Utilize APC solutions to resolve hydrocracker conversion optimization challenges

Improving profits and reducing costs remain priorities for owner/operators and management. Advanced process control (APC) solutions not only meet such expectations, but also very often exceed them.

In 2013, a solutions provider implemented two APC applications at the largest refinery in Central Europe, operated by PKN Orlen in Płock, Poland. Based on market conditions and a benefits study, PKN Orlen designated two units for pilot APC applications: the hydrocracker (HCK) and fluid catalytic cracking (FCC) unit. This article focuses on the implementation of the HCK and provides details of the suite of APC solutions that have helped the PKN Orlen facility to achieve greater profits and results.

Maintaining its edge as one of the largest oil and gas producers in Central Europe requires that PKN Orlen continuously improve its production standards, utilize the latest technologies and undertake a production optimization program for the whole PKN Orlen Capital Group. An APC solution is one of the main components of this program, mainly because of its ability to quickly improve production results and make a clear difference to the bottom line.

A suite of APC solutions was already delivering sustained process performance benefits at the Płock petrochemicals and refinery complex, covering everything from the basic loop to real-time optimization and all necessary maintenance tools. Using the same type of software on the control and global process optimization layer would make it easier and more efficient for operators and engineers monitoring the solutions across multiple unit sections, and would also minimize training requirements.

The solution is based on a commercial product and its associated components. As well as providing multivariable control, the controller provides a unified real-time (URT) platform for future implementation of specific and customized calculations that might be required for a specific process. It was also implemented to allow optimization across multiple process unit sections.

APC project methodology and control engine. The key software is responsible for optimal online control of the different processes. Most engineering activities are conducted online and on operating units requiring complex and deep chemical knowledge. To implement the system, APC engineers must first create a model of the investigated process that is built empirically and based on a series of step tests.

The scope of these steps must be large enough to discern the response of the process unit, yet small enough to avoid any significant disturbances to the process. Once the process responses to the step tests are established, the matrix of transmutation functions can be identified using a design software. Transmutation functions are the linear models of the investigated process, visualized in a two-dimensional space. The size of this space is defined by the numbers of process-controlled variables, manipulated variables and disturbance variables.

An example of the process model transmutation function matrix, which reflects the number of process relationships, is shown in FIG. 1. Because the model is empirically obtained, it can be customized for specific process units or particular unit sections. Such a solution guarantees more credible results than analytical models that are often far removed from real process conditions.

A controller reads the process data from the existing control system based on the earlier obtained process model and, by utilizing a range control algorithm (RCA), sends optimal data.
back to the control system.

There are three types of the controller inputs and outputs:
- Controlled variables (CVs), which are usually process values, such as qualities, flows, temperatures and pressures, that must be kept in safe and optimal ranges
- Disturbance variables (DVs), which are read-only variables, such as feed quality and ambient temperature or parameters outside the local control system's control (i.e., disturbances from other process units)
- Manipulated variables (MVs), which are the values the APC sends back to the control systems, are usually represented by the list of setpoint values for proportional integral derivative (PID) controllers.

FIG. 2 is a simplified scheme showing how the controller works.

The range control algorithm. The heart of the controller is the RCA, which calculates and predicts CV values based on the process model. Formulation of the RCA is based on a control theory, where the predicted CV is represented as:

\[ \hat{y} = Au \]  

where \( A \) is the process model and \( u \) is a set of MV moves. The range control formulation is defined as:

\[ \min_{u,j} \| W(Au - y) \|^2 \]  

where \( W \) is the weighting function. The above formulation is subject to the following constraints:

\[ ROC_L \leq u \leq ROC_H \]  

\( \Delta \text{MVs} \) lie within the rate of change limits

\[ MV_L \leq u \leq MV_H \]  

MVs lie within high and low bounds

\[ CV_L \leq y \leq CV_H \]  

CVs lie within high and low bounds

The solution \( u \) is the control moves, and the solution \( y \) is the optimal CV response trajectory. This control formulation minimizes energy input to the process (by minimizing the CV response error), minimizes scope for controller instability, and guarantees an optimal response because of minimum MV movement. Additionally, a tuning parameter, a "funnel," was implemented in the RCA to shape the optimal solution trajectory.\(^3\) The funnel feature improves noise rejection, facilitates a minimum-effort solution with robust gain control, determines the control speed, enhances control performance and makes tuning much easier.

The RCA itself guarantees robust control and, more importantly, when it comes to achieving benefits through optimization, the RCA formulation is extended to calculate a set of MV steady-state optimal targets, such that:

\[ J = \sum_{i=1}^{\# \text{MVs}} a_i \times MV_i^{SS} + \sum_{j=1}^{\# \text{CVs}} c_j \times (MV_j^{SS} - MV_j)^2 + \sum_{j=1}^{\# \text{CVs}} b_j \times CV_j^{SS} + \sum_{j=1}^{\# \text{CVs}} d_j^2 \times (CV_j^{SS} - CV_j^T)^2 \]  

where constants \( a \) and \( b \) are defined by APC engineers and process engineers or unit managers for product value optimization, and coefficients \( c \) and \( d \) are also defined by operation staff and are responsible for pushing the process to a defined "ideal operation point." In reality, coefficients \( a, b, c \) and \( d \) are set during APC tuning to define the optimization objective targets.

This optimization formula is then implemented in the RCA. Thus, a new RCA formulation with steady-state solution \( u_{SS} \) for MV moves looks as follows:

\[ \min_{u,j} \left[ \left( W_u \cdot \frac{W_y}{W_u} \right) \times \left( \frac{u - y_{SS}}{\sqrt{S}} \right) \right]^2 \]  

The objective is to push the steady-state MV values with minimum effort closer to an optimum as defined by \( u_{SS} \). \( A_{ij} \) specifies the process dynamics; \( S \) is a summation matrix; and \( W_u \) is a tuning weight to adjust the optimization speed and determine how dominant the controller and optimization parts of the controller are.

Once the model is built using the software tool, a multivariable controller can be generated and implemented in the existing control system. Operators and engineers at the unit control room use an online windows graphical user interface\(^6\) to control the process with the controller. This provides convenient access to review the recent work status of the implemented APC controllers and allows different privilege levels and access for different users.

To predict the laboratory analysis in most APC projects in real time, inferentials (artificial analyzers) are designed. For the HCK unit, more than 10 inferentials were designed using sensor software\(^7\) that is compatible with all main distributed control systems (DCSs) available on the market, and the software is located on the server computer. The server computer with APC software communicates with the existing control system [usually a DCS, but it can also be a programmable logic controller (PLC) or Scada system] via Ethernet connection using the open platform communications (OPC) interface.

APC application challenges on the HCK unit. The HCK unit is one of the most complex units at the Płock refinery. It uses a catalytic process with specialized catalysts in two reactors to convert high-boiling-range material into diesel, jet fuel and lighter products. During this process, significant aromatic saturation and isomerization occur, in addition to the cracking. These reactions also take place in the presence of a recycle gas with a high hydrogen (H\(_2\)) content. Effluent from the cracking reactor is cooled, and liquid products are separated from vapors. The vapor stream is then compressed and recycled to the reactors. The liquids are sent to the fractionation section, where various products are recovered.

In the HCK unit (FIG. 3), fresh feed is routed from the vacuum unit, or from a combination of the vacuum unit and the...
storage tanks. The HCK’s valuable products range begins with heavy diesel and ends at light naphtha.

Objectives and constraints. The HCK unit’s potential capacity is higher than 400 t/hr of fresh feedstock from the vacuum unit: vacuum oil, atmospheric oil and, optionally, diesel oil from hydrodesulfurization of vacuum residue. The boiling range of the feed is 330°C to 557°C. Unit performance is, therefore, strongly dependent on the catalytic cycle. The HCK distinguishes two phases of catalyst life: the start of run (SOR) variant and the end of run (EOR) variant, which differ in yields and operating characteristics of the HCK plant.

The primary objective of the hydrocracker reactor advanced control was to provide safe and stable operation within unit constraints. The secondary objectives included conversion/inventory control, bed profile control and feed maximization. Controllers were used for online control and economic optimization. The solution was dynamically integrated with other HCK sections, including parallel reactor trains and the product fractionator by using an optimizer technology.

The following general goals for the APC application were set:
• Throughput increase
• Conversion stabilization and maximization within constraints
• Reduction of standard deviation in the weighted average bed temperature (WABT) and conversion
• Middle distillates yield maximization through conversion improvement
• Cost-effective energy optimization
  ° Reactor temperatures reduction (while stabilizing conversion)
  ° Main fractionator heaters’ outlet temperature reduction
  ° Steam use reduction.

Among these general tasks, specific objectives were defined for the APC application:
• Maintaining reactor bed temperatures
• Maintaining heater skin wall temperatures
• Maintaining consistent-quality property values on the main fractionator (MF), with yields dependent on feed quality
• Controlling debutanizer temperature within constraints and product quality, and naphtha splitter top product quality
• Minimizing the H₂-to-feed ratio
• Keeping Δ temperature between reactor beds close to zero
• Maintaining proper wall temperatures on the H₂ heater
• Maximizing jet draw, light diesel draw and heavy diesel draw
• Minimizing heavy gasoline flow
• Minimizing residue by minimizing light fraction content (final boiling point below 360°C)
• Minimizing column pressure, oxygen (O₂) in heater flue gases and fuel gas to heaters
• Stabilizing MF column operation
• Maximizing light naphtha flow
• Stabilizing the naphtha splitter operation.

Reactor constraints. Most of APC goals at the HCK unit are subjected to some process unit constraints, with the most difficult constraints on the reactors section coming from reactor catalyst behaviors and H₂ heater limitations:
• The catalyst deactivation was very high (almost EOR) at the HCK unit during the project execution, which made the APC project even more complicated.
• The air coolers on the heat exchangers sometimes did not fully balance the heat, which limited throughput maximization.
• The H₂ heater often had limitations on the tube skin temperatures.

Fractionation constraints. Meanwhile, the most important constraints on the fractionation section were due to product specification requirements:
• When running in diesel mode, the jet product was limited by initial boiling point (IBP), final/end boiling point (EBP) and flash point.
• When running in jet mode, additional constraints surfaced: the naphthalene, asphalt and resins content in heavy products; the light diesel product is limited by 90% distillation, IBP and cold filter plugging point (CFPP); heavy diesel 95% distillation constraint is valid throughout the whole year, while CFPP is a limit only during the winter.
• Sulfur content is an important limit in summer, especially when light and heavy diesel products are combined.
• When the ambient temperature is very high, HCK operators have problems with cooling the top of the main fractionator column, which determines the heavy-naphtha final boiling point (FBP).
• Minimum pumpdown flows are often required in the fractionator column to maintain the proper column circulation.

As shown in FIG. 3, the main constraints for light end products of the stripper column were due to debutanizer column operation, where C₅ content in LPG should not exceed 0.5%,
and bottom C₄ in naphtha should be below 7.8%. On the naphtha splitter column, the C₄ content in light gasoline specification was 3% maximum. The FBP for the heavy gas oil product (180°C) was also constrained together with ΔP on an offgas vessel, which caused problems during very hot days.

Based on the objectives above and the unit constraints, six multivariable predictive controllers were designed for the HCK unit—one for each of the hyrocracking reactors, and separate controllers for the following: the stripper column; the main fractionator column together with a heater; the debutanizer column; and the naphtha splitter column.

Conversion control via optimizer. Conversion at the HCK was calculated based on feed to the unit and flow of the hydrocarbon residue from the MF column, shown here:

\[
\text{CONV} = \left(1 - \frac{\text{Residue flow from MF}}{\text{Feed to the unit}}\right) \times 100\%
\]

Theoretically, this simple formula is correct; however, it often provides inadequate results:
- The hydrocarbon cracking conversion process takes place on reactor beds, so product flows from the MF column (in this case, residue flow) might render the results of the above equation inaccurate, as they depend on current MF operation conditions, not solely on catalyst cracking on reactors.
- In this case, residue flow on the MF column was controlled in cascade with the column’s bottom level controller. This solution made conversion calculation very noisy due to level fluctuations at the bottom of the column.
- The response on MF draws has a big delay relative to the time for hydrocracking reactions on the reactor beds—a time lag of up to 5 hr or longer.

The first and the second points force APC to control variables, on which APC did not previously have a direct impact. It is very difficult to define the real conversion profile—the calculation requires a complicated nonlinear differential equation solver that must work in real time with an inadequate analytically evaluated model. In reality, by controlling conversion, the controller was not controlling the real conversion but the simplified formula (above) based on the real-time data provided from the DCS.

Hydrocracker inferential. Inferences were integral to the HCK APC project. Using historical data from lab samples and key process parameters, the inferences were designed and implemented for the most important process quality parameters. These inferences predicted the following product qualities:
- Nitrogen (N₂) content after the first reactor
- Unstabilized gasoline, 90% distillation
- Heavy naphtha, 95% distillation
- Jet, 95% distillation
- Jet, flashpoint
- Jet, naphthalene content
- Jet, aromatics content
- CFPP of light diesel
- Light diesel, 95% distillation
- Heavy diesel, 90% distillation
- Hydrocracker residue distillation, below 360°C
- C₅ content in liquefied petroleum gas (LPG)
- Light naphtha, 95% distillation.

Each inference requires a few days of bias updating. The bias update calculation is based on laboratory data, and it continually updates the relevant inference equation. This procedure makes artificial inference calculation very reliable and a close proxy for actual lab samples.

APC solution and results. The hardware solution (FIG. 4) for the HCK unit contains the APC server computer connected to the existing DCS through an APP-node computer, which serves as the OPC server. During the project execution, a number of additional features to help operators maintain the APC solution were delivered:
- On the DCS side, all PID loops (used as MVs) were given a special indicator on the operator graphics to show if the particular loops are in remote cascade mode with the controller.
- For safety reasons, an emergency shutdown button has been configured in the DCS on the DCS stations. The button ensures that the APC stops immediately after the operator enables it.
- For lab sample bias updates, an additional graphical interface was created.

The APC process solution had to fulfill all the process objectives and handle all unit constraints listed above. To achieve this, controllers were designed to work in different operation modes. Depending on current unit objectives, the APC solution can maximize jet production, diesel production or olefins yield. To automatically switch between the most frequently used production modes, a special DCS point and operator switch was implemented and visualized as a faceplate on the DCS graphic.
To overcome the conversion obstacles, it was decided (as in similar APC projects) to use an optimizer, another software tool from the portfolio. A cascade approach allows the optimizer to take over the task of optimization across multiple sections. It reuses the controller models to provide steady-state and dynamic optimization across multiple process sections. Moreover, the optimizer can be used for many units—the entire plant can work under one or more optimizers.

**FIG. 5** illustrates the hierarchical connection between the optimizer and the controllers. Three controllers were designed to work under one optimizer. Two controllers were responsible for optimization and control of the hydrocracking reactors, and one APC controller was designed for controlling and optimizing the main fractionator column. The built-in optimizer in the slave profit controllers was configured for reactor product value optimization, while H2 quench flows and product flows were adjusted to maintain conversion and unit throughput. Disturbance rejection was applied for bed temperature control stability to account for the exothermic and highly interactive nature of the hydrocracker operation.

Controlled variables in the optimizer included: reactor conversion, WABT; reactor profiles (or bed temperatures), H2 quench valves, H2 make up and H2/hydrocarbon ratios. Optimization coefficients (mentioned in the technical description of RCA) were assigned for conversion at very high values to maximize the conversion within unit constraints. This approach, using the controllers with the optimizer, increased the average cracking conversion compared to the pre-APC period by almost 3%, as shown in **FIG. 6** and **TABLE 1**.

**Modeling inferentials.** This higher conversion from the APC application still needed to be transformed into yield increase by optimal separation. Product separation mainly takes place in the HCK main fractionation column. It was, therefore, necessary to get sharp cutpoints based on high-quality inferentials.

Among the many possible ways of modeling inferentials in the software (including ordinary least square, partial least square and dynamic sub-space methods), the weighted least square (WLS) method was chosen to model the main quality properties. In the WLS method, soft-sensor models are based on robust regression, where they are desensitized to outliers in the data. While the robust regression models require a nonlinear solution, the final models in WLS are, in fact, linear. Despite the fact that linear models were used for all inferentials, a very good match with the real lab data was achieved.

**FIG. 7** shows some examples of the main product quality prosperities predicted by inferential modeling against laboratory analysis over three months of unit operation from March to the end of May 2015. As can be seen, even during disturbances in operations that took place at the end of April 2015, the inferentials were able to predict lab values quite accurately.

The automatic bias update mechanism for all inferentials was also configured for the HCK unit. All lab samples were fetched directly from the laboratory information management system (LIMS) via a specially customized function block created in the universal runtime (URT) platform and presented on DCS graphics with time/data stamps. Instead of updating bias values for inferentials manually, operators accept new laboratory samples using DCS dedicated graphics. This solution improves data entry and increases accuracy of online laboratory samples prediction.

With the implementation of controller and inferentials on the HCK fractionation sections, diesel yields were increased by more than 0.8%, while conversion stayed at the high 3% improved level. Results for diesel yield improvement based on real operation data are shown in **FIG. 8** and **TABLE 2**.

The APC at HCK units work like a process autopilot, boosting safety while maximizing yields of valuable products. As a result of the implementation on the HCK unit, PKN Orlen conservatively estimates that it has achieved increased profits of at least $2 MM/yr. Results were calculated and checked using real process data and standard benefit calculation methods. The return on investment (ROI) for the project was less than a few months.

**TABLE 1. HCK unit conversion pre- and post-APC application**

<table>
<thead>
<tr>
<th></th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case, without APC</td>
<td>65.55%</td>
</tr>
<tr>
<td>Test run, with APC</td>
<td>68.51%</td>
</tr>
</tbody>
</table>

**TABLE 2. HCK unit diesel yield pre- and post-APC application**

<table>
<thead>
<tr>
<th></th>
<th>Diesel yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case, without APC</td>
<td>45.30%</td>
</tr>
<tr>
<td>Test run, with APC</td>
<td>46.16%</td>
</tr>
</tbody>
</table>

**FIG. 6.** Conversion improvement at the HCK unit after implementation of the APC.
FIG. 7. Inferentials prediction vs. real laboratory results for some quality properties at the HCK unit.

FIG. 8. Improvement in diesel yield on the HCK unit after APC implementation.

Solutions’ inferential modeling for soft sensors with lab feedback, fully integrated with Profit Design Studio. The inferential models developed can be used as inputs in a multivariable or other control scheme. It also features static pressure control (SPC) as an option for smart lab feedback, removing lab noise and outliers.

In a multivariable or other control scheme. It also features static pressure control with Profit Design Studio. The inferential models developed can be used as inputs in process dynamics modeling.

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MAREK BOŻEK is a manager with long experience in production process management. An active participant in many investment and effectiveness programs realized in refineries, he is a former senior process engineer of the FCC and PrimeG+ unit. Mr. Bożek is the manager of the APC department and is directly responsible for the implementation and maintenance of advanced process control systems in the PKN Orlen refinery.

LITERATURE CITED


