Understand Advanced Process Control

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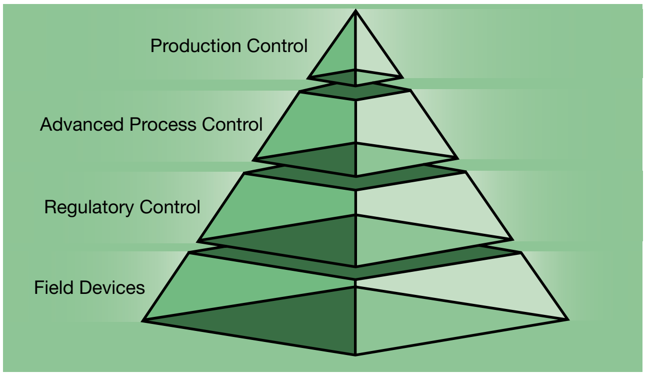
Multivariable processes are controlled by a hierarchical structure of control layers. Field devices and regulatory controls manage individual variables, while advanced process control and production control systems coordinate multiple variables to optimize operation.

Process control can be represented as a hierarchy (Figure 1). The base of the structure is comprised of field devices such as sensors, transmitters, actuators, and valves that measure process variables and implement control actions. Next are regulatory controllers, which keep values measured by field devices, such as pressure, temperature, and flowrate, within specified limits. While regulatory controls tackle each variable individually, the advanced process control (APC) layer evaluates a set of variables, and considers how each one relates to the performance of an entire process unit. However, running a single unit at its local optimum is not necessarily the best strategy for achieving overall profitability of the facility. This is where the production control layer steps in to manage the individual units' APCs in concert to accomplish plantwide optimization.



▲ **Figure 1.** Process control consists of four tiers: field devices, regulatory control, advanced process control (APC), and production control.

From field devices to production control, each layer depends on the previous layer in the hierarchy. The control performance of an individual layer directly affects the stability of the process, the quality of the product, and the costs associated with making the product. This article describes the hierarchical structure in more detail, and explains how model predictive control (MPC) fits into the APC process control layer.

Regulatory control: Managing individual variables

The basic building block of any control system is the regulatory control loop, which consists of three essential pieces:

• *an instrument* (or calculation) that provides a measure of some process variable (PV) to be controlled, called the control variable (CV). The CV could be a level, temperature, or flowrate, or something more complex, such as a Kappa number (*i.e.,* a measure of the lignin content remaining in wood pulp).

• *a controller* (or control algorithm in a distributed control system [DCS]) that targets the desired value of the CV, called the setpoint (SP). Relative to the SP, the controller calculates a compensating control move, or output (OP), and sends that signal to the control actuator. The variables affected by the control move are called manipulated variables (MVs).

• *a control actuator* that implements the control move received from the controller in the process. Control actuators are often valves; other common actuators include louvers and variable-frequency drives on pumps.

Regulatory control loops maintain each control variable at its setpoint to minimize variability if and when conditions change. Regulatory control loops can be broadly classified as either feedback or feedforward.

Feedback control. In feedback control, the controller compares the measured control variable to its setpoint, and computes a compensating move based on the deviation between the actual (CV) and the desired (SP) values. Think about feedback control — only responding to an error after it happens — like driving while looking in the rearview mirror; only after the car is in the ditch can a correction be made to get back on the road again.

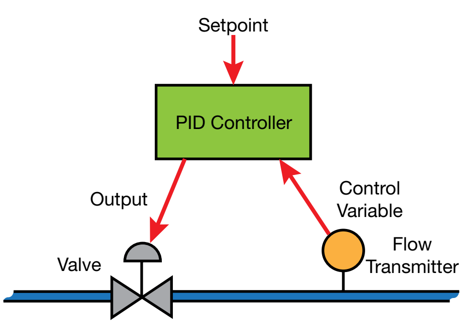
Feedforward control. In addition to monitoring the CV, the controller measures a disturbance variable (DV), such as a change in load, and tries to predict the effect this change will have on the CV. This requires prior knowledge of the process response patterns. Unlike feedback control, which compensates for errors after they occur, feedforward control aims to combine feedback with another process signal to minimize errors and compensate as they happen.

PID control

The most common type of regulatory controller is the proportional-integral-derivative (PID) loop (Figure 2). There are an estimated 5 billion control loops running a PID algorithm throughout the world. (Read the Back to Basics series "PID Explained for Process Engineers," *CEP*, Jan. 2016, pp. 37–44, Feb. 2016, pp. 27–33, and Mar. 2016, pp. 51–58, for more details.)

PID refers to the way the control problem is solved within the controller. Each term corrects a different type of potential disturbance.

A proportional (also called proportional band or gain) control move is calculated directly from the current error signal (the difference between CV and SP) multiplied by the proportional coefficient. It does not consider past error, but only the error in the current cycle.



▲ **Figure 2.** The PID control block compares the user-specified setpoint (SP) to the control variable (CV) measured by instrumentation, such as a flow transmitter, and provides an output (OP) that manipulates the process, such as opening or closing a valve.

Integral (or reset) control acts on accumulated error over multiple cycles. The longer the CV is out of specifications (above or below the SP), the more integral action is applied.

Derivative (or rate) control evaluates the rate of change of the error from the last cycle to the current cycle. The larger the rate of change is in the undesired direction, the more control action is applied. Derivative action is generally used sparingly because it can introduce variability.

In every PID cycle, the CV is compared to the SP, and then the proportional, integral, and derivative elements are combined to calculate the move (OP) to be sent to the process. The combination of proportional, integral, and derivative factors is determined by the type of control block used, which depends on the control infrastructure (*e.g.,* DCS). For example, a standard PID block adds the contributions of proportional, integral, and derivative to the OP signal, but a PID Gap control block allows for tuning within a user-specified range around the SP.

Advanced regulatory control

The regulatory control layer includes a series of technologies collectively referred to as advanced regulatory control (ARC). It consists of some combination of PID loops that provide enhanced stability and disturbance rejection, and it may include feedback and feedforward approaches. These control schemes can typically be implemented directly in the DCS and do not require additional hardware or software.

ARC is sometimes placed under the umbrella of APC. However, although ARC is an important step toward enhanced control, it lacks the multivariable and model-based aspects that distinguish APC.

Advanced process control: Optimizing an entire process unit

APC is an intelligent and active software layer above the regulatory control layer that treats an entire process unit as a single, multivariable system and corrects for predicted future errors using an empirical linear model. The addition of APC to a process reduces variability, thereby improving process stability, which enables operation of the process unit closer to its specification limit — the point at which the process is most profitable.

To continuously maximize the efficiency of a process unit, APC uses dynamic models of the process that show how a manipulated variable affects the control variable over time. APC coordinates and decouples these effects while keeping the unit within its defined operating window. Many APC controllers include an integrated optimizer that pushes the process unit toward its most profitable state by solving for the maximum value of all economic variables in each iteration.

APC has four significant features. It is:

• multivariable — which helps coordinate and decouple the effects of interactions among multiple process variables

• model-predictive — MPC uses dynamic models to predict process behavior in the future, and this information is then used to proactively control the process and correct for future errors

• constraint-aware — monitoring and maintaining MVs and CVs within limits

• optimized — integrating optimization capabilities to drive applications toward specified design objectives.

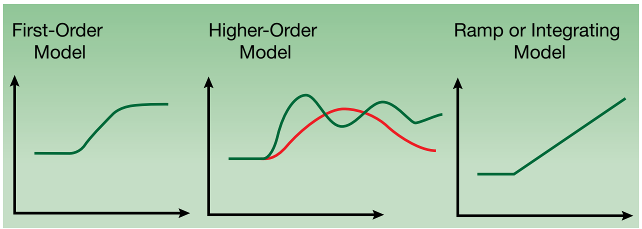
Model predictive control

MPC is an advanced, optimization-based control strategy applicable to a wide range of chemical process industries (CPI) applications. It is a multivariable strategy that encompasses constraints, actuators, process states, process outputs, and other variables.

If feedback control is like driving while looking in the rearview mirror, MPC is like looking out the windshield. However, the accuracy of MPC is only as good as the model. Low-quality models can point you in the right direction, but high-quality models enable benefits such as enhanced optimization and better insight into the process. MPC in combination with quality models enables the controller to correct for errors before they occur.

MPC employs dynamic models to capture and control complex interactions among process variables. The three general types of models used for simulating a process are: first-order, higher-order, and ramp or integrated (Figure 3). Models are selected based on step-testing, which involves making a succession of step-changes to an MV, measuring how the process responds, and generating a control matrix (Figure 4).

Although step-testing was once performed manually, automated stepping software that incorporates decades of experience is now available. The software automates many tasks that were once manual, including stepping the process, collecting data, identifying models, and validating models. The software even makes it possible to conduct these tasks



▲ **Figure 3.** First-order models have a simple and predictable response, whereas second- and higher-order models can have multiple peaks and valleys. Ramp or integrating models imitate the level of a tank: if the input and output flows are equal, the tank level remains constant, but if there is a disparity, the tank will overflow or empty.

The addition of APC to a process reduces variability, thereby improving process stability. This enables the process unit to operate closer to its specification limit.

while an MPC application is controlling the process, which enables step-testing with less impact on process operation and stepping while the process is being controlled.

The final dynamic models are the heart of an MPC application. Measurements of CVs and DVs are sent to the controller, which uses this information to optimally control the process unit. Changes to the MVs are generated based on the dynamic models, established setpoints or ranges, and optimization parameters such as pricing or cost data. These changes are then passed along to the regulatory control system.

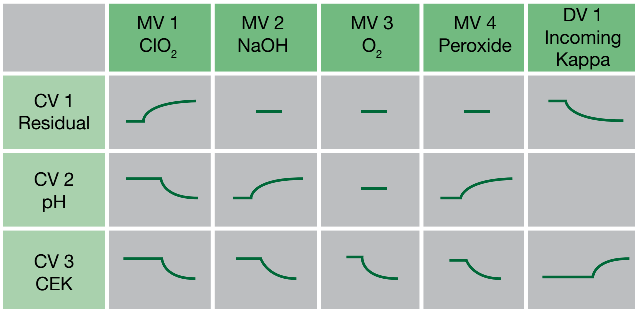
Deployment and challenges

Over the past 25 years, APC has been applied successfully in a variety of process industries, where it has:

• increased throughput and improved yields
• reduced energy consumption and operating costs
• ensured consistent product quality
• provided operational flexibility
• improved process stability.

APC is suitable only for units that are operated as continuous processes, such as fluidized beds, boilers, and distillation columns. For example, in a pulp mill, APC could be implemented across the continuous digesters, thermomechanical pulping systems, brown stock washers, oxygen delignification units, bleach plants, evaporators, recovery boilers, lime kilns, and causticizing plants. However, APC could not be used for batch digesters, which require a different type of control strategy.

A prerequisite to any APC deployment is to ensure that



▲ **Figure 4.** In this dynamic model control matrix for a pulp-mill bleaching unit, an increase in peroxide has no effect on the residual, a positive effect on pH, and a negative effect on the caustic extracted Kappa (CEK). Similarly, an increase in caustic (NaOH) has no effect on residual, but increases pH and reduces CEK. A model-based controller uses these relationships to predict future errors and calculate the optimum response.

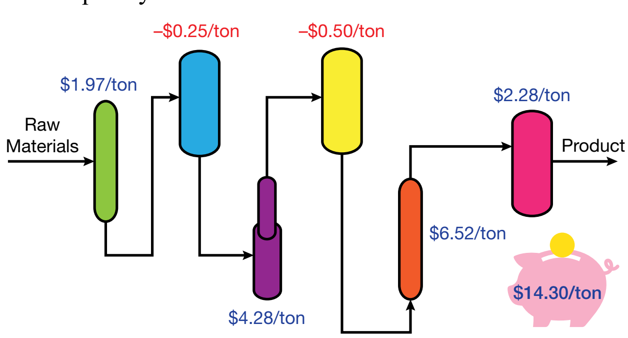
the field devices and the regulatory controllers are functioning optimally. Tuning the existing instrumentation, valves, controllers, and control infrastructure to their optimal performance setting can yield substantial performance and optimization gains even before APC is implemented.

A comprehensive plantwide performance audit that identifies key optimization areas and provides an estimate of target values (*e.g.,* savings, emissions) can reveal where APC can be deployed and where it would have the biggest and most immediate impact on plant operation. These may include relieving production bottlenecks and focusing on specific external or internal challenges, such as raw material and/or chemical savings. The project team then implements APC solutions in other areas of the plant to achieve the targets identified during the audit.

Operator acceptance is often one of the main hurdles APC implementation teams encounter. Operators have to relinquish control to the intelligence embedded within the system and accept changes that affect established procedures. It is important to involve plant personnel early and ensure they receive the training necessary to effectively work with the new system. Operator skill level is a key factor in the long-term success of an APC system.

If not properly monitored and maintained, APC applications may degrade in a short period of time and yield only minimal benefits. Equipment modifications, operating strategy changes, feedrate and quality variations, instrumentation degradation, and fouling affect process units over time and can contribute to a decline in the regulatory and economic performance of an APC system.

Issues related to how operators interact with the APC system may arise. Many plants fail to monitor APC controller uptime, which can reveal instances of operators turning off a controller during an abnormal situation they do not know how to handle. Plants may also mistakenly assume that APC controller uptime indicates that the controller is running at its original design specification. If operators are not adequately trained to understand how a multivariable controller functions, they may reduce the available control range of the manipulated variables, eliminating opportunities to optimize the process.



▲ **Figure 5.** The production control layer coordinates multiple APCs to control the entire plant as a single entity. Optimum operation of a single unit does not necessarily benefit the entire process. It may be better to run some units below their optimum point to obtain a larger overall benefit.

There are three common approaches to monitoring APC functionality and ensuring its benefits are sustained:

• designate an onsite engineer to manually monitor the APC system and how it is being used

• employ an external partner to provide monitoring and diagnostics and to help sustain the benefits of APC

• for the highest degree of automation, purchase dedicated control performance monitoring (CPM) software to handle the task of monitoring and sustaining the APC assets.

Production control: Pulling it all together

At the top of the process control hierarchy is production control, which focuses on optimizing the entire process plant or line (Figure 5). Optimization has traditionally been limited to individual unit operations, which yields benefits but does not necessarily represent the best operational scheme for the entire plant.

As APC is implemented in various units, the need to coordinate the controllers becomes more apparent. With conventional control applications, overall coordination of plant operations is typically accomplished manually using a planning and scheduling tool; plant operators move the process to the new steady-state operating point and maintain it at those conditions. Production control looks at the entire manufacturing process to ensure the correct amount of product is produced, at the optimum quality level, and on schedule for delivery to the customer.

However, coordinating these three goals is far from simple, and can be further complicated by variations in energy costs, material prices, and markets. The technology and framework to solve this problem has been pursued for decades, and finally industry is on the brink of a commercially viable approach. To be feasible, production control must take into account the limitations of the underlying process to calculate a solution that can actually be achieved without overstressing equipment or attempting to bend the laws of physics. New methods of solving this problem are emerging, providing dynamic coordination of multiple units to maximize profits, manage constraints, and minimize energy requirements. CEP

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