A STEP BY STEP APPROACH
TO ADVANCED PROCESS CONTROL

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Model-based advanced process control strategies are common applications in the hydrocarbon processing industry. A close look at the references available in literature reveals that the overwhelming majority of these projects are concentrated in refineries and in some specific petrochemical plants (e.g., ethylene). This is due to the excellent economic returns demonstrated in an abundance of experience dating back to the eighties.
Nevertheless, APC and optimization practices may also greatly benefit relatively smaller plants. Although previous experience may be found on a few sites, process owners don't have the same perception of a "must-do technology" as with other applications (FCC, crude units, hydrocrackers, etc.).

A flexible, more controllable and less invasive implementation procedure is a valuable alternative to big "win-or-lose" projects. It may make APC and optimization technologies more practical for less obvious processes and help customers to exploit the benefits of innovation without big investments that may be felt to be too risky.

For example, a plant-wide application of APC strategies has been successfully implemented on a butadiene plant in Southern Italy, using step-by-step implementation to contain risks, ensure profits and reduce the impact of the APC strategy. In this case, the application consists of two different multivariable controllers, some non-conventional APC schemes and several inferential measurements.

This paper gives a brief overview of project goals and process details, describes the three implementation steps and the hardware and software architecture, and then summarizes the first operative results and further developments, partly in progress and partly planned.

PROCESS DESCRIPTION

The main objective of a butadiene plant is to separate butadiene from butene and other components of the feed. Since butadiene and butene have boiling points that are very close, butadiene separation requires an extractive distillation section, featuring the injection of large quantities of a solvent and a multi-stage purification process. The high solvent-to-feed ratio needed to achieve the purity specification on butadiene (>99.6%) causes large steam consumption.

In addition, the final stage of the purification is performed at a very high level of purity, with increased chances for polymerization reactions. Polymerization of the butadiene forms clogs that can eventually shut down the plant. Therefore, one of the most challenging tasks in running a butadiene plant is to operate safely and continuously, reducing the need for maintenance shutdowns.

The butadiene plant where this application took place has a processing capability up to 140 000 tons/year. Its throughput can change very much, typically from 18 tons/hour to 36 tons/hour, depending on feed availability and market demand [2].

Feed composition can change, depending on feed origin; typical values for feed composition are as shown in Figure 1:

? ?	Butadiene	43 to 52 %
? ?	Butene	46 to 55 %
? ?	Heavy Tails	? 1 %
? ?	Light Tails	? 0.6 %

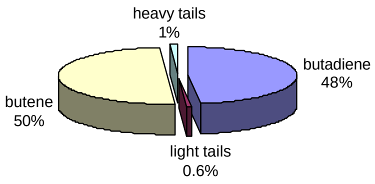

Figure 1 - Feed Composition

The main feed components, butadiene ($CH_2=CH-CH=CH_2$ and other isomers) and butene ($CH_2=CH-CH_2-CH_3$ and other isomers) have boiling points that are very close. To enhance the separation, butadiene distillation is performed with the addition of acetonitrile (ACN, CH_3-CN, also known as metyl-cyanide) as a solvent. The plant consists of six separate sections, and has many interconnections, as shown in Figure 2.

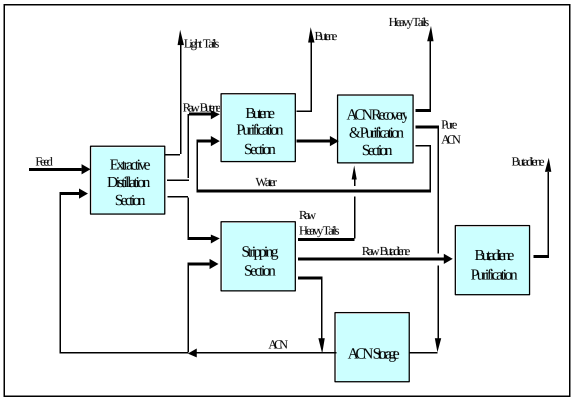

Figure 2 – Plant overview

The sections interact as follows:

- Extractive Distillation section separates butadiene, butene and light tails. To enhance distillation, acetonitrile is used as solvent. The acetonitrile-to-feed ratio is a key factor for this section and for overall plant cost-efficiency. Reducing this ratio while maintaining product quality within specification can provide a significant energy savings.

- Butene Purification section receives raw butene from the Extractive Distillation section. The Butene Purification section separates residual ACN and butene, using injected pure water to increase separation; pure butene is sent to storage, while recovered ACN and water are sent to the ACN Recovery and Purification section.

- Stripping section receives its feed from the Extractive Distillation section. This feed is composed mainly of butadiene, ACN, heavy tails and traces of butene. The section separates butadiene from heavy tails and ACN; to increase the separation between butadiene and heavy tails, additional ACN is used. Raw butadiene is produced and sent to the Butadiene Purification section; raw heavy tails are produced and sent to the ACN Recovery and Purification section; ACN is recycled and sent back to the Extractive Distillation section.

- ACN Recovery and Purification section receives its feeds from the Butene Purification section and Stripping section; it produces heavy tails, recovering and purifying ACN and water. Pure ACN is sent to storage (ACN Storage section), while pure water is sent back to the Butene Purification section.

- Butadiene Purification section receives raw butadiene from the Stripping section; the feed is processed to produce high-purity butadiene.

PROJECT BASIS

The plant had a history of safe and continuous operations long before the automation revamping job was started; sound process management and many improvements in plant design were able to successfully address the key operational issues, so that:

- the plant was able to easily maintain its butadiene purity specifications

- polymerization problems were addressed in a very effective way, so that maintenance shutdowns were very rare and there were no clog-related shutdowns in the last years

In 1997 the customer decided to upgrade the existing automation equipment on the plant with a state-of-the-art Distributed Control System (DCS), able to provide easy and powerful functionalities for process control, data collection and monitoring [3].

During the technical evaluation of the new control system, the implementation of modern APC strategies was considered and discussed.

A strong interest was expressed in the possibility of reducing energy consumption, without affecting final product quality or compromising the outstanding running time of the plant, one of the best performing in the world. Other typical APC project benefits (increased throughput, extended production time, improved yield, etc.) could not justify the initial investment, so the customer was rightly concerned about the pay-back period of the application.

The introduction of a plant-wide APC application could have been performed either with an all-at-once approach or with a step-by-step approach.

The client and ABB decided to proceed with a step-by-step approach, because it:

?? allows more flexibility
?? reduces the impact on plant operations and production
?? introduces operators to the APC world in a smoother way
?? reduces the initial investment by distributing the costs over more years
?? is less risky (the customer invests in a new step only if the previous one demonstrates its profitability)

The project started in late 1997. It was decided to divide the project into three main steps (Figure 4):

?? Distillative Extraction section
?? Stripping section
?? Butene Purification section and ACN Recovery/Purification section

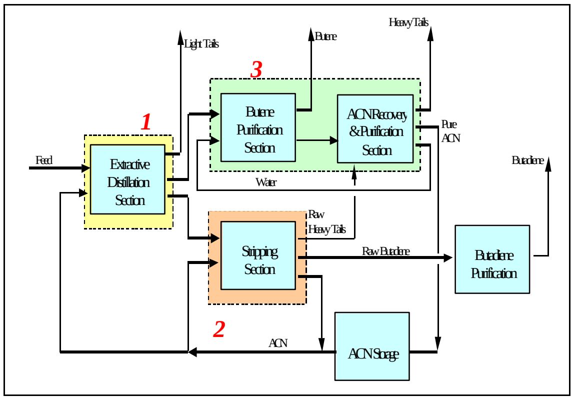

Figure 4 - Step by Step approach

It was also decided to have a careful cost/benefit evaluation after the completion of each step. If and only if the actual achieved benefits justified the previous APC application, a new step would be approved and started.

APC IMPLEMENTATION -PRELIMINARY ACTIVITIES

The first APC step started with the DCS installation and commissioning phase. The installed DCS was an ABB INFI 90, featuring two separate Process Control Units (PCU), each one composed of a few MFP03 modules, dedicated to the base process control and connected to field I/O modules.

The process management and operator interface relied on two ABB OIS Signature consoles, each one provided with two terminals. Historical data collection and storage and reporting capabilities were provided by ABB APMS 1090, a supervisory system, deeply integrated with the DCS.

The APC design was performed while the DCS was being installed. A key feature of the proposed APC strategies was the implementation of multivariable controllers, able to provide superior handling of mutual correlations among key process variables. A multivariable controller uses dynamic models of processes to calculate the optimal movements on the manipulated variables (MV) and then drive the controlled variables (CV) either to their desired value or within the selected constraints. A multivariable controller operates at the upper level in respect to base control loops, and it achieves its targets of control and optimization for controlled variables by proper management of setpoint movements issued to the lower level regulators [5].

A key factor in a successful APC project is the ability to provide the client with a tight and effective integration between the multivariable controller and the DCS.

From this point of view, it is crucial to have the ability to monitor and command the APC application from standard operating stations; with this approach, operators have all the control displays (both basic and MPC related) on the same interface: there is no no need to train operators with different equipments, applications, operating systems, etc and no need to move between different consoles during plant operations.

It was therefore decided, from the initial stage of the project, to use standard operating stations as the only interface to the APC system for both operators and engineer.

APC IMPLEMENTATION - FIRST STEP

Right after the DCS commissioning, plant data collection started, taking advantage of the ABB Infiview software tool that records, stores, displays and converts to universal formats any data available on the DCS.

For a few weeks the Extractive Distillation section was slightly perturbed with step-tests on the manipulated variables, and process data were collected.

After the step-tests, process models were identified and the multivariable controller was built and tuned through intensive offline simulation. In July '98, the first multivariable controller was successfully commissioned. The controller was interfaced to the DCS base loops by using a standard ABB MFP03 module, located on an existing PCU. Data flow I/O was provided through standard ABB INFI 90 functions.

Key variables for the application were:

?? solvent-to-feed ratio for the section
?? raw butadiene flow composition

The latter, which represents raw butadiene product quality, is measured by means of an analyzer that calculates the content of butene in the butadiene-ACN stream.

The step-test and process knowledge showed a significant delay time between the main section MVs and the analyzer. To improve process control performance, which was heavily affected by the process delay, an inferential online measurement to estimate butene content was implemented on the DCS.

On-line analyzers (Figure 5) are crucial elements in any APC scheme, because they allow the control strategy to push operation against specification and so maximize profits. It has become common practice to build predictive models that are able to supplement the analysis in real-time. This practice can significantly increase the application pay-back [7].

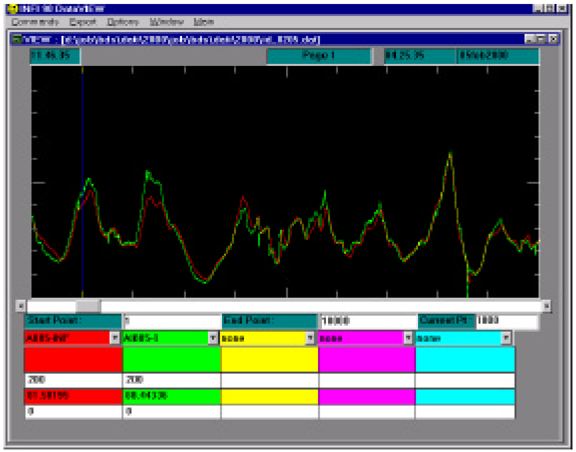

Figure 5 - Prediction (green) and actual analyzer data (red) over 7 days (no closed loop control)

The implemented inferential measurement allows tighter and more effective purity control, achieving three basic advantages:

?? clearing off the process delay
?? continuously controlling the CV over time
?? establishing independence from field analyzer failures and periodic maintenance cycles

The relationship was built starting from the boiling points of the involved hydrocarbonates, using a specific model built on actual plant data. To reduce the impact of process non-linearities, the model links process measurements to the logarithm of the butene content. The inferred logarithm of the composition value is included as a controlled variable in the multivariable controller, so the controller operates to maintain the amount of butene very close to the desired setpoint. The improved stability and reliability of butene content control allows less conservative management of the section, avoids product quality giveaways and decreases the total energy consumption.

The APC application reduced steam consumption. In fact, the ability to maintain impurities close to and still within the maximum limits, while reducing the solvent-to-feed ratio, was the key issue in improving the Extractive Distillation section's efficiency.

APC IMPLEMENTATION - SECOND STEP

After a successful 6-month test period, it was decided to begin the second step, devoted to APC implementation on the Stripping section.

The Stripping section is heavily correlated with the Extractive Distillation section. Actually most of the ACN is recycled within these two sections and only a tiny fraction is sent to the ACN Recovery and Purification section, so the biggest benefits from an APC point of view could come only by addressing the control problem of the two sections as a whole with a single multivariable controller. Therefore, the second step featured the extension of the existing controller to the Stripping section

A key issue of the second step was the overall ACN management. The Extractive Distillation and the Stripping sections feature big, tall columns, with large levels, mostly containing ACN. These columns are closely and mutually correlated; the management of the levels has therefore to be taken as one unified problem, not as several individual problems.

The levels handling can be viewed as global solvent inventory management in that

- some large internal refluxes can shift solvent from one column to another one without any impact on the global solvent inventory
- a few tiny flows set the pure solvent injection from storage and the extraction to purification; these flows affect the global inventory, but their impact is small and can change the solvent overall inventory only after some hours

The multivariable controller for the Extractive Distillation and Stripper sections takes care of the column levels simultaneously, tackling the level control problem from a plant-wide perspective. The controller leads the value of each level to its respective setpoint by manipulating the most relevant flows. To reduce unnecessary flow movements, the controller is set to neglect small differences between the current level value and the setpoint. It also minimizes the column-to-column flows, when that is possible, since they are directly correlated to energy consumption.

Another very important issue concerned raw heavy tails production. An existing field analyzer measured vinylacetylene and ethylacetylene content in the stream. The process model for the analyzer showed large changes in the estimated steady-state gains for the most relevant MVs as the process operating conditions changed. The dynamic profile of the response, on the other hand, showed a similar shape whatever conditions the plant was experiencing. That suggested the implementation of a gain scheduling strategy to perform a real-time gain adjustment on the multivariable controller's internal model of the heavy tails analyzer. The gain scheduling strategy was implemented on the DCS: a devoted logic calculates the estimated steady-state gain, based on plant measurements. The multivariable controller reads the calculated gain and adjusts its internal model, before each cycle execution.

The second step succeeded in further reducing the steam consumption. It was therefore decided to proceed with the third step.

APC IMPLEMENTATION -THIRD STEP

The objective of the third step was to design and implement an APC application to improve overall management of the Butene Purification and ACN Recovery/Purification sections. These two sections provide:

- ACN recovery from butene
- ACN recovery from heavy tails
- ACN purification

The key issue for optimal management is how to determine the amount of water to be used in the two sections. An increase in water injection improves ACN separation and recovery, but causes additional energy consumption in downstream units to separate and purify water and ACN. At the same time, it is very important to continuously maintain product quality within the specification and avoid any solvent leakage to the water recycle.

A controlled reduction of the water injection flows, while maintaining the product specification, results in major energy savings. A multivariable controller, devoted to these two sections was developed and implemented. The correlation of these sections with the Extractive Distillation and Stripping sections is negligible from a plant management point of view, so it was decided to have a separate, new controller, devoted solely to the Butene Purification and ACN Recovery/Purification sections.

Additional features of the application are:

- an inferential estimation of the vinylacetylene content in heavy tails, developed and implemented to validate the existing analyzer and substitute for it in case of failure. The inferential measurement is based on field measurements and features an internal model of the section

- a gain scheduling strategy connected to the multivariable controller, which can adjust the vinylacetylene model gain as the process operating conditions change

The third step reduced steam consumption in the ACN Recovery and Purification section, thanks to water injection reduction in both sections and to less conservative section management.

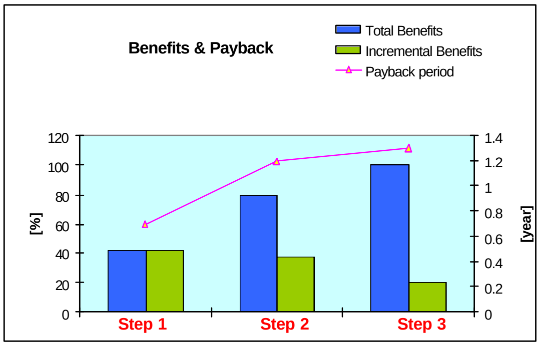

Figure 6 – Project Full Benefits and Paybacks

OPERATIVE RESULTS

The Advanced Process Control strategy has delivered wide benefits:

? ? a substantial decrease in steam consumption
? ? a significant reduction in the solvent usage.
? ? a reduction in variations in product quality and in key process variables

Further benefits for the plant come from a set of improvements that, although clearly apparent, cannot be easily translated at once into economic terms.
The following remarks belong to that class:

? ? better stability of the plant against process disturbances
? ? reduction in low-level actions by operators

As shown in Figure 6, all the project steps achieved major improvements in process control and economic-related benefits.

LESSONS LEARNED

A careful evaluation of the project showed that a key issue in its success was the close cooperation established between the plant personnel and the APC engineers. Because the project team involved a range of people responsible for the plant production, the team had a better understanding of and better management over targets that were often very different and sometimes conflicting. In the end the advanced control strategy was designed and developed by taking into account requirements from control room personnel, who are the end users.

Training classes have shown a very good impact on the successful completion of the project. Training courses have been designed and delivered both to process engineers and to operators; every course has been purposely customized for the different duties involved, and it includes an accurate user handbook

Another very important issue in this application was the decision to divide the project execution into steps.

Dividing the APC implementation into three separate steps reduced the impact of APC development and implementation on plant operations, both from a financial and management viewpoint.

As a final result of this approach, all the plant personnel developed trust and confidence in the advantages of APC strategies.

FUTURE PERSPECTIVES

The step-by-step approach has been such a successful application that the customer commissioned a further feasibility study to possibly extend the advanced control application and achieve the utmost possible savings of resources. This activity has yielded a planning/first pass design which has identified the following possible extensions (Figure 7):

? ? multivariable predictive control on the Butadiene Purification section
? ? use of Neural Networks technology to develop inferential measurements on a few relevant process variables
? ? development of an optimization layer, able to drive MPC on the most profitable operating points (mainly by a controlled reduction of the solvent usage), featuring a real-time, SPC-based optimization

The first extension, awarded to ABB, is actually in progress and will result in the whole plant coverage of MPC by Fall 2002.

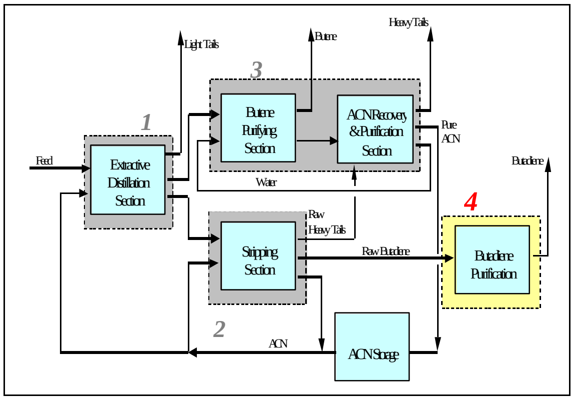

Figure 7 – Step actually in progress

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