INCA APC for Distillation Columns

APC (Advanced Process Control) is a discipline focused on controlling processes in a multivariable and predictive manner to improve control performance and optimization. These processes can range from electrical applications, production processes to entire chemical plants and petrochemical refineries. This paper focuses on the application of APC on one general topic: distillation towers. More specifically, it is focused on the application of APC by using the INCA software package, property of IPCOS. First of all, the typical project workflow of an APC project is given. Then, the INCA software package is briefly described. Finally, a case study of the INCA environment applied to a distillation tower is presented.

Contents

1 Executive Summary

IPCOS is an engineering solutions company specialized in Advanced Process Control (APC) applications and services for the process industry. IPCOS provides APC solutions for a broad variety of process units, including distillation columns.

The operation of distillation columns is generally subject to different constraints. The column might be the bottleneck for increasing throughput in the plant. The energy consumption might be significant, raw material and product concentrations may vary greatly over time, unexpected column upsets (flooding, weeping) might occur and so on.

APC (Advanced Process Control) brings stability to the process (as can be seen in the example in the below figure), and optimizes the operation of the process, generating benefits including increased capacity, improved energy efficiency, etc.

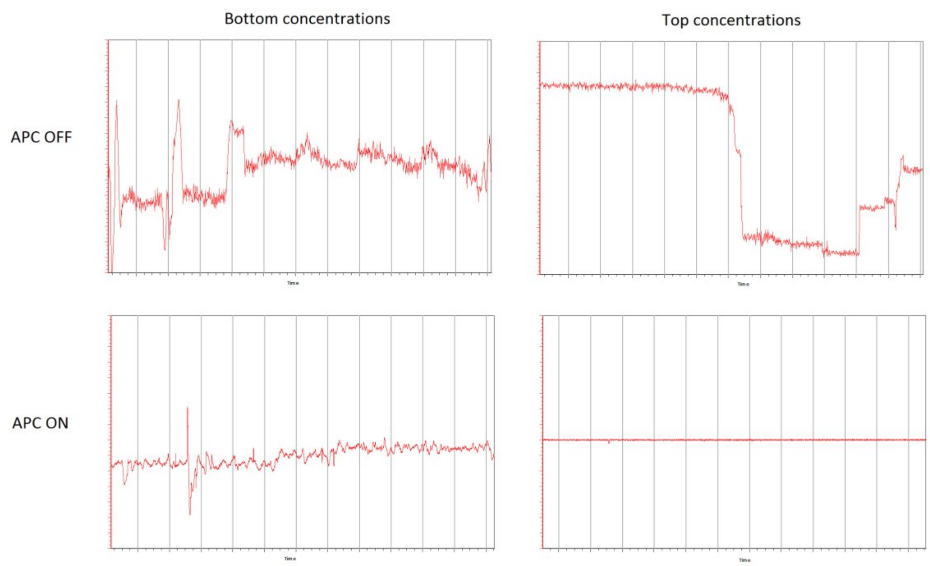

Figure 1: Bottom (left) and top concentration (right) trends over time. Upper plots: APC is turned off. Bottom plots: APC is turned on.

IPCOS provides the technology and engineering capabilities to implement high value APC solutions on distillation columns, ensuring fast ROI. If desired, IPCOS provides these solutions on a "pay for performance" basis. This white paper discusses the typical benefits and implementation aspects of IPCOS' APC solutions for distillation columns (Sections 2 and 3), and includes a case study showing the benefits that were obtained by applying IPCOS' APC technology (Section 4).

2 Project workflow

Every APC project follows a standard methodology that ensures the best results and the greatest benefits for the customer. In this workflow, three main phases can be identified. The first part consists of all work involving the base layer controls of the distillation column. This is work that's done primarily on the DCS system. In the second phase softsensors or inferential measurements are developed with INCA Sensor™, a dedicated modeling tool. The third part consists of the APC applications themselves, that reside on a separate PC connected to the process through OPC servers. The following sections will give specific information about each of these phases.

2.1 Base layer control

First of all, the base layer control of the distillation tower has to be considered. "*Advanced process control applications can only be as strong as its base layer control foundations*", is a well-known statement. The control objectives of the distillation tower should be translated in an appropriate base layer control structure that incorporates both safety constraints and production specifications. When a control structure has been chosen, all controllers have to be appropriately tuned to ensure a stable and adequate performance. These elements are explained in more detail in the sections below.

2.1.1 Base Layer – Control Structure

The first phase of an APC project is the analysis of the current control structures. Often the applied control configuration is not optimal. The optimal control structure is dictated by process constraints & specifications, typical operating regions and expected behavior.

Typical operational requirements for distillation columns include keeping top- and bottom concentrations between certain limits, keeping the pressure above a threshold, maximizing heat recovery, etc. Generally, one or more of these requirements are correctly addressed, but not all. IPCOS has both the experience and technical knowledge to define the optimal control structure based on process characteristics. A successful control structure implementation is discussed in the case study.

2.1.2 Base layer – Tuning

Once the control structure has been defined and implemented, the tuning of the individual controllers comes into play. IPCOS engineers use the INCA AptiTune™ software package, the primary tool to do this. INCA AptiTune™ is a model based approach to tune PID loops. It is an easy-to-use software package for tuning multiple PID control loops at the same time. It is especially well suited for tuning PID control loops that interact with each other.

Proper PID tuning can have a significant positive impact on production benefits. Reducing oscillations on temperatures, pressures, flows throughout a chemical plant leads to more constant operating conditions, product qualities, less alarms and overall process stabilization.

2.2 Soft sensors

In chemical plants, quality measurements are crucial to assess plant performance. When a measurement exceeds the quality limits, operational changes will be made to make sure the quality returns within its boundaries dictated by safety, market demand and/or downstream processes.

Measuring the quality in a robust, reliable manner has long been a cumbersome task. Online analyzers tend to require a lot of resources for calibration and maintenance and come at a high price. Furthermore, measurements are sensitive to influences from outside. For instance, a concentration analyzer can show deviations when the ambient temperature or humidity change. Taking a representative sample of the total product flow is another difficulty. In addition, taking samples to analyze in the lab also requires quite some human resources. Additionally, lab samples are typically taken once every few hours or days, which is too infrequent to be of any use in an online control loop.

This is where soft sensors come in as a cost effective and reliable alternative. Soft sensors, also called inferential sensors or inferential measurements, deduce product quality from other available and continuous measurements in the plant. Some examples are temperature measurements, pressure measurements, flow indicators, density indicators, and level measurements. A soft sensor usually consists of two parts: a model constructed offline, connecting all inputs to the quality output; and an online updating part that accounts for small deviations between the model and the actual plant. (A perfect model, if it existed, would not need this updating mechanism.)

Typically, a lab campaign is carried out where time stamped lab samples are taken on a more frequent basis, e.g., once every four hours, depending on the time-to-steady-state of the process. The column is brought into different operating regions (within production constraints) to obtain a rich data set for modeling purposes.

Process knowledge is then used to preprocess the actual plant data. This includes calculating indicative signals, e.g., pressure difference over the column or pressure compensated temperatures, and transforming existing signals, e.g., linearizing a bottom temperature. Data can also be filtered, bad slices can be removed and peaks can be shaved.

All this preprocessed data is then presented to the INCA Sensor™ software package to construct static or dynamic black-box models, with different numbers of inputs and complexity. The model accuracies and standard deviations can be compared and the best model can be exported to the INCA APC Environment. Softsensor outputs are typically used as controlled variables in the APC application or used as inputs to other base layer control structures, e.g. a ratio controller adding an amount of water based on the softsensor output.

2.3 APC – Model Predictive Control

Once the base layer has been optimized and the necessary soft sensors have been developed, the APC system can be implemented. An APC controller is a multi-variable dynamic predictive controller. It typically runs once every minute and writes setpoints to key variables to control and optimize the process. The APC is constantly monitoring the current situation and predicting where the process will be in the future. If the predicted future operation is not within operating constraints or at the optimum operating point then the APC proactively makes small changes well in advance to push the process to the desired operating point. The advantage of an APC is that it can monitor and predict multiple interacting variables at once giving the operator more time to focus on other areas of the process.

The APC essentially pushes the process to its operational constraints in an optimal manner depending on the customer's objectives. This could be maximizing the total throughput, minimizing the specific energy (i.e. energy used per unit mass product produced), pushing a concentration closer to its market specification demands, or a combination thereof.

The operational strategy for the process, in this case a distillation column is translated into a ranked list of objectives. The APC controller will calculate a solution that satisfies as many constraints as possible, starting from the most important ones and working its way down to the least important ones. Therefore, IPCOS engineers group the constraints in the following three groups:

1. Safety constraints
2. Product specification constraints
3. Economic optimization

Safety constraints are always more important than specification constraints, which in turn are always more important than economic optimization. The first two groups, safety & specification constraints can be regarded as needed for process stabilization. This is always the primary goal of an APC controller. Once the distillation tower is stabilized, the step to optimization can be made. Benefits are generated from both steps: more stable operation leads to less upsets, fewer concentration breakthroughs requiring blending or recycling, and/or less unplanned shutdowns. Optimization leads to energy gains, product savings and more economic turnover because the product is brought closer to the market specifications (less "give-away").

2.3.1 APC – Modeling

The central part of the APC controller is the multivariate model. This model has a number of inputs, called the independent variables. They are divided into manipulated variables (MVs) and disturbance variables (DVs; also known as Feed Forwards or FFs). The model outputs are called the dependent variables or controlled variables (CVs).

All possible process knowledge is brought together when constructing these models. Input from process and planning engineers, instrumentation engineers, operators etc. is combined by IPCOS engineers when the MVs, CVs and DVs for the APC controller are selected. Once the selection is made, step tests are conducted on the distillation tower. This includes making small "steps" on feed rates, reflux flows, temperature controllers, level controllers, pressure controllers and so on.

When all necessary data is collected, the multivariable model matrix is constructed with the INCA Discovery™ software package. INCA Discovery™ is a sophisticated software package for constrained linear dynamic model identification. It can identify smooth models from step test data by automating most of the work flow. For example, the software can determine dead time, Time to Steady State and "Null" relationships. In addition, it has the ability to detect if dynamic variations towards the end of the model curve are real or not, based on statistical analysis. However, adding and implying process knowledge and knowhow to the model identification step is important to deduce robust and reliable models.

2.3.2 APC - Commissioning

Once the model matrix is constructed, IPCOS engineers will run simulations to find the appropriate tuning for the APC controller. By adjusting the tuning, a great number of things can be accomplished. A subset of possible objectives is summarized below:

- Appropriate CV and MV ranks are chosen to translate the control strategy as explained above to the APC controller.
- It can be defined how important a CV constraint is compared to others within the same ranking. If the APC could not satisfy more than one constraint at the end of its prediction horizon, this determines which one will be given up first.
- In a given situation, it is possible the APC will satisfy all constraints in its steady-state solution, but will not satisfy one or more constraints dynamically. By setting appropriate weights, the APC will be more or less aggressive when keeping the CVs in check dynamically.
- Tank levels can be controlled by different strategies: minimizing, maximizing, as stable as possible etc. They can also be incorporated when deciding the optimal feed distribution to different columns.

When initial tuning parameters have been chosen, the controller is installed and connected to the process. One by one, CVs and MVs will be taken into use and scenarios are tested to verify that the controller does the right things. Because of process disturbances, signal noise and a mismatch between the model and the actual plant, tuning parameters are adjusted until the controller does the desired (and safe!) moves under all circumstances.

Once the controller is commissioned, a Site Acceptance Test (SAT) meeting is held with the customer to sign off on the delivered controller application. The results are assessed and a warranty period starts in which IPCOS engineers resolve issues if and when they might occur.

3 INCA Environment

The INCA environment consists of an extended list of all necessary tools to assist the engineers when building the APC controller. An overview of the applications is given in Figure 2. One can distinguish between the offline tools and the online tools. The offline tools are all software programs for PID tuning and modeling purposes. The online tools are the tools running inside a working APC environment connected to the customer's DCS system.

The offline tools are:

PID Tuning tools

- INCA PID Tuner: An engineering tool for the design and implementation of optimal PID Controllers. It integrates data acquisition, system identification, optimal PID control design and controller validation.
- INCA AptiTune: An easy-to-use software package for tuning multiple PID control loops at the same time. It is especially well suited for tuning PID control loops that interact with each other.

Modeling tools

- INCA Discovery: A sophisticated software package for constrained linear model identification.
- INCA Sensor: A software tool that creates online predictive models starting from historical data. These softsensors (inferential sensors) augment hardware instruments and laboratory analyses to provide real-time estimates of process and product conditions. INCA Sensor also offers the functionality to load, view, compare and preprocess your data.

The online applications run in an embedded desktop environment. A screenshot of this environment is given in Figure 3. A typical APC setup consists of the following applications:

- INCA DataServer: OPC Server where all tags are located that are read from or written to the DCS, or are used internally for the APC controller.
- INCA Test: A measurement and test system used to log data in files for later analysis (modeling, troubleshooting…) and impose dedicated test signals on the process.
- INCA OPC Exchange: OPCExchange performs a transfer of data from one server to the other by reading it from the source server and writing it to the destination server and the other way around, as defined in the configuration files.
- INCA Scheduler: The scheduler application will coordinate the execution of the various modules with respect to each other by using sync-signals in the DataServer.
- INCA Calc: The module in the APC configuration that performs specific calculations, when applying model predictive control. The calculations, that can be performed within INCA Calc range from a simple average calculation of two temperatures or the calculation of pressure compensated temperatures to advanced data processing functions like filtering, outlier correction or controller performance monitoring.
- INCA Engine: The core of the APC controller. Each control cycle, the following main steps are performed:
    - Validation and transformation of the input data
    - Steady state optimization: Determining the solution of the steady state problem.
    - Dynamic optimization: The dynamic optimization of the controller determines the best trajectory for the MV's to come from the current process values to the optimum

steady state process values (MV's and CV's) determined in the steady state optimization.
  - Validation and transformation of the output data
- INCA View: INCA View offers the possibilities to look into and adjust the controller tuning, trend controller information, log controller output to text files etc.
- INCA Sensor Online: INCA Sensor Online calculates inferential process variables starting from lab data (asynchronously supplied with timestamp), measured process data and a (non) linear model designed with INCA Sensor.

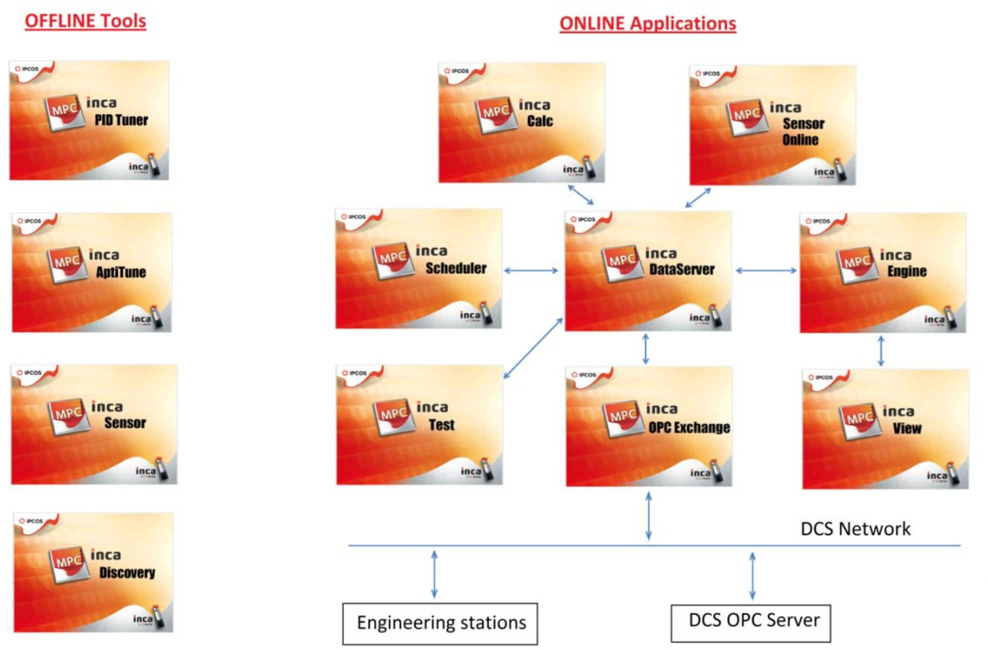

Figure 2: Overview of the INCA Suite.

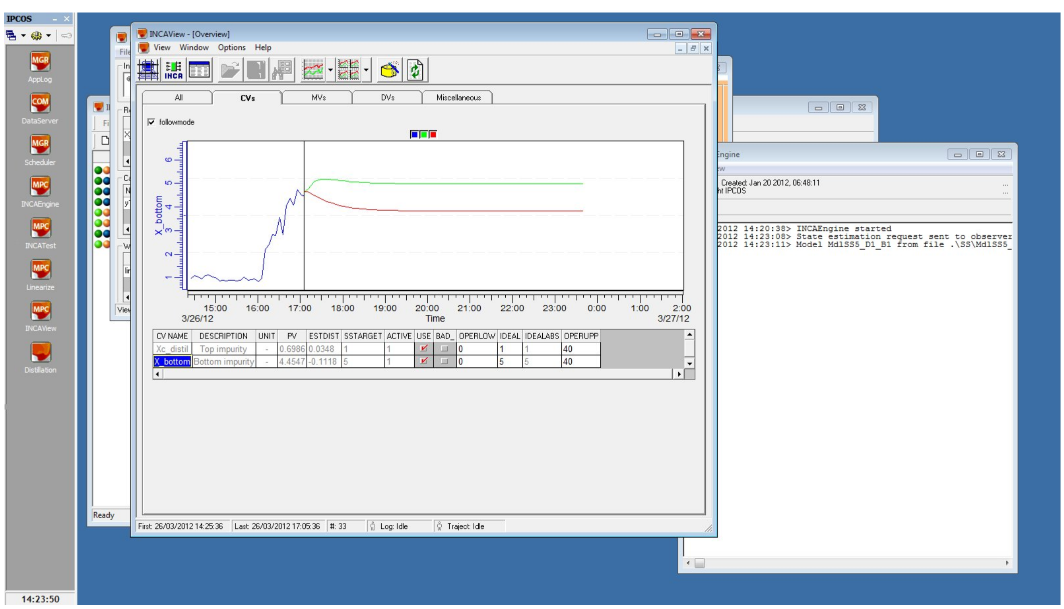

Figure 3: Screenshot of the IPCOS Desktop.

4 Case study

The following section will show the results of the different project steps applied to a distillation column. Consider a column where the main goal is to have a very pure bottom stream, with impurities in the ppm range. The secondary goal is to use as much recuperation heat as possible, to reduce the steam consumption. Thirdly, the overhead concentration should be in a certain range.

4.1 Base layer – control structure

To accomplish these goals, columns with the control structure of Figure 4 on the left are encountered in industry. Bottom concentration is controlled by a temperature controller on a tray in the stripping section of the column. Reflux is coupled with the feed through a ratio block. The recuperation flow is controlled by a flow controller. Operators typically have this controller in manual mode, where they entered a certain valve opening depending on pressure in the recuperation column.

This control scheme has a number of disadvantages:

- The reflux ratio in the top ensures a fast dynamic regulation of the top quality, which (in this case) has a lower priority than the bottom purity.
- The control structure does not take pressure variations into account.
- Recuperation flow is only 'optimized' manually.

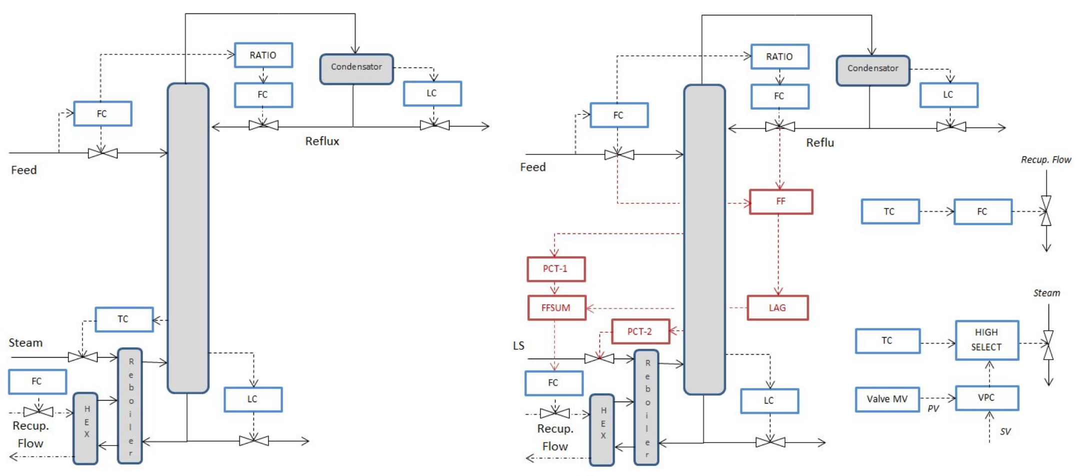

Figure 4. Left: Original control scheme. Right: Proposed control scheme that better fits the control objectives. New blocks are shown in red. The safety structure is conceptually shown by the six blocks on the right.

IPCOS engineers altered the control scheme drastically to improve performance of the column. The resulting scheme is shown in Figure 4 on the right.

First of all, a feedforward from feed and reflux to the bottom reboiler was implemented. This improves stability of the temperature controller because the reboiler will proactively add heat to the column before the temperature starts dropping or rising.

Second of all, the temperature controller is directly connected to the heat recuperation instead of the steam valve. This makes sure that the heat recuperation is maximized at all time. Temperature control is now based on pressure compensated temperatures instead of pure temperature. This leads to a more constant product quality, independent of the column load.

Third of all, some safety systems were put in place to avoid unwanted situations: a valve position controller to make sure the pressure in the recuperation column remains controllable and a back-up temperature controller to enable normal operation when the recuperation column is out of use or insufficient recuperation heat is available. The structure also prevents the steam valve closing more than a certain set value, to avoid that the reboiler is too cold when steam heat is rapidly needed.

The resulting performance of this control structure is shown in Figure 5. The timeframe of the figure is about 48 hours. It is evident that the steam valve is closed to its minimal allowed value most of the time. The spike in steam usage is caused by the pressure valve of the recuperation column that is closing too much. By adding steam, the valve could open again to its regulatory range, proving that the implemented control structure functions correctly. Absolute temperature variations are smaller than 1 degree Celsius!

4.2 PID Tuning

As indicated Section 2.1.2, tuning PID controllers has an immediate effect on process stability. Figure 6 shows an example of a level controller in the bottom of a distillation column. The upper part shows the situation with the original PID parameters. Clearly large variations were noticed, which has an impact on pressure, column residence times and downstream flows. The bottom plot shows the situation after the controller was retuned. The large oscillations have clearly been removed, and the overall variance has been reduced by more than 70%!

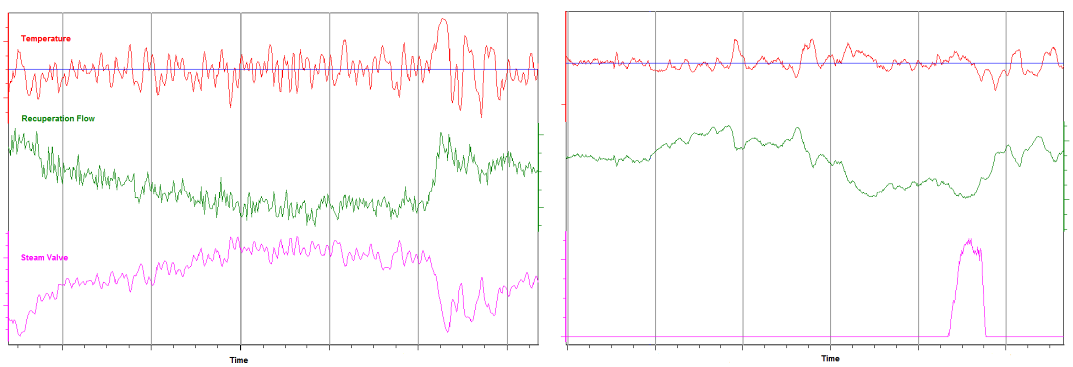

Figure 5: Performance of heat recuperation structure. Red: Temperature. Blue: Temperature Setpoint. Green: Recuperation flow. Pink: Steam valve position. Left: old control structure. Right: new control structure.

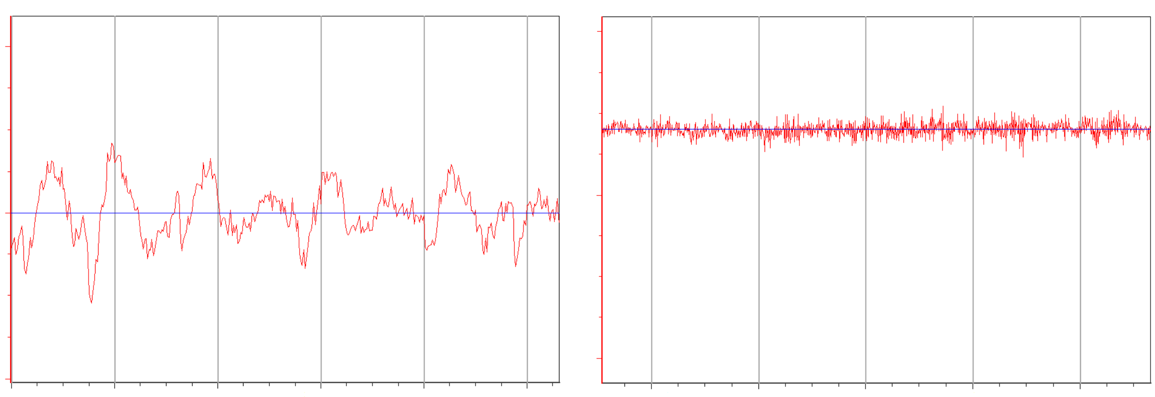

Figure 6: Level measurement (red) versus setpoint (blue). Upper plot: Performance before PID retuning. Bottom plot: Performance after PID retuning

4.3 Soft sensor

In this APC project, soft sensors were needed for top and bottom product concentrations. As explained in Section 2.2, soft sensors are constructed by a combination of process knowhow and black-box modeling.

A screenshot of (part of) the user interface of INCA Sensor^{TM}, with the comparison between the process data and the model prediction of the overhead concentration of a binary distillation column is shown in Figure 7. The correspondence is clear, resulting in a soft sensor of very good quality.

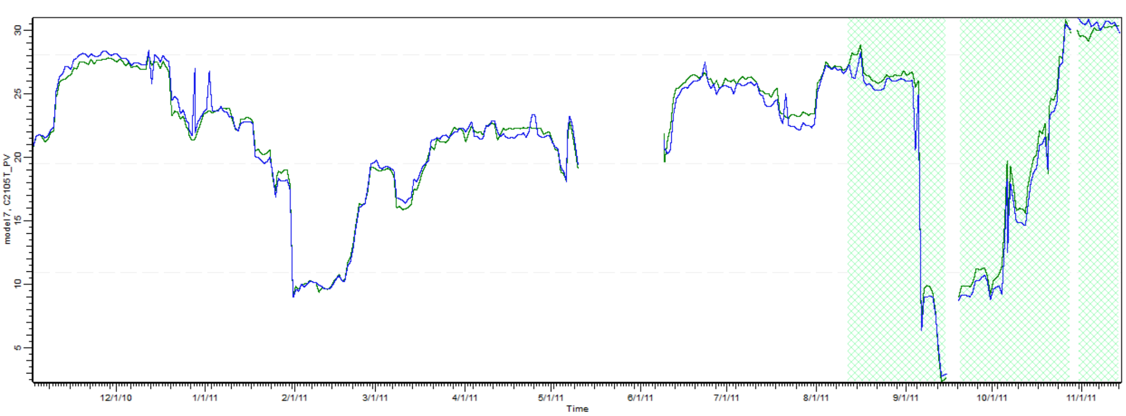

Figure 7: INCA Sensor: Process data (blue) versus Model Prediction (green).

Because a density measurement is one of the inputs, the model dynamics are very good. In other cases, input filtering can be applied to ensure that the output has the correct dynamics. Dynamic information can also directly be used in the INCA Sensor^{TM} configuration. The dynamics of the updating mechanism can be configured as well, to ensure smooth transitions when a new lab sample is entered.

4.4 APC Application

4.4.1 Model matrix

For the considered distillation column, the model matrix is shown in Figure 8. MVs include feed rate, reflux rate and bottom temperature. The CV's include column pressure, feed tank level, reflux–to-feed ratio and reflux valve position as safety constraints. The reflux-to-feed ratio was added to ensure that the column has enough load in both stripping and rectifying sections. The product concentrations are used as both specification and optimization constraints. An additional specification constraint is the bottom temperature rate-of-change.

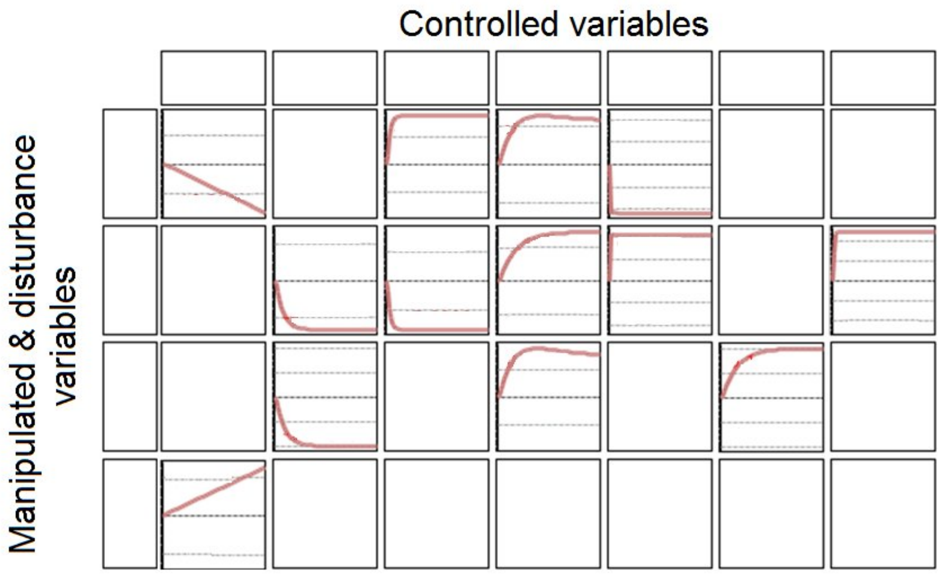

Figure 8: Model Matrix for the INCA APC controller on the considered distillation column.

4.4.2 Constraint definitions

As specified in Section 2.3, constraints can be divided into three groups: safety constraints, specification constraints and process optimization. The constraints as used in this APC case study are detailed in the next paragraphs.

Safety constraints

The valve opening of each MV can't exceed a set range. When the high or the low limit is hit, the APC is not allowed to write out MV setpoints that would lead to even more extreme or impossible valve openings, e.g. a valve opening of 105%.

Tank levels have to be balanced between the operator limits. The APC will manipulate the flows into and out of the tanks to balance the level, avoiding that the tank is drawn empty or overflows. If the APC fails to balance the level for a configurable amount of subsequent cycles, the APC switches off.

Last, the pressure has to be governed to avoid extreme column behavior and unwanted phenomena like flooding and weeping. Similarly, the reflux-to-feed ratio has to be kept between boundaries, deduced from operational data, to ensure that internal vapor and liquid flows throughout the column allow normal operation.

Product Specification

Once the safety constraints have been satisfied, the APC will make sure the product flows meet a predefined quality standard. In the example of the distillation column, the main specification was keeping the impurities in the bottom stream under a predefined threshold. The top product concentration has to lie in a certain range, for correct functioning of downstream units.

Process Optimization

For this case study, saving energy by reducing the steam input is the major goal of the customer.

Benefits from pushing the impurity levels to the upper constraint are small in this case, both from an economic as an energy point of view. The top concentration however did have a significant impact on the energy balance, so the optimization of this concentration was given priority.

4.4.3 Results

Trends of these concentrations, comparing the situations when the APC is turned off and on, are given in Figure 9. It is clear the quality variation is diminished significantly. The overhead concentration when the APC is turned on (bottom right plot) is always at the high limit, which corresponds with the largest energy savings.

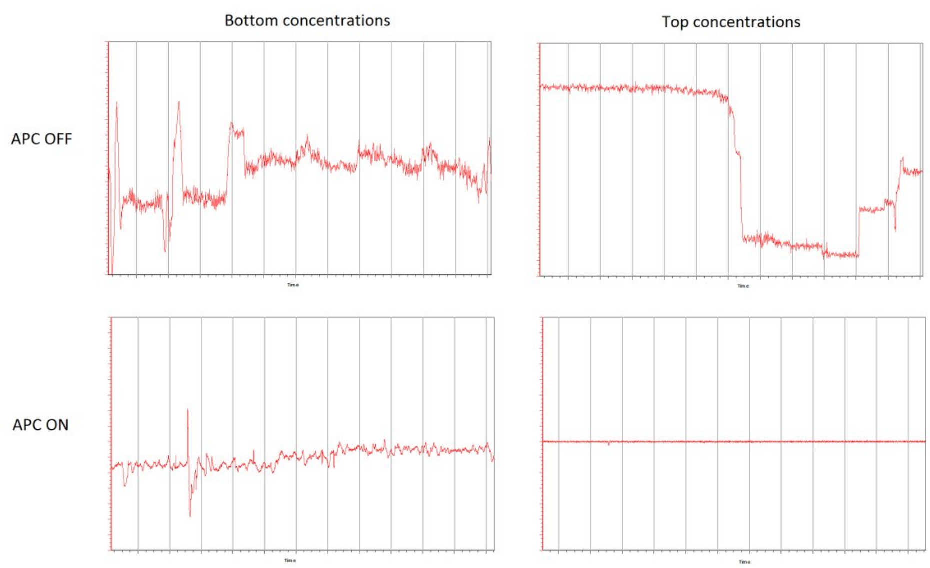

Figure 9: Bottom (left) and top concentration (right) trends over time. Upper plots: APC is turned off. Bottom plots: APC is turned on.

5 Conclusion

A typical distillation APC project follows a standard methodology that consists of the base layer optimization, development of soft sensors, the process modeling effort and the commissioning of the APC controller. Base layer optimization comprises implementation of new control structures, adaptation of existing structures and tuning of PID controllers.

Benefits for the customer are generated from all different activities. The goal is always process stabilization, followed by process optimization and constraint pushing. Process stabilization generates benefits due to less upsets like flooding or weeping, more constant product quality, less off-spec product that needs to be blended in or recirculated etc. Process optimization typically results in higher throughputs; product qualities closer to the market specifications and/or lower specific energy consumption, i.e., energy usage per unit mass of product, depending on the economic situation of the customer, process bottlenecks etc. Soft sensors play a crucial role in this because they allow for online quality monitoring.

The IPCOS APC framework, INCA, provides all tools to reach the enlisted goals. The offline tools, most prominently INCA AptiTune, INCA Discovery and INCA Sensor, are used respectively to calculate optimal PID tuning parameters, to develop accurate dynamic models and soft sensors with the best reliability.

The online tools are running in every APC implementation tuned to the customer's needs and desires. OPC communication to the DCS OPC Server is the only requirement for the INCA controller. All calculations, predictions and validations happen on the dedicated APC computer. The INCA Engine, the central piece of the controller can be tuned to ensure optimal behavior in all different scenarios.

The case study on a real-world distillation column shows the proven functionality implemented by IPCOS engineers, as well as significant benefits on a quality, an economic and an energy basis.