1999), (Skogestad *et al.*, 1999) have developed methods focused on optimization whereas (Lyman *et al.*, 1995), (Groenendijk *et al.*, 2000) have developed methods using simulations.

Methods based on optimization and simulation need a process model and do not deal with all the PWC tasks. Heuristic methods require process control knowledge from the person who apply them.

This paper shows a method using an expert system that generates automatically a control structure for the entire plant. This method is suitable for use by a wider range of users. This expert system has been programmed using CLIPS, an expert system tool developed by the Software Technology Branch (STB), NASA/Lyndon B. Johnson Space Center.

The main advantage of the method proposed in this paper over the methods mentioned above is that the expert system does not need to be linked to any simulator and does not use any process model. The person who uses the expert system does not need process control knowledge because the user only has to enter the information about the plant and its running conditions.

Section 2 explains the architecture of the expert system and how it works and section 3 shows its application to the Tennessee Eastman process, the most widely used example in the literature.

2. EXPERT SYSTEM ARCHITECTURE

The expert system is composed of three independent modules. Two of them are implemented by means of a user interface. The third stores the experimental knowledge about process control. The generic architecture of the expert system is shown in Fig. 1.

Different rules of the knowledge base are activated depending on the data (about the plant and its specifications) entered by the user. The inference engine fires these rules and, as a result, the control structure is generated. The expert system can also show the explanation of the reasoning followed during the decision process.

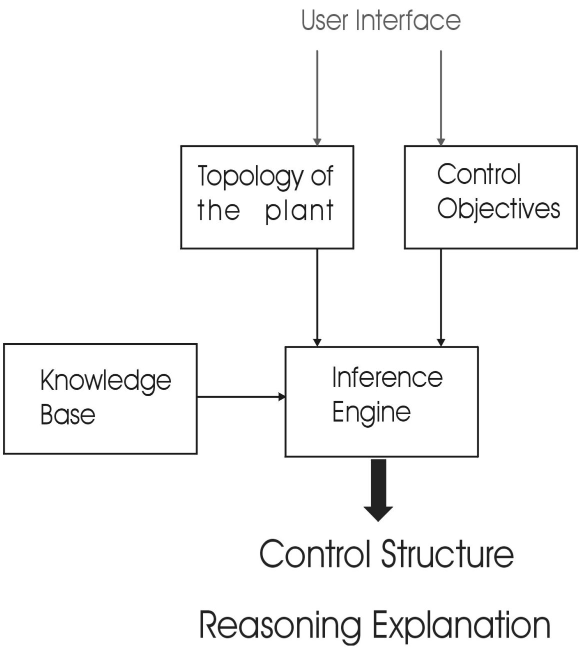

Fig. 1. Architecture of the expert system

2.1 *Module I: Topology of the plant and information about components and reactions.*

This module asks for the necessary information to the user. This information includes the following:

- the units that integrate the plant (reactors, distillation columns, separators, ...), some important features from a control perspective (the presence of utility streams in the units) and the type of the units (if the reactor is a continuous stirred tank reactor or a plug-flow reactor, ...);
- the topology of the plant: how the units are connected,
- the components that are present in the process: type (reactants, inerts, products or by-products) and paths that follow these components within the process,
- the phase of each stream,
- the reactions occurring in the process: the components involved (reactants and products of each reaction) and reactions features (exothermic or endothermic reactions, ...).

An object is created for each unit and for each stream. In these objects is stored the information entered by the user. After this input the expert system is ready for matching the rules that will be executed by the inference engine.

One of the most important functions of this module is to identify the recycle streams to the reactor because the control structure must be able to prevent the building up of the process components in these streams.

2.2 *Module II: Control Objectives*

In this module, the user will introduce the control objectives: process specifications (product quality specifications, production goals, ...) and operation constraints (pressure or temperature limits, ...). This module is extremely important because, for the same plant, the best control structure will change if the control objectives are modified.

When the user enters which variables must be kept at a specific value, a set of rules are fired and the expert system selects the manipulated variables for these controlled variables. The remaining degrees of freedom will be used for keeping the variables subjected to constraints between the specified limits and for achieving a smooth and economic process operation. For doing that, the expert system will have to select the controlled and the manipulated variables using the control heuristics. An explanation of each decision made by the expert system is shown in a file that helps the user to understand the reasoning followed.

The control strategy must be able to handle disturbances in the plant (composition variations of the fresh feed streams, changes in the flowrate or in the temperature of these feeds, ...) and to stabilize the process. The influence of the disturbances in the plant operation is reflected on the rules for ensuring a robust control.

2.3 *Module III:Control Heuristics*

This module is the core of the expert system. The experimental knowledge of the rule base has been collected mainly from the literature review and from control structures developed for real industrial processes. The rules consider first the control of the entire plant and later try to optimize the operation of each individual unit.

A rule is activated when its conditions are satisfied. The execution order of the activated rules depends upon the priority of the rules and the priority is established in accordance with the criterion of bearing in mind the overall plant. Some basic rules for dealing with complex problems are the following:

- The control structure must ensure that energy disturbances do not propagate throughout the process (the exothermic heat of reaction and the heat supplied are dissipated to utilities).
- Component inventories must be controlled, taking into account that we want to minimize losses of reactants and products and that its necessary to prevent reactants from building up within the process.
- If possible, production rate changes must be achieved by changing the reaction section to avoid disturbing the separation section.
- To prevent the snowball effect, a flow is fixed in every liquid recycle loop.
- To improve yield, flowrates through gas recycle streams are maximized.

Later, the control of the individual units is considered. The expert system always tries to select the manipulated variables that have the largest effect on the controlled variables.

During the rules execution it is possible to introduce slight modifications in the process design (such as adding bypass lines around heat exchangers, including auxiliary heat exchangers,) to improve the plant controllability (Fisher *et al.*, 1988).

When the rules execution is finished, the result is a valid structure that complies with the PWC premises and a output file that explains why are the variables selected.

The application of the expert system to a real process is presented below.

3. CASE STUDY 1: THE TENNESSEE EASTMAN PROBLEM.

To show how the expert system works, the Tennessee Eastman problem has been the selected example because this process has been widely studied in control but the expert system has been applied to other processes developing valid control structures for these processes because the heuristic rules implemented are generally applicable.

3.1 *Description of the problem:*

The problem of (Downs *et al.*, 1993) was first proposed at an AIChE meeting in 1990 and has since been studied by many authors. The process has four feed streams, one product stream, and one purge stream to remove an inert.The main reactions are:

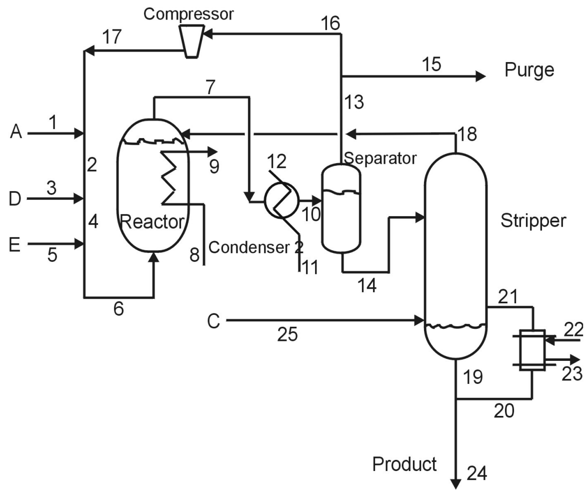

Fig. 2. Flowsheet of the Tennessee Eastman Process

$A + C + D \rightarrow G$
$A + C + E \rightarrow H$

These reactions are irreversible and exothermic and there are also two side reactions that produce by-product F:

$A + E \rightarrow F$
$3D \rightarrow F$

A small amount of an inert B is introduced in a feed stream.

After the user has entered this information, the expert system creates an object for each unit and for each stream of the plant. There is one reactor, one partial condenser, one separator, one stripper, one compressor, one reboiler, three utility streams, three mixers, two splitters and twenty five streams. The input and output streams of each unit are defined and also the paths followed by the eight components present in the process. It is also necessary to indicate which streams are in liquid phase and which are in vapor phase. All process components are recycled to the reactor and the gas recycle stream is identified in this first module.

The process flowsheet is shown in Fig.2.

3.2 *Control objectives:*

- The flowrate of the bottoms stream from the stripper is fixed by a downstream consumer.
- There is a quality specification: component G in the product should not vary more than ± 5 mol $\%$.
- There are two safety constraints: reactor temperature must not exceed 175 C and process pressure must not exceed 3000 kPa.

3.3 *Development of the control structure:*

Starting from the topology information and the control objectives the expert system fires the rules whose patterns are matched by the existing objects and the control loops generated are explained next.

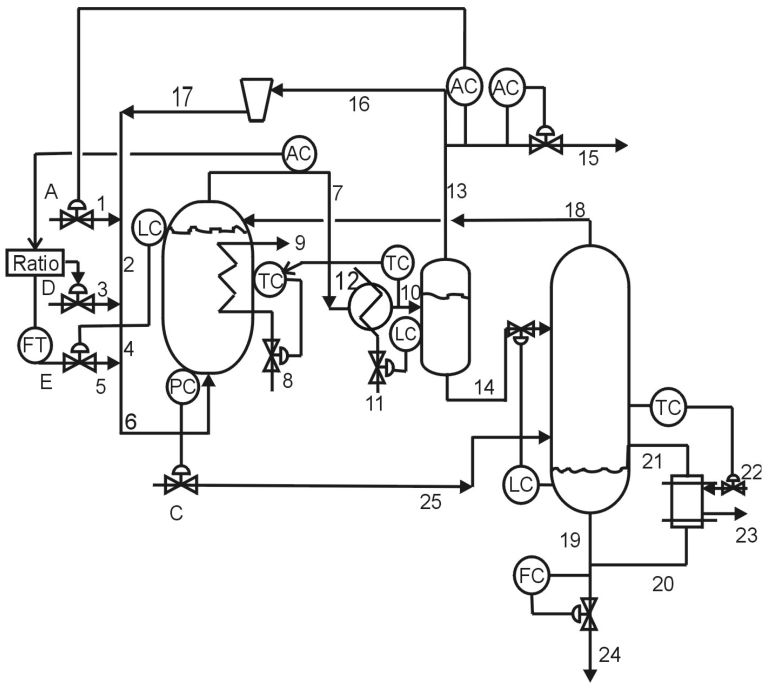

Fig. 3. Control Structure of the Tennessee Eastman Process

The product stream is flow-controlled to satisfy the demand and the setpoint of this flow controller is a process disturbance. This control loop has influence mainly in the level control loops. The levels will be fixed opposite to the direction of flow.

If there is a variation in the product demand, all the control structure will have to ensure that the plant is able to provide the required product quantity satisfying the quality specification.

The flowrate of the gas recycle is maximized. This way, one degree of freedom is removed and yield is improved.

The reactor temperature is controlled manipulating reactor cooling water flow. This temperature is controlled because the reactions are exothermic and the runaway effect must be prevented. Reactor temperature usually is a dominant variable and, besides, there is a constraint about its value. The feed stream C is used to control pressure because it is the largest fresh feed stream. These two control loops ensure that the process operation constraints are met.

The bottoms level of the stripper is controlled manipulating the liquid feed. Bottoms composition is adjusted using heat input and here it is used the inferential composition control. To control the separator level, the cooling water flow at the condenser can be manipulated and to control the reactor level, the fresh feed E is selected because the quantity of the heaviest product H depends on the quantity of the reactant E feeded to the process. If the control objectives were changed and a fresh feed flow were fixed by an upstream process ,instead of having set the product stream flow, the control strategy would be different and the stripper and separator levels would be controlled in the direction of flow.

The exothermic heat of the reactor must be dissipated from the process using the utility streams in the reactor and in the condenser. The heat exchange in the condenser can not be modified so, to ensure that the heat is removed from the process and is not recycled to the reactor, the set point of the reactor temperature controller is changed.

To achieve the quality specification a ratio of the feeds of reactants D and E must be assured because the proportion between products G and H depends on this ratio (A and C are reactants of both main reactions). The main reactions are simultaneous and E and D are the non common reactants: the proportion between the reactants flowrates is modified in function of the measured proportion between the reactions products. There is an analyzer whose output signal is the setpoint of the ratio controller.

The inert component B is removed from the process via the purge stream, so the composition of B in this stream must be controlled. For doing this, the purge flowrate is selected as the manipulated variable. Thus, it is prevented the building up of the inert within the process. The composition of the reactant A leaving the process in the purge stream is controlled manipulating the feed stream A flow.

The control structure generated by the expert system is shown in Fig.3. This structure is similar to the structures found in the literature.

4. CONCLUSION

A method using an expert system to automatically obtain a control structure for a complete process has been presented in this paper.

The expert system is focused on three of the PWC tasks: the selection of the controlled variables, the selection of the manipulated variables and the selection of the control configuration. In some cases, the selection of measured variables is also implemented in the rules (for example, in distillation columns temperature measurements can be used for composition control if the temperature profile is appropriate) and it is found that the existing procedures always lack in solving this task.

Some advanced control strategies are also implemented in the rules for improving the dynamic performance.

The solution is obtained quickly from information about the topology of the plant and its running conditions, without using any process model.

During the program execution, the expert system also generates a file that explains why the variables are selected to be controlled and how the manipulated variables are chosen (the manipulated variables should have a large effect on the controlled variables). This way, the user can learn from these explanations.

The system has been verified by application to some real processes, such as the Tennessee Eastman process, a isomerization process to convert normal butane into isobutane and the process for the hydrodealkylation (HDA) of toluene. In every process, the expert system provides a valid control structure and can be applied to a completely different process.

The expert system can be programmed to generate alternative structures depending on several factors as the selection of the dominant variable in a reactor. If several manipulated variables can be selected to achieve the control of a variable, several control structures will be generated. The expert system is being completed with a procedure to analyze the alternatives and select the best.

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