CLOSING THE GAP BETWEEN OPTIMIZATION AND OPERABILITY WITH RESILIENT ADVANCED PROCESS CONTROL

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Abstract:

Advanced Process Controls (APC) are designed to yield a certain benefit but are demanding to sustain in the long term. Several factors such as wrong strategy philosophy, instrumentation maintenance and human factors may attempt against APC performance and endurance to dynamic situations. Even artificial intelligence analysis may not be enough against a wrong strategy.

APCs are well known for pushing unit limits to its constraints and therefore delivering additional margins. Nevertheless, they have been around the industry for a long time and some consider them as "old" or well-known techniques which do not have much more to exploit.

This study shows the roadmap applied on a Fluid Catalytic Cracking APC, with decreasing uptime year to year, in order to make Operations embrace the technology again.

Advanced measurement calibration techniques and model structuring were used to gain overall robustness which led to higher uptime. Additionally, a thorough analysis in the process and comprehension of the human factor involved was held.

Results showed that uptime was improved, and feed throughput increased by an additional 5% during the harshest season conditions. Additionally, process variance and product sent to flare system was minimized. This confirms that understanding the human factor role and harnessing specific techniques to ensure a resilient APC capable to withstand the disturbances of a continuously changing operation is the key to success.

Introduction

Industrial refining processes are characterized for involving hundreds of instrument signals, equipments (pumps, fans, reactors, separators, etc.) and countless disturbances that make them fluctuate in a continuum changing status. In this situation there is a constant demand for pushing the Operations to the very edge of the limits in order to gain more value and reduce give away. This optimization philosophy is not new to the industry but instead, has been approached with the help of APC (Advanced Process Controls) for the past decades.

APC applications help optimize a specific operation by taking into account multiple process variables. It calculates and predicts the future trajectory of the variables by means of a model matrix which contains specific relationships between model inputs MVs (manipulated variables) or DVs (disturbance variables), and model outputs CVs (controlled variables), . In this way, the mathematical power of the APCs is harnessed to reduce the process standard deviation to half (Martin 2004). Once this is achieved, the average operation can be shifted towards the limits to increase benefits.

Even though the technology is quite mature, the path from stable and unconstrained operation towards full optimization is still a major challenge for most of APC implementations. While for Planning and Scheduling department pushing the operation to the limits may be economically beneficial, for Operations (specially for the board operator) it means a higher risk for non-desired events just as off-spec product or an equipment shutdown.

In this paper, the key factors needed will be shown in order to ensure that Operations embrace the APC technology and deliver both operability and optimization while keeping Process Safety as a priority. The demonstration is applied on an FCC (Fluid Catalytic Cracking) unit where an existing APC philosophy had to be improved.

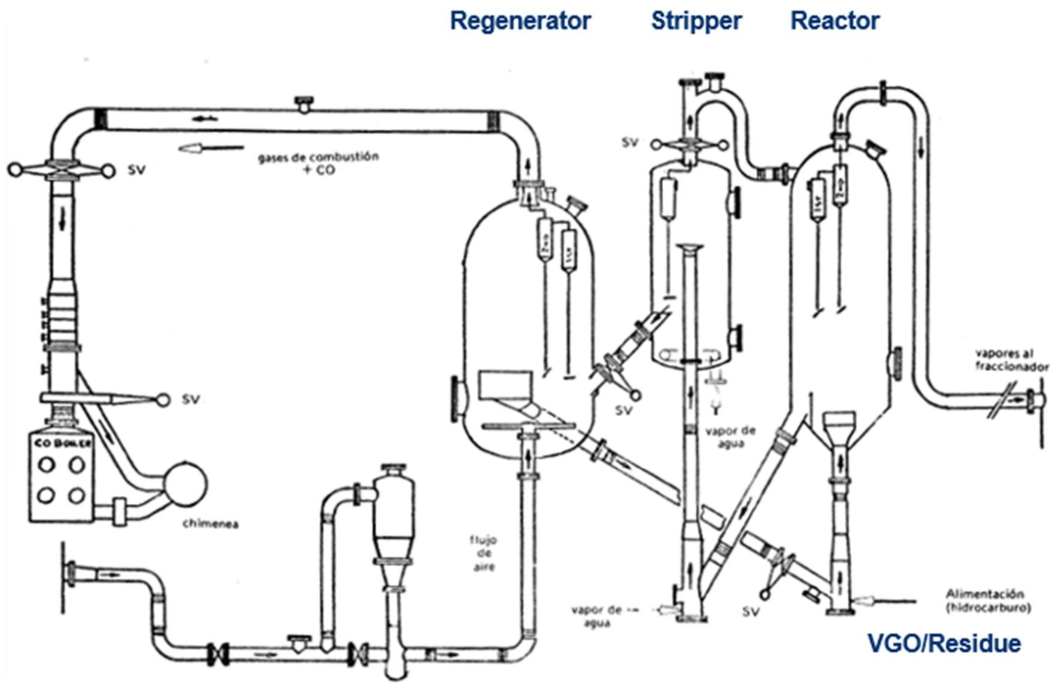

Figure 1. 3-vessel configuration FCC unit.

The process consists of conversion of high molecular weight hydrocarbon into more valuable gasoline, olefinic gases and other products. Figure 1 shows a schematic of the FCC unit analyzed which consists of a 3-vessel configuration, reactor, stripper and partial burn regenerator. The feed, which mainly consists of middle distillates from vacuum unit and long residue from atmospheric column, enters the reactor riser and cracking reactions are promoted by the circulating catalyst which is fluidized. The reaction gases are sent to the fractionator for separation. At this point, one of the main constraints usually met is the wet gas compressor maximum load which is desired to be kept in control to avoid sending product to the flare system. Spent catalyst is then stripped from any remaining hydrocarbon in the stripper. Afterwards, the stripped spent catalyst is regenerated in the regenerator by the injection if air for partial combustion. The air blower represents another main constraint to the operation. Finally, regenerated catalyst returns to the reactor while the flue gases from regenerator are fed to a CO boiler.

Recognize the need for an improvement

For every existing APC optimizing a unit, there is a specific technical resource in charge of performing maintenance in order to keep it operating and delivering results. The reason for this is because APCs rely on models which are a representation of the relationships of different process variables. These models are obtained from step tests performed on the unit at a certain moment in a controlled condition. Usually this is performed in a normal operating condition or where it will be expected to be operating most of the time once the APC is commissioned. Unfortunately, process units are constantly changing due to plant revamps, diminished equipment performance, instrumentation deterioration, base layer control modification, feed composition change between other motives. These will generate inconsistencies between what the APC predicts (what expects to happen in the process) and what really ends up happening. This is what is called model mismatch in the language of APC.

Every APC is followed up with KPI (key performance indicators) or some sort of indicator in order to track its performance. These KPI must fulfill specific requirements so that the value that they show have a specific meaning and is susceptible to changes when the APC has lost precision due to any non-desired situation (Kern 2018). Once these KPI demonstrate the APC performance is lower than expected, it is fundamental to take the decision to review the model in order to find out which are the weak points.

For the case study of our FCC unit, one of the KPI used, and probably the most common upon all APCs, is the Uptime metric. We define it as the time the APC was actively controlling and manipulating the MVs out of the total time the unit was in service. It was observed that the uptime of the APC began to decrease continuously year to year, reaching as low as 12% (Figure 2).

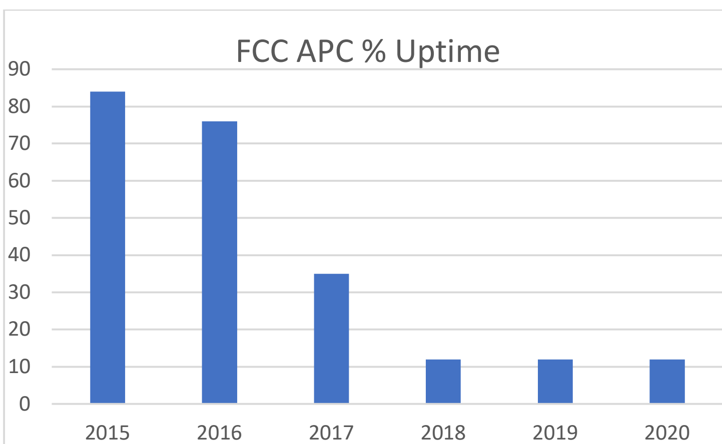

Figure 2. FCC APC uptime metric decreasing year to year as a result of underperformance

There are some other factors that are not directly measurable but directly threaten the APC uptime metric. They may not impact in the KPI in the short term but will eventually affect it in the middle and long term. Some of these factors involve the level of acceptance the DCS (Distributed Control System) board operators have of the APC, how much do they feel the APC is helping them and the level of comprehension they have of it. This subject related to human factor will be addressed in more detail in the following sections.

Get to know your stakeholders

APC is the nexus to different stakeholders and each of them interact with it in different ways. The APC can be considered as a service provider and the rest of the stakeholders that take benefit from the APC in different ways are the clients. Figure 3 shows the main stakeholders that interact with APC.

Figure 3. APC main stakeholders

APCs fulfill different purposes, their objective is not only to obtain an economical margin out of the unit, they maintain a harmonic relationship between Planning and Scheduling and Operations so mutual benefit can be achieved. Four main stakeholders were identified in relationship to APC performance. These are Process Control Engineers, Process Engineers, Scheduling and Planning and the DCS board operators:

- DCS Board Operators:

  DCS board operators play a major role in relationship to the APC performance. They have the ultimate decision whether to use the APC or not. Their main objective is to ensure that all products meet the specifications required by Scheduling and Planning group, keep all process equipment running within their operative range and more important, keep the process unit up and running.

  Board operators are continuously interacting with the APC, since it overrides the command of certain base layer loops. Therefore, while the APC is running these main variables cannot be manipulated directly by the operator any longer. DCS operators set the CV limits of the APC in order to comply with Scheduling and Planning requirements if the process unit allows it.

  Their level of time-frequency scan of the process variables is in the short-term period. This means that they usually make actions based on the actual measurement shown on the DCS screen and are not constantly aware of their rate of change over time. They may make use of historical trending but only to refer short and relatively recent events and under specific conditions. Their knowledge of the process may or may not be very accurate in terms of knowledge of chemistry, thermodynamic or fluid transport but they usually have gathered a good amount of plant experience throughout several years that enables them to make right decisions on the DCS. They have an instinct on how the process unit is performing, how it reacts and what needs to be done to return the operation to desired condition.

- Scheduling and Planning:

  They specify the unit average feed rates and product specifications to be met and, according to these requirements, they transmit this information to the Operations group who will then make necessary adjustments to fulfill this demand if possible.

  They rely on modelling software that guides them on how to adjust feed rates in the whole refinery based on market demands and prices. Even though they do not have any direct action over the APC, all the decisions they make will impact indirectly the way APC operates.

  Their level of time-frequency scan of the process variables is in the medium to long-term period. They compare feed rates, product rates and qualities in weeks or months.

- Process Engineers

  Process Engineers keep track of the operating unit performance, making sure all the conditions are met in order to comply with Scheduling and Planning requirements. They usually are experts in the operation technology and are the nexus between Operations and the rest of the disciplines.

  They deal with process bottlenecks on a daily basis but also give support on mid/long-term follow-ups.

- Process Control Engineer

  Process Control Engineers give maintenance to the DCS regulatory control (also known as base layer) and typically APC. According to each site, these roles may be separated or performed by the same person.

  Process control engineers give maintenance to APC systems and make sure their performance meet the requirements in order to deliver expected results. They have a good knowledge of the technology and know the key variables of the unit. Giving maintenance to APC may involve developing KPIs to help detect reasons for underperformance, tune model relationships and modify the APC to withstand dynamic situations.

Align the expectations

In every project there are different stakeholders involved and each of them have specific expectations to meet. In the case of APCs, it is evident that Planning and Scheduling aim to the optimize the units, increasing yields and profits. But what are the costs of achieving this? In the world of Scheduling software programs and mathematical calculations, optimal conditions can be figured out without many problems. Typically, these depend on unit Operations performance models which will find the most beneficial result according to market conditions. In the world of real plant operation, achieving those “mathematical” results to their very limits will lead to exponential efforts due to dynamic process conditions that are constantly changing and alter the operation and how the unit performs.

Different stakeholders have different expectations on how they benefit from the APC. Without APC, Operations will try to follow the feed rates and specifications as per requirements as close as they can, but, as it was mentioned before, their primary objective is to keep the units running stable and safe from undesired events such as trips. Sometimes they will need to slightly deviate from the plan in order to ensure stability and operability.

Optimization and operability will naturally pull in opposite directions since optimizing the unit to the very limits will take the operation closer to trip limits while maintaining operability means taking safer decisions at the expense of give away. Figure 4 details some characteristics of each operation philosophy.

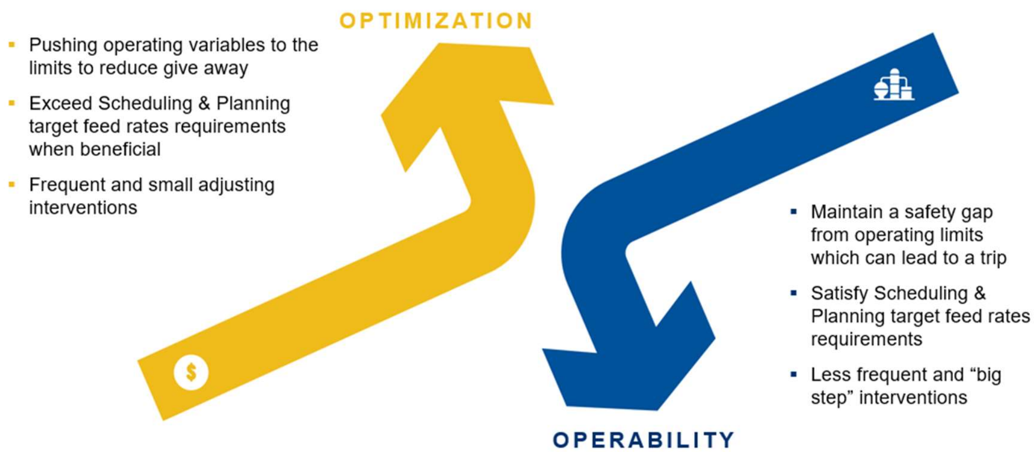

Figure 4. Optimization, Operability and their characteristics

The key to ensure a successful APC project execution is to manage expectations of different stakeholders in order to find a harmonic relationship between them and satisfy everybody in a middle position. This can be understood as enabling the APC to optimize the operation as per process engineer recommendations but not compromising the stability of the unit. This trade-off condition can be achieved with APC technology, since its inherent process variation reduction enables a closer operation to the limits (Singh 2016).

Make the DCS board operator your ally

Automation has been the ally of optimization for decades and is the main reason why it is achievable. Automation of processes enable 24 hours action over a variable without the need of board operator intervention. This applies from base layer loops controlling local variables such as flow, to APCs that control a whole unit automatically.

Even though APCs have the advantage of having a multivariable model matrix in order to predict process variations and therefore operate the unit more efficiently, DCS board operators have the final decision whether they will enable the APC to act or not. They make these decisions based on how the APC operates, how stable it keeps the process and if it makes the same movements as they would do or not. Process engineer specialists may have recommendations on how to operate the unit based on their experience in the given process technology, but DCS board operators are the ones that are looking constantly to the DCS screens 24 hours a day. They have a keen eye to detect process anomalies and have information of the unit equipment and instrumentation that will help them to take specific decisions.

In order to achieve a high APC uptime, DCS board operators have to feel comfortable using it, and therefore it is crucial that the process control (or APC) engineer has a good communication with them. Process control engineer should understand board operators concerns in relationship to the operation and what type of actions they would perform in each occasion.

With this information, process control engineers should analyze the actual APC configuration and constraints specifications to ensure its actions replicate what the board operator would do.

Training in any format possible needs to be provided by the APC engineer in order to avoid the APC being considered a black box. Board operators comprehension of APC fundamentals is crucial for success. Achieving this will gain the trust of the Operations and contribute towards a higher uptime that will enable the APC to increase margins over a larger period.

Make the APC resilient to external disturbances

FCC is a very complex technology that involves a high amount of instrumentation and equipment essential for the operation. Some of these critical instrumentations may include slide valves to control catalyst circulation, pressure differential transmitters to control catalyst density and height, air compressor to adjust the right amount of oxygen that enters the regenerator and CO Analyzer to control the carbon partial combustion.

Process is always subject to disturbances, which may be due to upstream or downstream process units or due to equipment or instrumentation failures or unexpected behaviors. These events generate a wrong interpretation of the APC model of what really is happening in the unit and if it is not treated properly, may lead to a unit trip. Board operators are very susceptible to how APC handles these situations and build their trust on it according to its outcomes. As an example of this, if a measurement freezes due to an instrumentation failure and the APC still considers it as valid, then the actions taken would probably be erroneous. This will lead to a mistrust from the operators and make them reluctant to put it in service. In this paper the specific techniques used to make our FCC APC resilient will be detailed:

1. Check validity of abnormal deviations of critical measurements during maintenance tasks

   FCC depends on critical instrumentation that undergo maintenance with relatively short frequency in order to keep their reliability. While APC is in service, if these critical measurements show abnormal values, the predictions based upon these will start to deviate probably to uncoherent values as well. This can cause the APC to perform incorrect MV movements to try control a CV that will mistakenly deviate in the future. The impact of these situations is more severe in model relationships with longer deadtime. It is important to mention that these maintenance tasks affect the APC predictions whether it is actively operating over the unit or not, since these calculations are running even when the APC is in standby mode, actively scanning process variables. For the FCC case, feed measurement deviation impacts reactor temperature, regenerator temperature and lastly the CO content of the flue gases to the CO Boiler. Figure 5 demonstrates a real example of what can happen with predictions in these cases.

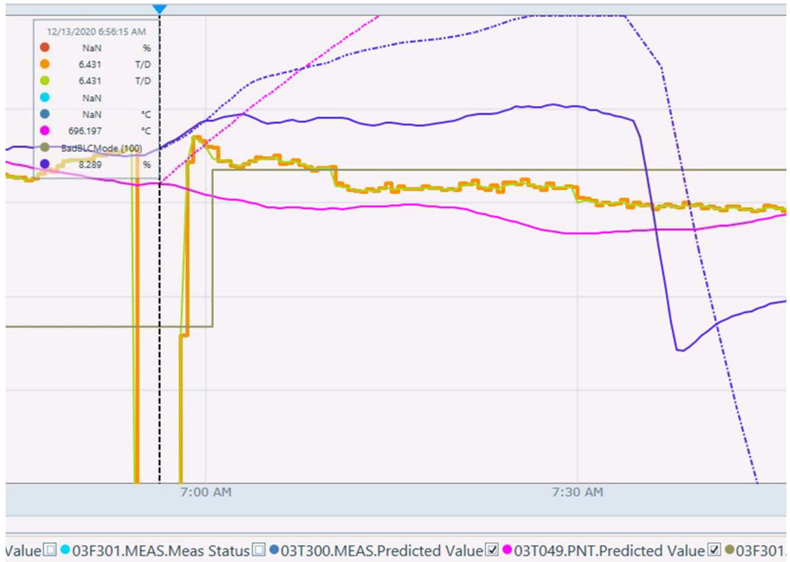

Figure 5. Feed measurement abnormal deviation during maintenance tasks. References: Orange-Feed DCS raw measurement, Green-APC measurement value, Pink-Regenerator temperature, Purple-% CO in regenerator. Doted lines represent APC predictions.

When maintenance takes place, feed measurement drops to zero. If no validation is performed, then the APC measurement value (value that has been processed with validation and calibration) follows the raw DCS measurement exactly. APC will predict that carbon content in the regenerator will drop, therefore leading to a more complete combustion (while having constant inlet air to the regenerator) and an increase in the temperature. Figure 5 shows how temperature prediction deviates from real process values and therefore generating wrong MV moves.

When applying correct measurement validity, these events can be disregarded, thus making the APC resilient against these maneuvers. Figure 6 shows how a correct measurement validation keeps healthy predictions for the future, therefore avoiding unwanted MV moves.

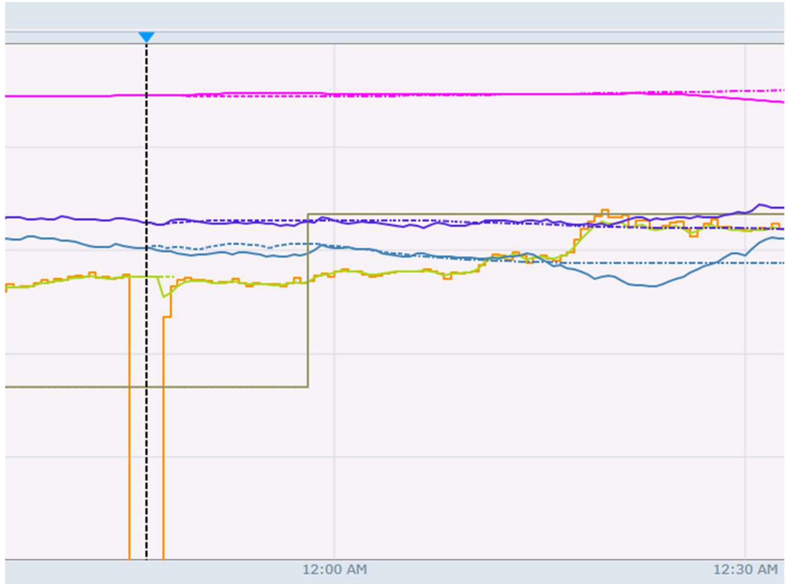

Figure 6. Feed measurement with correct validation. References: Orange-Feed DCS raw measurement, Green-APC measurement value, Pink-Regenerator temperature, Purple-% CO in regenerator. Doted lines represent APC predictions.

2. Calibrate measurements for process disturbances

Measurement validation is crucial for detecting a process value outside the expected range, but it is not enough to contemplate all the possible disturbances that can generate instabilities in the APC and therefore lose confidence of the board operators.

APCs typically have built-in functionalities to filter instrument measurement noise that otherwise would propagate to downstream process variable relationships. Signal filtering is a great feature but may become a problem when real process upset happens, causing an important CV value to change rapidly. If the CV raw value signal from field falls below the low limit value in a fast manner, signal filtering may cause the APC to think that the CV has not violated the limit, hence not acting with an MV when it should.

Specific techniques are available in the APC software used for the FCC unit which involve calibrating the variable before it is handled by the calculation engine in order to decide the next steps. Calibration is a series of treatment of the signal in order to prepare it for calculation. Figure 7 depicts the workflow of calibration performed in the FCC APC. Raw value is checked against validity limits preconfigured by APC engineer. If value is outside valid bounds, then it is rejected. Next the value is checked for outliers in order to exclude bad data like for example instrumentation going off scan one or two rounds. Following, is the event threshold. Events are something that can be explained process wide speaking, not just random data. They may include things like heater swaps, delayed coker drum swap and others. If the event threshold is triggered, an event detection speed is applied, in other words, a fast event Kalman filter type in order to capture the rapid change of the process due to a real process event. Finally, a second Kalman filter is applied regardless the detection of an event or not (it must be a slower filter than the one applied in the event detection) and is adjusted in order to actively take process noise off the measured variable so it is not reflected in the controlled variable. This second case will be referenced as noise Kalman filter onwards.

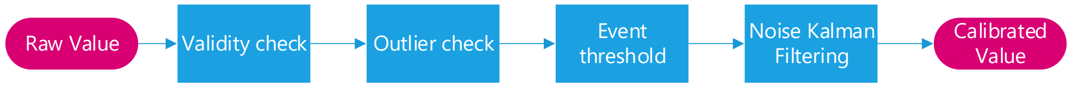

Figure 7. Calibration process of a measurement.

An example where applying advanced calibration to a measurement made the APC robust against dynamic situations is the CO boiler control limit, where a key variable is the pressure differential between the CO boiler air blower discharge and the boiler box. A minimum positive value must always be maintained to ensure inlet of air. Differential pressure is very sensitive to the total amount of air entering the regenerator since flue gases end up in the CO boiler. Any sudden change in the operation of the regenerator or the boiler air blower has a direct impact on this CV. On the other hand, pressure differential instrument has a certain degree of noise which can affect APC steady state calculations if signal is not treated properly. Figure 8 shows how these two conditions can be addressed without losing performance.

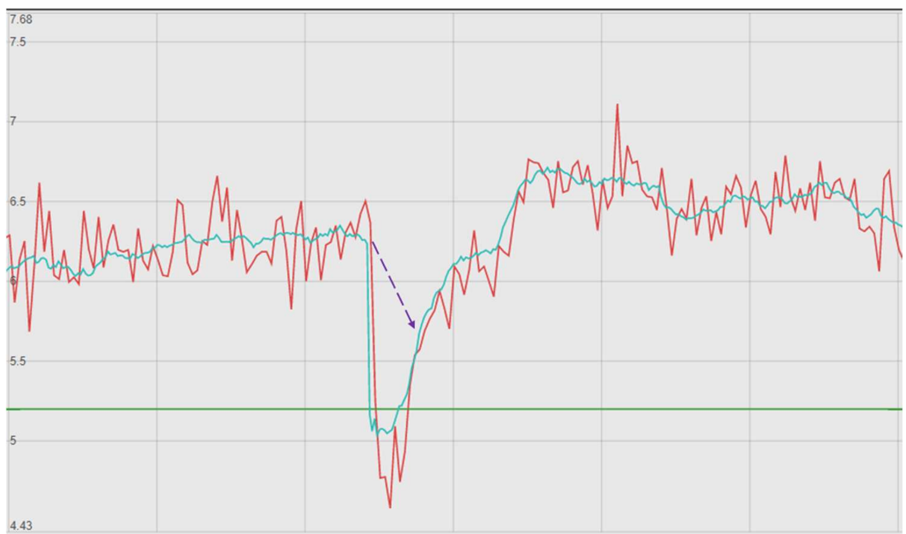

Figure 8. Raw measurement calibration. Kalman filter removes noise while event threshold check detects relevant process changes and produces a faster Kalman filter type update. Red is the raw measurement, light blue is the calibrated value, green is the CV low limit and slashed purple line represents a calibration with pure Kalman filter.

During a normal operation, raw measurement depicted by the red line is filtered with a noise Kalman filter, to produce a more stable signal for the APC to use. This calibrated signal is shown in light blue. Noise Kalman filter produces a clean signal for the APC to perform prediction calculations and therefore delivering stability. Right in the middle of the graphic an event occurred, causing the rapid decrease of the pressure differential. APC detects the event and generates a rapid update on the calibrated variable to quickly detect that it has violated the low limit. This is what was referenced as an event Kalman filter update. If a feature as event threshold was not available, then a pure noise Kalman filter would have filtered the event as shown qualitatively in purple dashed arrow, generating a more unsecure condition for the process since the rapid drop of the measurement would have been filtered out.

3. Keep the APC variables estimation as reliable as possible

APC predictions of the CVs trajectories in the future are the key to a good performance. The better the estimations are, the better the APC will perform (Cott et al 2015). Traditional APC model for an FCC regenerator would involve having relationships between MVs to the CV (% CO). Some of the typical inputs to the model are shown in figure 9 like the feed rate, the feed pre-heat, the residue ratio and the air to the regenerator.

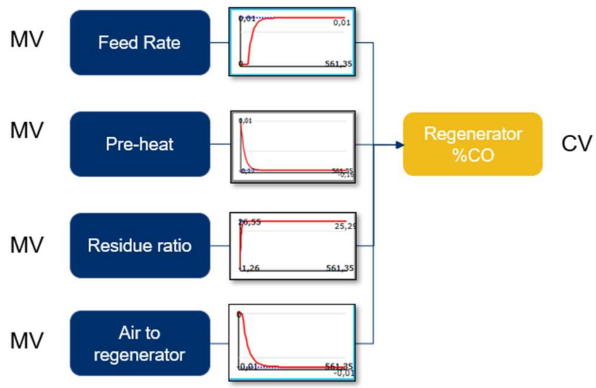

Figure 9. Traditional APC estimation of CV variables. A direct connection between MVs to CVs is used.

Although the beginning and the end of the CV estimation is shown here, there are more process considerations that can give important information. With the model scheme shown here, the APC can only correct model mismatch by acting with full feedback action. If there is any variable that has real process impact but is not considered in the model, then CO estimation will not be faithful to the process.

The way to make the APC more robust against these situations is to use additional process measurements as inputs that will provide additional information on whether the CV will respond as expected or there is a process response bias due to an unmeasured disturbance. These are called IVs (intermediate variables). Figure 10 shows how an IV can detect model mismatch even before the CV starts to respond. For the FCC case, the riser temperature and the regenerator temperature can be used as IVs to perfectionate %CO estimation.

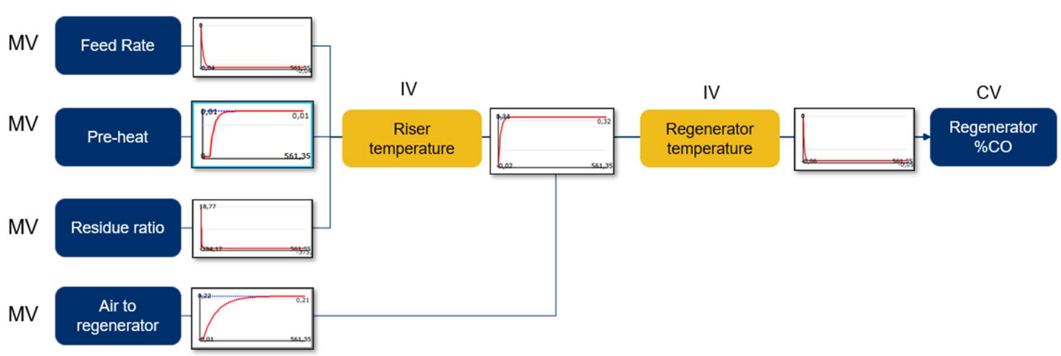

Figure 10. Advanced APC estimation of CV variables. The use of intermediate variables such as riser and regenerator temperatures can greatly improve CV estimation quality.

An example of how predictions improve with this technique is shown on figure 11, where the same process variables are shown for a period. The upper graph has the traditional model of MVs to CVs while the lower graphic applies the advanced estimation technique making use of IVs. It can be observed that IV produce a more accurate raw prediction (predictions using internal model only, without updating from field signal) when compared to the non-IV option.

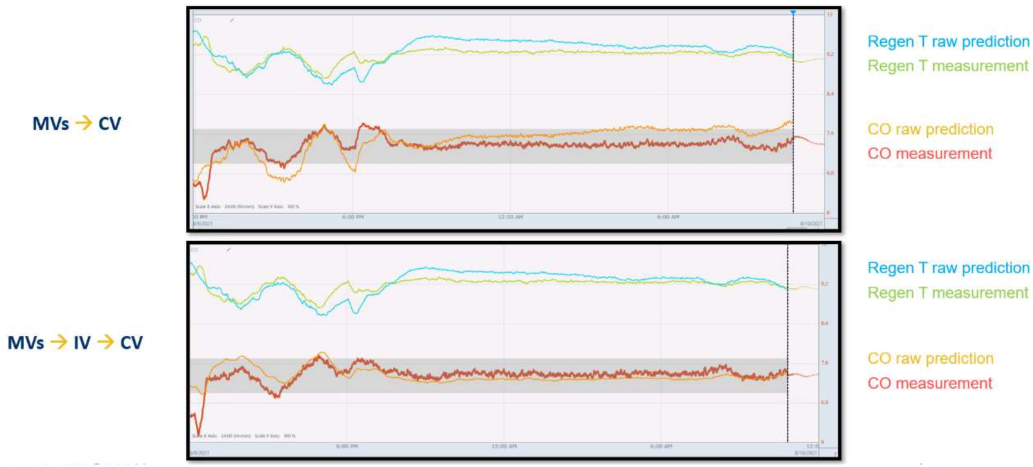

Figure 11. Non-IV vs IV model estimation. Predictions improve with the use of intermediate variables

Conclusions

The process of revalidating the FCC APC performance was a long process that involved understanding technical and humanistic bottlenecks. The whole practice resulted in 3 major benefits that are listed below:

- Operations embracing the APC technology
- Process stability
- Maximizing economical margins

Operations embracing the APC technology:

DCS board operators were reluctant to use the APC due to undesired MV moves caused by instrument maintenance affecting CV predictions which led to lack of confidence. After the APC model was made more robust to ensure correct predictions, Operations embraced the technology again, increasing APC uptime significantly. Figure 12 shows how uptime greatly improved during the year 2021.

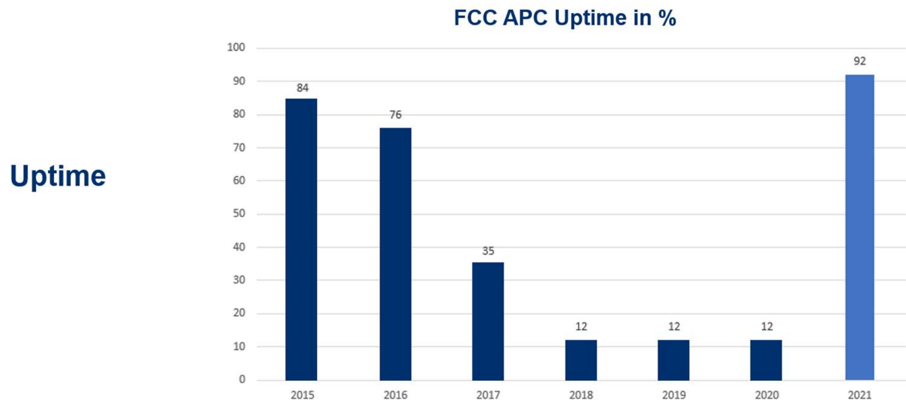

Figure 12. Uptime increase after model revalidation in year 2021

Process stability

A great effort was applied in the APC in order to ensure a stable process. This enabled the possibility to optimize the process as well as maintaining operability in the unit. Figure 13 shows the process distribution of the regenerator flue gas %CO versus regenerator temperature. Results show that %CO, which is the main variable of the process, variability was greatly reduced, depicted by a narrowed distribution of the variable.

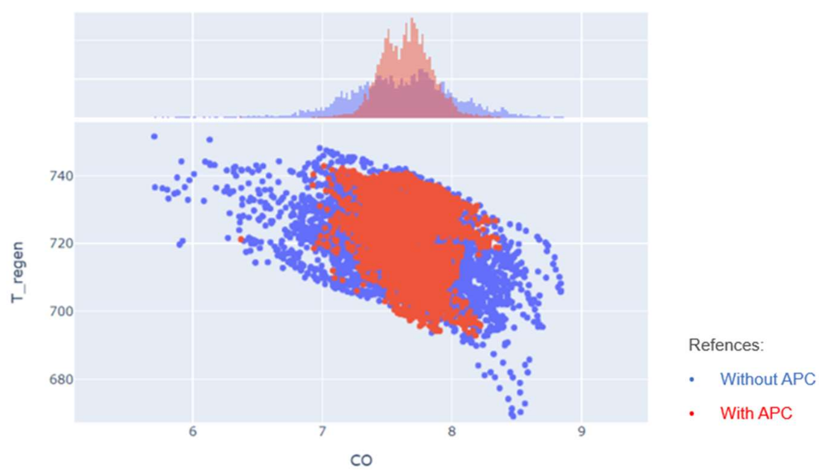

Figure 13. %CO in regenerator variability reduced as a result of a more reliable model prediction

Maximizing economical margins

With an increased uptime and confidence from Operations, FCC unit margins were maximized by seizing the plant cooling capacity over a whole day. Typically feed rates set by Planning and Scheduling cannot be met at noon where temperatures are high, but there is room for optimization during the evening, ending in a higher average feed throughput for a day. Figure 14 shows a 24-hour operation of APC, managing the feed rate according to the wet gas compressor load limit. Higher ambient temperatures decrease the compressor performance, hence feed rates must be lowered to avoid sending wet gases to flare system due to lack of condensation capacity during warmest hours. During night, feed can be increased again for economical purposes.

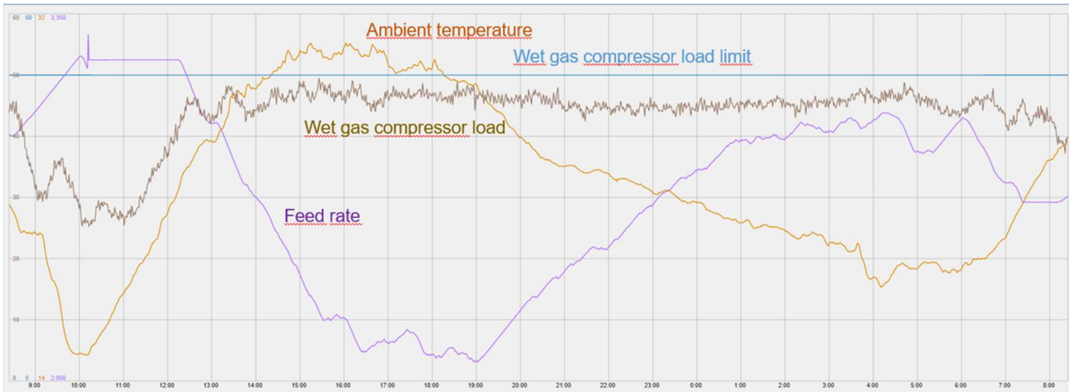

Figure 14. FCC APC feed rate maximization according to wet gas compressor load capacity subject to ambient temperature

Results have shown that the APC was able to increase average maximum feed rates in about 5% while maintaining the operation stable.

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