# Operation-Oriented Advanced Process Control

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## Abstract

*Since the 80's, the world-wide process industries have adopted and benefited from the applications of advanced process control (APC), particularly the Model Predictive Control (MPC). Among many implementations of the APC technology, some successfully demonstrated substantial financial benefits but others failed to exhibit much advantage over conventional control technologies. These failures might have cost general acceptance of this technology in the process industries. In several regions, the acceptance of APC in the process industry has been extremely slow. The slow adoption of this well-proven technology has caused the losses of the industry's potential productivities and financial benefits. As the global-oriented economy is driving for the future of process industries, applications of such technology can become crucial to boost the competitiveness of the industries regardless of the cultural differences. The failures of APC can be attributed to various factors. Based upon the observation from many successful applications, an APC design that addresses more of the daily process operation issues has better chance of successes. Therefore, using a successful project as an example, the article presents the concept of the "Operation-Oriented APC."*

## 1 Introduction

In the process industries, new plants are being constructed in developing countries. Such new construction is simply driven by low cost labors. With challenges from the low-cost operation plants, not only do the existing plants have to face their ever increasing operation costs, but also do they lose their profit margin. Yet, their process technology can be out dated and it makes less room for their profit margin. Looking for approaches to lowering operation cost and improving profit has always been constant efforts in the industries.

Owing to the complexity of a plant as a business entity, there is tremendous room for cost reduction and profit improvement in the areas of people, asset, process, operation, business agility, etc. Process engineer usually concentrates on process improvement. The process here refers to the complex of equipments and devices where the raw materials are turned into the products. With the discipline of chemical engineering, process engineers easily focus on activities often referred to as "process de-bottlenecking," and those as "process optimization." The process improvement often leads to finding the optimal operation conditions such as the optimal reaction temperatures, pressure or to looking for process constraints (bottleneck) to remove in order to increase capacity.

However, the de-bottlenecking usually demands some degree of capital investment and often requires many years to have the return on investment (ROI). The process optimization on the other hand needs an experimental facility such as a pilot plant or high fidelity simulation model. Investment for process optimization also requires multiple years for its financial payback.

Thanks to the low cost and advances of computers, digital control systems, and sophisticated computational algorithms, more process control technologies become accessible to process industries. In the 80s, the process industries started to adopt the process control technology as an additional approach for cost reduction and profit improvement.

In general, the scope of "Process Control" is extremely subjective and is often situation-dependent. Thus it is not the objective of the article to define or argue what exactly Process Control or Advanced Process Control (APC) is all about. The article will instead focus on bringing about the experiences from a group of experienced APC engineers.

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For convenience purposes, the paper likes to classify "Process Control" into a number of categories. These categories include: 1) Measurement & Control Devices, 2) Basic Regulatory Control, 3) Advanced Regulatory Control, 4) Multivariable Control & Unit Optimization, and 5) Multi-Unit Optimization. Figure-1 depicts these categories in a pyramid to show their interrelationships and dependencies. The boundaries among theses categories are vague and extremely subjective. Measurement & Control Devices and Basic Regulatory Control are usually excluded in the scope of APC. However, today's smart sensors and high-spec controllers have expanded their functionalities beyond the limitation of conventional ones. The technologies have blurred these boundaries even further.

As a result, the scope of a typical APC project can often be a blend of all those categories depicted in Figure 1. The differences among projects are the distributions of their focuses among these categories. As computers have become more and more powerful, more computation and/or memory demanding control algorithms and strategies can be implemented without too much investment on hardware. Most APC projects nowadays employ very sophisticated control algorithms.

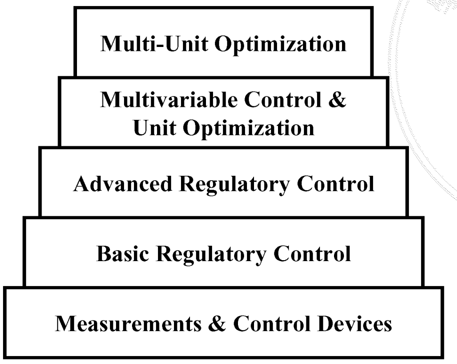

**Figure 1: The Scope of APC.**

One of the most computation and memory demanding control algorithms is the multivariable model predictive control (MPC). In today's markets, there are quite a number of such applications excluding those made in-house by research lab of some bigger companies or universities. Among the most widely used are the DMC Plus by Aspen and RMPCT by Honeywell. Successes of these applications have demonstrated tremendous financial impacts to the process industries and thereby generate quite a lot of businesses. Recently, a few other vendors also come up with other applications and attempt to take a share of the APC business.

Although the scope of an APC project can include as much as all five categories, the centerpiece of an APC project is in fact the design of the multivariable MPC. This technology is no longer new to academia or industry after its introduction in early 80's. Some textbooks already introduce such technology at the collegiate levels. Most industrial engineers have also learned in various occasions such as conferences, short courses, internal training, etc. The concept of this technology is rather easy for a novice engineer to comprehend. Therefore, the article assumes some fundamental understanding of the MPC technology from the readers.

Via some university training, in fact, some talented college graduates with proper discipline might be able to follow limited instruction and install a controller without too much difficulty. In particular, the improvement on the user interface of some commercial MPC software such as RMPCT or DMC+ has made implementing a large dimension multivariable MPC a relatively simple task. The guideline of configuring and tuning of an MPC controller has become ever easier thanks to software developers' efforts.

Despite vendors' claim of the unique functionalities of their own application software, the success of an MPC application depends almost entirely on the qualification and experiences of the APC consultant who conducts the design. Since the introduction of such technology, nevertheless, not all APC applications in real life are considered successful.

In a recent internal forum of a large petrochemical company in Asia, the author was invited to participate and join their discussions. It was reported that nearly all their MPC applications but one failed to deliver what was expected or promised. Most of these applications ran for less than a year. Some even failed before the project was considered completed.

With such an easy-to-understand and easy-to-apply technology and software, why could an MPC controller fail? What really went wrong in these failed projects? What are the differences between the successful and failed projects? Why was the success rate of these APC projects this low in Asia whereas there have been successes elsewhere?

In an attempt to answering these questions, the article will present an "Operation-Oriented APC" design concept. The paper takes a real example of an APC project took place in the United States, and illustrates the concept of Operation-Oriented APC in details.

## 2 Operation-Oriented Control

At a college/university level, the teaching of process control always starts with single variable controls. It is easy for a student to understand what "process control" really is. In real world, an operator has to deal with hundreds or even thousands of measurements in order to keep the process in check. They are making adjustments (control) based all information available to them. The idea of the process control in the real world seems far more complicated than what is taught in school.

Furthermore, regardless of how the concept of process control was delivered to students, the concept of the PID control always plays a fundamental role (Seborg et al., 2003). What drive the control actions are the discrepancies (differences) between the setpoint (SP) and the process variable (PV). A simple control block diagram as depicted in Figure 2-(a) is basic knowledge of all control engineers. Although the idea of “multivariable” is natural to academia, its application to the real world seemed quite unrealistic if the idea of a predictive model is never in the picture. Since the work of Internal Model Control (IMC) (Morari & Zafiriou, 1987), the model predictive control (MPC) becomes the buzz word in the world of process control. Figure 2-(b) depicted block diagram of the IMC. The uses of predictive models in a controller make the multivariable control more acceptable to the process industries. Only then, the theoretical and the particle sides of the process control world seem to get closer than ever.

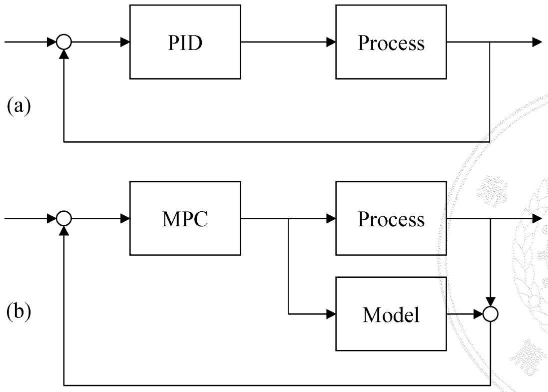

**Figure 2: Control Block Diagrams**

The multivariable has become so popular in the process industries. One of the key reasons for its popularity is that the multivariable controller works more like a human operator than any other complex control loops. The controller does not only regulate the process to reduce its variation around its normal operation targets. If properly designed, the controller looks at all causal information and makes appropriate adjustment in order to address the “operational” issues when process upset does take place. In other words, a multivariable controller “operates” the process in addition to its fundamental “control” functionality.

Inevitably, the predictive capability of the multivariable controller plays a crucial role. It makes the controller smarter than a human. The predictive capability comes in two places.

One is its transient model and the other is the inferential models or referred to as soft sensor. The transient models are developed via a procedure often referred to as “step test” or “plant test.” In a plant test, pre-medicated disturbances are introduced to the process and the responses of the process are collected. Transient models can then be developed using the response data. The inferential model is developed using process operation data and lab measurements. As long as the data is statistically repeatable, a model can be developed. In a mathematic form, these models represent the knowledge of an experienced operator in real life.

### 2.1 Regulatory Control Objectives

Most control engineers understand the fundamental principles of a controller. The controller regulates the variation of the process variable of interest with a certain range of a target (setpoint). Figure 3 depicts the variation relative to the process limit. If the process runs near the process limitation or some safety constraints, a more stable (smaller variation as depicted by the thicker red curve) process always ensures a safer operation. Apparently, the operators can take the process closer (blue curve) to its limit if it is more stable.

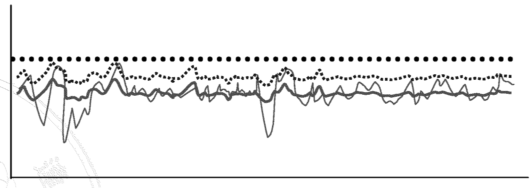

**Figure 3: Regulatory Control**

### 2.2 Operation Objectives

In addition to the regulatory objectives to maintain the stability of a process, the operation of a process is to drive for maximum profit and minimum cost within the safety limits. A single variable controller like a PID controller cannot live up to such objectives. In reality, the operation crew including operators, superintendents and plant managers have the responsibility to drive for profit regularly. In fact, the operators care more on the safety issues than profit or cost issues. However, the managers whose performance is normally measured financially care more otherwise. Any safety incidents are likely to be converted financial indices.

### 2.3 APC Objectives

What should an APC control be if it should be accepted in a plant? Whatever the proper objectives of an APC may be, the managers, the engineers and the operators must all accept the design and like to use the APC. In any cases, the APC must be able to regulate the process as well as “operate” the process like all parties involved in running the process. The design concept is therefore referred to “Operation-Oriented APC” in the article. The APC controller must constantly be looking for room for profit improvement and cost reduction as long as it is safe to do so. The APC controller must also pay attention to any foreseeable safety upsets and takes precautionary measure to prevent them from happening.

Figure 4 depicts the concept of the operation-oriented control. Regulatory functionality should not take up the major portion of its behavior. As shown, the process can often run as the red curve shows. The blue curve is what an operation-oriented controller shall do. When the process is safe, the APC should drive for more profit and less cost. Whereas the APC should back off to address the safety issues when it might not be. As the predictive model can know better than a human being, the APC can back-off less aggressively than operators.

In order to illustrate the concept, the article presents an example of a simple APC design from an APC project executed in the west coast of the United States in 2001. The project is successful in terms of its financial impact and the likeness from the operators.

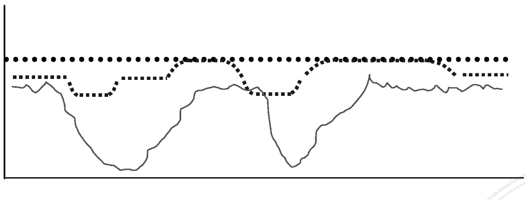

**Figure 4: Operation-Oriented Control**

The article uses the desalter control as an example to demonstrate the subtle differences of a conventional control approach and an operation-oriented control approach. Their differences can be attributed to preferences from a team of experienced APC consultants rather than any theoretical concerns. As often claimed "Control is not a science but an art," the approach to addressing a control issue can be extremely subjective. Its results can also be viewed from different perspective depending on the reviewers' preferences and view-angle. The desalter control example is taken from a crude unit APC project conducted in a decades-old refinery. However, it is not the purpose of this example to bring out the argument of such disagreement but to elaborate the concept of "operation-oriented" control.

## 3 Example: Desalter Control

A crude unit usually consists of preheat trains, desalters, furnaces, atmospheric towers, vacuum towers, and/or gas treatment plant. However, most APC projects for a crude unit focus mainly on the operation and control of atmospheric, vacuum towers, and the gas plant. In particular, controls of the desalters are often implemented at the base level (e.g. at the DCS level) as their control objectives are mainly to quickly reject disturbances and to maintain a constant desalter pressure. A constant desalter pressure ensures a steady charge to the stable operation of a crude unit.

### *3.1 Process Description*

In a recent APC project of the Crude Unit, the desalters were found to frequently cause major upset to the crude preheat furnace system and thus renders potential risk to the success of the APC project. Further investigation concluded that the control problems of the desalters were difficult and challenging, and yet they must be resolved prior to the APC work.

Firstly, there are two desalters running in sequence (as depicted in Figure 6) and the wash water is run counter-currently with the crude. The wash water pump is limited and is always run at its highest capacity. Secondly, the water drainage pipes out of both desalters do not have flow indicators. In addition, the interface level sensors are prone to give unreliable readings, and require frequent manual re-calibration. Thus the levels cannot be easily maintained. Thirdly, the drainage out of the primary desalter (D-100) is hydraulically driven thus the pressure and the level exhibit sever interaction. Due to the geometry of the desalters and the effect of hydraulics, the levels also exhibit highly non-linear response to the valves' positions.

The design of the regulatory control scheme is also depicted in Figure 6. As shown, the pressure controller and level controllers run with three independent PID controllers on a decentralized control scheme. The pressure controller regulates the crude charge pressure; whereas each of the level controllers regulates the interface levels of the two desalters respectively. The wash water runs at a desired flow rate via a flow controller; so does the crude feed to the Crude unit.

It is worth noticing that the desalters have been in service for a couple of decades. The decades-old oil-water interface sensors have become extremely unreliable. Often operators must often rely on visual observation in the field to take the level measurement. As frequent as once every couple of hours must they recalibrate the level sensor in order for the controller to work. Yet, the level sensor cannot truly indicate interface level. Moreover, the water flow rates out of both desalters are not available—no flow sensors are ever installed to measure these flow rates. No material balance is possible due to the lack these flows.

As the interaction among these PID controllers is so severe with unreliable level indicators, water is frequently carried over the down stream crude tower furnace. When the water goes through the furnace, it will create dramatic pressure upset. The pressure upset will then lead to insufficient back pressure to push feed through and thus causes lower than desired throughput. If the level controller runs in automatic mode, the pressure upsets on a cyclic basis. The left hand side of the trend shows how the pressure gets upset every couple of hours as indicated Figure 5. As a result, operators normally choose to set the level controllers in manual mode and only keep the pressure control in automatic mode. They must pay much attention to these levels in order to avoid the water being carried over downstream or draining out to the environment.

### 3.2 Solution Strategy

One of the easiest approaches is to ask the site to replace the extremely out-or-date level sensors. It is quite an acceptable solution approach by many in APC projects where the desalters are not in the scope. Without a steady crude feed back pressure, the APC on the crude units can make no sense. Surely, it makes more practical sense to address the control issues around the troubling desalters prior to the crude APC project.

If the level sensors were reliable, the PID controllers might have been working just fine. Some decoupling method can also be useful to address the interaction among them. However, the fact is that: 1) the level sensors are extremely unreliable; 2) the PID loops are highly interactive; and 3) there exists geometric nonlinearity of the desalters. The PID controllers cannot satisfy the operation needs.

### 3.3 Operation-Oriented Design

Nevertheless, the desalters are still in service for decades regardless of their control issues where the water does occasionally get carried over to the furnace. The operators do know how to "operate" the desalters if they do pay attention. The penalties can be some throughput losses or human fatigues. Yet, the fact is that the desalters under its current situation are "controllable" and "operable."

With an APC project in place, it is natural if the APC is to include the desalters into the project scope and to design a multivariable controller to address the control issues. Usually, the design of a multivariable control takes the approach as follows:

1. choose the dependent variables, i.e. the controlled variables (CV), and the independent variables including the manipulated variables (MV) and the disturbance variables (DV)
2. run a plant test to learn the causal relationship among the dependent variables and the independent variables.
3. identify the mathematic models of the causal relationship
4. tune the controller and commission it

It is quite obvious that the two levels and the pressure of the desalters are the controlled variables. The manipulated variables are the three valves positions as indicated in Figure 6 and the wash water flow rate. The downstream feed flow can be a good disturbance variable. Unlike other conventional control approaches, however, the control must also take into account of the semi-manual read-out of the level sensors. A matrix presentation of the selected CV, MV, and DV can be depicted in Table 1. The two bias variables in the DV column are used to address the frequent re-calibration of the un-reliable level sensors. The objectives are to prevent from the water carry-over and oil drain-out and to maintain constant back pressure to allow steady crude feed.

The blank blocks mean that there is negligible or no causal relationship between the respective dependent and the independent variable pairs. For example, FIC100.PV does not affect the interface level LIC001.PV. The "A" through "E" blocks do express significant causal relationship. These labeled models stay as is or are left blank on purpose for various reasons as follows:

- A & B: Operators never uses the drain valve LIC002.OP and wash water for pressure regulation.
- C & D: Although pressure does significantly affect the draining flow rate out of Desalter D-100, the pressure valve regulates the feed rate. Operation will never use it to regulate the interface levels.
- E: The pressure control is to maintain the steady feed rate. The pressure therefore takes into account of the crude feed rate which is set by operators. Although it affects the interface levels of Desalter D-101, the effects can be addressed by the feedback.
- X: There are strong causal relationships between the respective dependent and independent variables. All models stay for the purpose of predictive control.
- Y: This particular CV-MV pair shows an interesting behavior during the plant as discussed below.

**Table 1: CV/MV/DV Configuration**

| CV | MV | | | | DV | | |
|---|---|---|---|---|---|---|---|
| | PIC001.OP Press Valve | LIC001.OP Drain Valve | LIC002.OP Drain Valve | FIC100.PV Wash H2O | FIC001.PV Feed | BIAS001 Level Bias | BIAS002 Level Bias |
| PIC001.PV Back Press | X | X | A | B | X | | |
| LIC001.PV Level #1 | C | Y | X | | | X | |
| LIC002.PV Level #2 | D | | X | X | E | | X |

It seems obvious that opening the draining valve will drain more water (dense phase) out of the desalter. Thus the interface level should recede. During the plant test, however, the interface level rises instead of recedes as the valve opens. It seems contradicting. Understanding the physical law of the liquid filled vessel, it is understandable that opening valve in fact releases the pressure. The pressure drops leads to less water out-flow. As a result, the level rises.

As a precaution measure, several re-stepping of the valve is to confirm this peculiar behavior. It is interesting to see that the level and valve exhibit un-predictable but causal relationship. Under some conditions, the level does recede as expected. Under others, the level rises or even sometimes the level stays undisturbed. A process engineer or control engineer will probably try to develop a sophisticated model to deal with such behavior.

If operators can and do run the process without too much difficulty, the "advanced" controller should be able to without too much effort. There should be no need for any sophisticated model. With the "operation-oriented control" concept in mind, the model is therefore replaced with one that comes from the "rule-of-thumb." As valve opens, the level will eventually recede. The peculiar behavior described above is completely ignored for the APC design.

## 4 Results & Discussion

Based upon the concept of the "operation-oriented APC" design, the final controller matrix is a block diagonal one. As shown in Table 1, the final matrix has the elements labeled with "X" and "Y" (and shaded) only. Most importantly, the APC must honor how the operators run the unit. The functionality of the controller can be summarized as follows:

- The pressure is regulated by the pressure valve PIC001.OP and the drain valve LIC001.OP. The regulatory performance of the controller is far better than that of the PID. It takes into account of the interactive effects of the two valves and the feed-forward information of the crude feed.
- The interface level LIC001.PV is regulated by the two drain valves LIC001.OP & LIC002.OP.
- The interface level LIC002.PV is regulated by the drain valve LIC002.OP and wash water flow.
- The interface level's readings LIC001.PV & LIC002.PV are not reliable. The operators manually recalibrate them, and these recalibration information is made available to the controller when it becomes so. The controller must the operators to take care of adjustment when the recalibration is done.
- With the help from experienced operators, the constraints of all MVs are set up just like the way the operators will run the unit.

After the APC commissioned, the regulatory performance of the pressure is drastically improved as illustrated in Figure 5. The black curve represents the pressure; whereas the blue and the red curves represent the corrected interface levels LIC001.PV and LIC002.PV respectively.

According the technical manager, the averaged crude feed rate turns out higher than before the commissioning the APC. The feed rate in fact is set unchanged before and after the APC. The crude feed rate averages higher because of less furnace upsets. The furnace upset mainly results from the wash water carry-over. A steady desalter pressure prevents the furnace upset from happening.

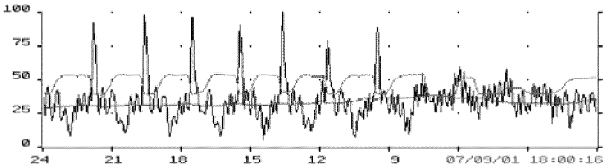

Figure 5: The performance of the APC.

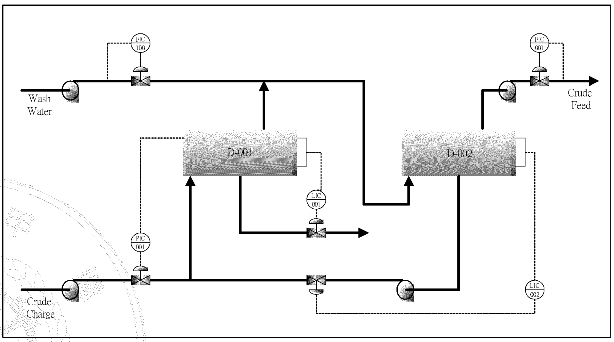

Figure 6: The process flow diagram of the desalters.

## 5 References

[1] Camacho, E.F. & Bordons, C. (1995). "Model Predictive Control in the Process Industry (Advances in Industrial Control)," Springer Verlag.

[2] Marari, M. & Zafiriou, E. (1987). "Robust Process Control," Pearson.

[3] Seborg, D.E., Edgar, T.F., & Duncan, A. Mellichamp, D.A. (2003). "Process Dynamics and Control," Wiley.

[4] Shinskey, F.G. (1996). "Process Control Systems: Application, Design, and Tuning," McGraw-Hill.

[5] Su, H. T. (2003). "Practical Methodology of Advanced Process Control," Process Systems Engineering Conference 2003, Taipei, Taiwan.