CHAPTER

ADVANCED PROCESS CONTROL SYSTEMS

19

19.1 INTRODUCTION AND NEED FOR ADVANCED PROCESS CONTROL (APC)

Control designs in the process industry are almost exclusively based on PID controllers these days. Even though they are simple to implement and easy to integrate into a control system, these feedback control strategies have their inherent drawbacks of dead time (lag in system response to changes in set point). Although feed forward control avoids the slowness of feedback control, the effects of disturbances should be perfectly predicted for them to be effective. However, most of the complex processes have many variables that are to be regulated and have multiple control loops. These multiple control loops often interact, causing process instability. Thus, the traditional feedback and feed forward control strategies quickly reach their limits when more complexity is involved. Advanced Process Control or APC opens up new opportunities at this juncture.

The area where APC applications operate is described in Figure 19.1.

With APC, even complex situations can be mathematically described with process parameters or variables and then used for automatic and flexible plant operations. APC provides process management that can significantly reduce the consumption of energy and raw material, consistently maintain high quality standards, and contribute to more flexible production.

19.2 HISTORY OF PROCESS CONTROL

A brief look into the history of process control will show the significance of APC.

By mid 1950s, process sensors, pneumatic transmission of process data, pneumatic controllers, and valve actuators had become highly developed forms of automated control. Through these technologies, significant savings in operations were achieved. During this period, process analyzers for on-stream analysis became available providing operators with more specific and timely information than just process flows, temperatures, pressures, and levels. The classical control theory began to be developed by academic institutes and the major control companies.

From the late 1950s to the early 1960s, electronic instrumentation involving electronic transmission and control became more prevalent. The instrument industry held heated debates on the relative merits of electronics versus pneumatics. Some standardization was achieved while instrument vendors championed their own systems. Also, data logging was introduced.

The appearance of low-cost digital mini-computers in the early 1960s brought about a significant milestone – the use of digital computers to control refineries and chemical plants. Joined development efforts between major users and instrument and computer companies were undertaken and computer control systems software began to evolve rapidly.

Optimizations

Optimization	Local LP/QP optimization	Multi unit LP/QP optimization	Rigorous model-based optimization
Model-based control	Smith predictor, IMC, etc.	Multivariable control	
Advanced control	Feed forward control	Dynamic decoupling	Online analyzers, constraint control
Regulatory control	Single PID	Cascade control	

Different technologies at different levels

FIGURE 19.1 Different technologies at different levels

By mid 1960s to mid 1970s, electronic analog instrumentation became prevalent due to its ability to meet industry requirements and provide reliable computer backup and interface to the process. But, the shift from analog to digital was already underway. Visionaries saw that Distributed Control System (DCS) could place multiple loops under one computer chip and implement operator communications through an electronic data highway rather than dedicated panel instruments.

While the hardware as well as operating system software for implementing process control was of primary importance to the success of projects, it was applications and process control strategies that reaped the major economic benefits. Process Control practitioners in the refinery and chemical industry recognized that the control concepts of the period generally outplaced the practical implementation and that much of the theory was difficult to apply to real process. The most prevalent reasons for lack of practical implementation were:

- Lack of understanding of the process
- Strong interactions among variables
- Process nonlinearity
- Few accurate mathematical models.

However, as practitioners in the industry gained experience with computer control of commercial plants, the incentives were recognized and realized. These incentives derived from:

- Improved regulatory and advanced control
- Better understanding of process dynamics and unit operations
- Operating closer to constraints
- Finding the most profitable operating conditions.

With feed forward and interactive controls, the relationships between different variables had become much more complex and far less apparent.

With the advent of much more powerful microprocessors in the late 1970s and early 1980s, the architecture of the microcomputers at the bottom performing repetitive, simple operations and the host computer at the top doing the complex calculations requiring a lot of number crunching power became the backbone of most subsequent computer control installations. By the late 1980s, multivariable model-based predictive controllers enabled control in a single program. With predictive capability, a controller can make the moves necessary to precent any constraint violation before it occurs, rather than reacting after the fact as PID controllers are forced to do. Increasingly, plant testing of process response dynamics to develop and improve the multivariable control models became a strong priority.

By the mid 1990s, essentially every refinery was using LP (Linear Programming) or other simulation models for off-line business optimization and to provide volumetric signals or guidance for raw material selection, operating throughputs and intensities, and desired product slates. By 1995, the technology was working better due to the emergence of the larger model-based multivariable predictive controllers that used the actual plant test data to simulate plant dynamics. Many companies were switching to these multivariable controllers and deactivating some of their single-loop advanced controllers. These large model-based controllers could just manage the dynamic complexities and interactions much better and with some synergy. These predictive controllers were installed on an outboard computer to the DCS and deactivated many loops in the DCS.

19.3 ADVANCED PROCESS CONTROL

Advanced Process Control (APC) is a broad term composed of different kinds of process control tools for solving multivariable control problems or discrete control problems. APC draws its elements from many disciplines ranging from Control Engineering, Signal Processing, Statistics, Decision Theory, and Artificial Intelligence.

Few different process control tools involved in APC are:

- Model Predictive Control (MPC)
- Statistical Process Control (SPC)
- Run2Run (R2R)
- Fault Detection and Classification (FDC).

Some of these are briefed in the sections below.

19.3.1 MODEL PREDICTIVE CONTROL

Model Predictive Control or MPC is an advanced method of process control that has been in use in the process industries such as chemical plants and oil refineries since the 1980s and has proved itself. Model Predictive Controllers rely on the dynamic models of the process, most often linear empirical models obtained by system identification.

MPC possesses many attributes that make it a successful approach to industrial control design:

- Simplicity: The basic ideas of MPC do not require complex mathematics and are "intuitive."
- Richness: All of the basic MPC components can be tailored to the details of the problem in hand.
- Practicality: It is often the resolution of problems such as satisfying control or output constraints, which determines the utility of a controller.
- Demonstrability: It works! – as shown by many real applications in industry where MPC is routinely and profitability employed.

While MPC is suitable for almost any kind of problem, it displays its main strength when applied to problems with:

- A large number of manipulated and controller variables.
- Constraints imposed on both the manipulated and the controlled variables.
- Changing control objectives and/or equipment (sensor/actuator) failure.
- Time delays.

MPC models predict the change in the dependent variables of the modeled system that will be caused by changes in the independent variables. In a chemical process, independent variables that can be adjusted by the controller are often either the set points of regulatory PID controllers (pressure, flow, temperature etc.) or the final control element (valves, dampers, etc.). Independent variables that cannot be adjusted by the controller are used as disturbances. Dependent variables in these processes are other measurements that represent either control objectives or process constraints. MPC uses the current plant measurements, the current dynamic state of the process, the MPC models, and the process variable targets and limits, to calculate future changes in the independent variables. These changes are calculated to hold the dependent variables close to target while honoring constraints on both independent and dependent variables. The MPC typically sends out only the first change in each independent variable to be implemented and repeats the calculation when the next change is required.

19.3.1.1 Linear MPC

While many real processes are not linear, they can often be considered to be approximately linear over a small operating range. Linear MPC approaches are used in the majority of applications with the feedback mechanism of the MPC compensating for prediction errors due to structural mismatch between the model and the process.

Theory behind MPC

MPC is based on iterative, finite horizon optimization of a plant model. At time t, the current plant state is sampled and a cost-minimizing control strategy is computed (via a numerical minimization algorithm) for a relatively short time horizon in future: $[t + T]$. Specifically, an online or on-the-fly calculation is used to explore state trajectories that emanate from the current state and find a cost-minimizing control strategy until time $t + T$. Only the first step of the control strategy is implemented, then the plant state is sampled again, and the calculations are repeated starting from the now current state, yielding a new control and new predicted state path. The prediction horizon keeps being shifted forward, and for this reason, MPC is also called *Receding Horizon Control*. Although this approach is not optimal, in practice it has given very good results.

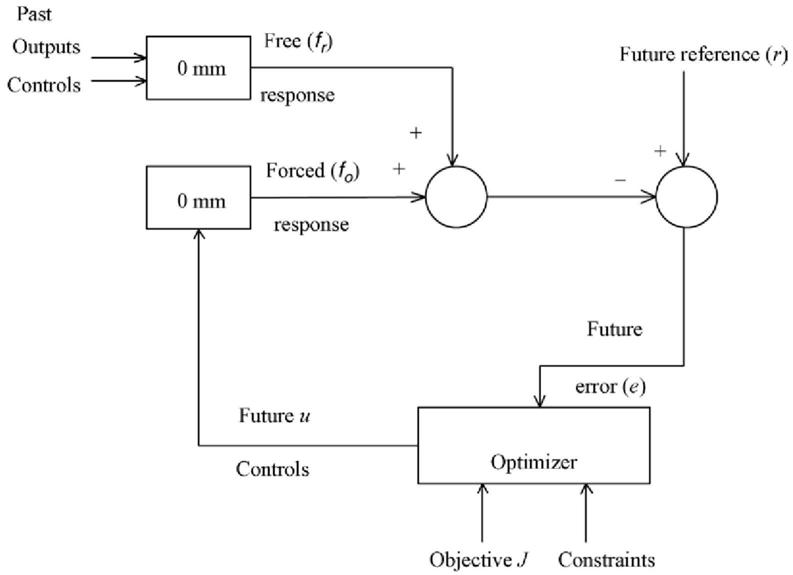

FIGURE 19.2 Principle of MPC Controller

Principles of MPC

MPC is a multivariable control algorithm that uses:

- An internal dynamic model of the process
- A history of past control moves
- An optimization constant J over the receding prediction horizon.

A conceptual diagram illustrating the principles of an MPC controller described above is shown in Figure 19.2.

The heart of the controller is a model M(θ), parameterized by a set θ, which is used to predict the future behavior of the plant. The prediction has two main components: the free response (f_r), being the expected behavior of the output assuming zero future control actions, and the forced response (f_o), being the additional component of the output response due to the "candidate" set of future controls (u). For a linear system, the total prediction can be calculated as $f_o + f_r$.

The reference sequence (r) is the target values the output should attain. The future system errors can then be calculated as $e = r - (f_o + f_r)$, where f_o, f_r, and r are vectors of the appropriate dimensions.

An optimizer having a user-defined objective function $J(e,u)$ is used to calculate the best set of future control actions by minimizing the objective function, $J(e,u)$. The optimization is subject to constraints on the manipulated variables (MVs) and controller variables (CVs).

What makes MPC a closed-loop control law is the use of the receding horizon approach. This implies that only the first of the set of control actions, u, is transmitted to the plant, after which the complete optimization and prediction procedure is repeated using the current plant output.

19.3.1.2 Nonlinear MPC

Nonlinear Model Predictive Control (NMPC) is a variant of MPC that is characterized by the use of nonlinear system models in the prediction. As in linear MPC, NMPC required iterative solution of optimal control problems on a finite prediction horizon. While these problems are convex in linear MPC, in NMPC they are not convex anymore. This poses challenges for both NMPC stability theory and numerical solution.

19.3.2 STATISTICAL PROCESS CONTROL (SPC)

Statistical Process Control (SPC) is the application of statistical methods to the monitoring of a process to ensure that it operates at its full potential to produce conforming product. Under SPC, a process behaves predictably to produce as much conforming product as possible with the least possible waste. While SPC has been applied most frequently to controlling manufacturing lines, it applies equally well to any process with a measurable output. Key tools in SPC are control charts, a focus on continuous improvement, and designed experiments.

19.3.2.1 Concept

No matter how tightly controlled and well run a process is, variations exist in the quality of the resulting product. It is important to evaluate these variations to determine if the resulting product characteristics are within acceptable quality limits.

The causes of variations can be separated into two distinct classes. Some variations are inherent in the process itself and can be called normal (sometimes also referred to as common or chance). Other variations can be attributed to “special causes” that are outside of the process. Possible “special causes” could be improperly calibrated instruments, insufficient training, outdated reagents, etc. As these “special causes” of variations are detected, procedures can be developed and implemented to ensure that these do not continue. SPC allows us to detect when these few special causes of variation are present. Once removed, the process is said to be stable, which means that its resulting variation can be expected to stay within a known set of limits, at least until another special cause of variation is introduced.

SPC techniques use random sampling and statistical analysis instead of continuous monitoring to determine, with almost complete confidence, whether the variation is due to the process itself or due to special causes. When SPC techniques are used, the frequency and timing of measurement testing are usually defined by a statistician.

19.3.2.2 Advantages

Much of the power of SPC lies in the ability to examine a process and the sources of variation in that process using tools that give weight to objective analysis over subjective opinions and that allow the strength of each source to be determined numerically. Variations in the process that may affect the quality of the end product or service can be detected and corrected, thus reducing waste as well as the likelihood that problems will be passed on to the customer. With its emphasis on early detection and prevention of problems, SPC has a distinct advantage over other quality methods, such as inspection, that apply resources to detecting and correcting problems after they have occurred.

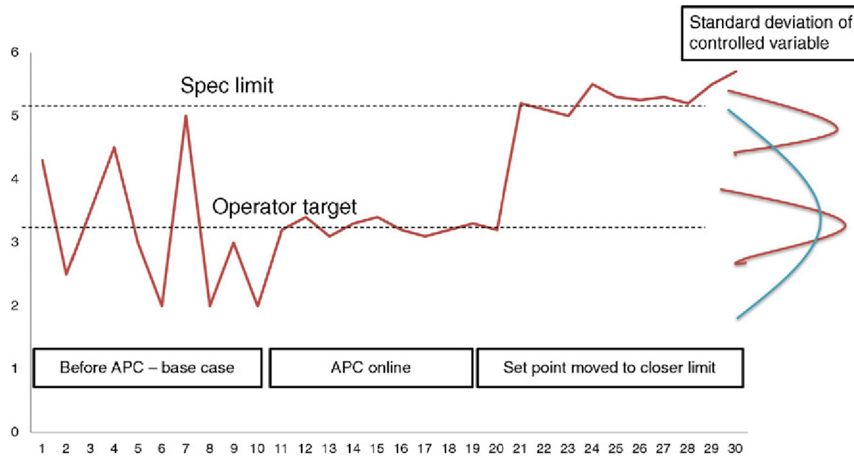

FIGURE 19.3 Sample benefits of APC

19.4 ADVANTAGES OF APC

Typical benefits of APC are improved bottom line results including:

- Efficiency gains
  - Increased yield
  - Increased throughput
  - Reduction in energy and raw material per unit of product
  - Decreased operating costs
- Quality gains
  - Consistent product quality
- Agility gains
  - Increased operating flexibility
  - Improved process stability

By implementing APC, benefits ranging from 2% to 6% of operating costs have been quoted. These benefits are clearly enormous and are achieved by reducing process variability, hence allowing plants to be operating to their designed capacity (Figure 19.3).

19.5 ARCHITECTURE AND TECHNOLOGIES

Many leading companies recognize that APC applications can produce significant improvement in control of complex processes, particularly those with long dead/lag times, interacting loops, highly constrained operations, or inverse response. Historically, APC implementation required very specialized skill-sets and experienced resources to implement and maintain – limiting use of the technology to only very large refineries or petrochemical plants that could justify such an expense. New embedded APC tools offered by some automation suppliers are starting to change this situation. Ease-of-use features designed into these tools aim to make APC blocks almost as easy to use as a PID loop.

A worldwide survey conducted by Qin and Badgewell showed that, of the roughly 2200 installations surveyed, over 82% of all APC applications were implemented in the refining and petrochemical industries and the majority of these applications were in large facilities of the major refineries.

Traditional APC technology is usually implemented in a supervisory architecture similar to that depicted in Figure 19.4.

In this environment, the APC applications are executed in a separate computer interfaced by some means to a DCS. The APC application will calculate the moves required, which are sent to the DCS that

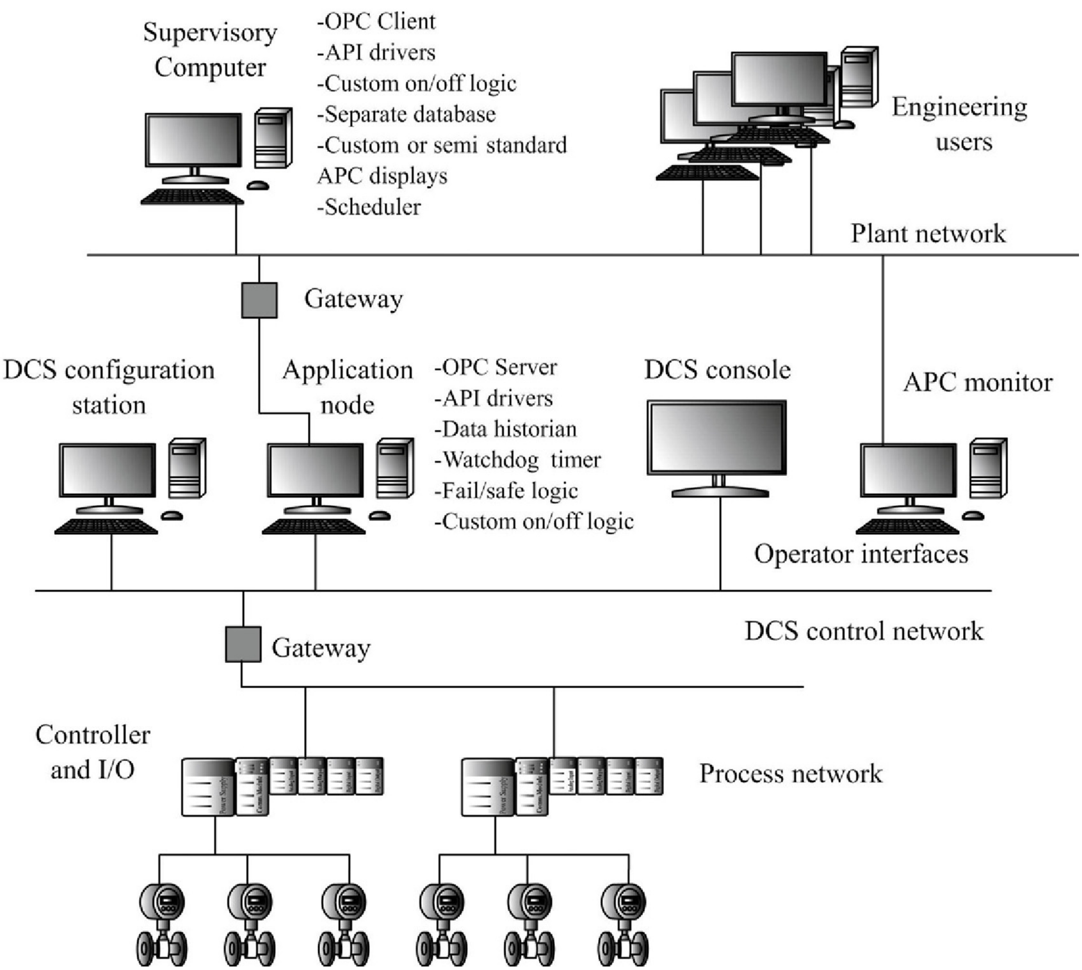

FIGURE 19.4 Typical architecture of automation system

performs the basic control functions through the regulatory controllers and field IOs. In many cases, the DCS and APC systems are interfaced via the industry standard OLE for Process Control (OPC) protocol.

The supervisory system usually has its own user interface, DCS drivers, database, scheduler, and tag synchronization issues. Usually, at least some level of custom programming is required in the DCS to provide the operator on/off functions, fail-safe logic, and watchdog timer functions. Step-testing the process often required 24-h engineering coverage for days or weeks at a time. Furthermore, APC applications historically required very experienced consultants with specialized skills to implement and maintain. As a result, only the largest process with the biggest potential benefits could afford to implement these technologies.

Unfortunately, a significant portion of APC applications implemented over the years have been turned off within a few years after commissioning. The major reasons for this step are:

- Regulatory control problems – The basic regulatory loops must work well before an APC application has any chance of success. Malfunctioning valves, poor tuning, and controllers in manual can cause APC performance to deteriorate.
- Process changes – Any change to the process that affects the controller design or significantly changes the dynamics or gain of the process models will require additional work to update the APC application.
- New constraints or limits – Process or equipment limits that were not considered in the original control design must be incorporated into APC strategy.
- Different control objectives – Sometimes the process operation objectives change from the original design due to changes in economics, feeds, constraints, or operating conditions.
- Controller requires restepping process – Any time process dynamics change significantly, the process needs to be restepped and the models refit to reduce model errors. This can be an expensive and time-consuming process.
- Applications not maintained – Applications need to be continually revised to stay up with the latest operating systems and software versions. Once the applications get too far out of date, it becomes prohibitive to upgrade them without significant investment.
- Lack of operator training – If the operators do not understand what the APC controller is doing, it will get turned off. It is important that operators are properly trained on APC technology and advanced control strategies to ensure uptime is maintained.
- Budget constraints – Many a times, software maintenance is not budgeted like other equipments in the plant. Also, the cost to hire APC experts to redesign, reconfigure, step-test, model, update documentation, and recommission an existing APC application can be almost as much as the original engineering services.

With the advent of new embedded APC tools, many of these problems go away. Embedded APC functions eliminate the need of a separate supervisory system and all the extra databases and programming that go along with it. The new tools are just part of the automation architecture – like a PID block – completely removing a whole layer of complexity in systems, software, databases, and interfaces.

Under the new architecture, APC functions can be distributed and executed on multiple controllers or application stations running on the native control system bus as in the architecture shown in Figure 19.5.

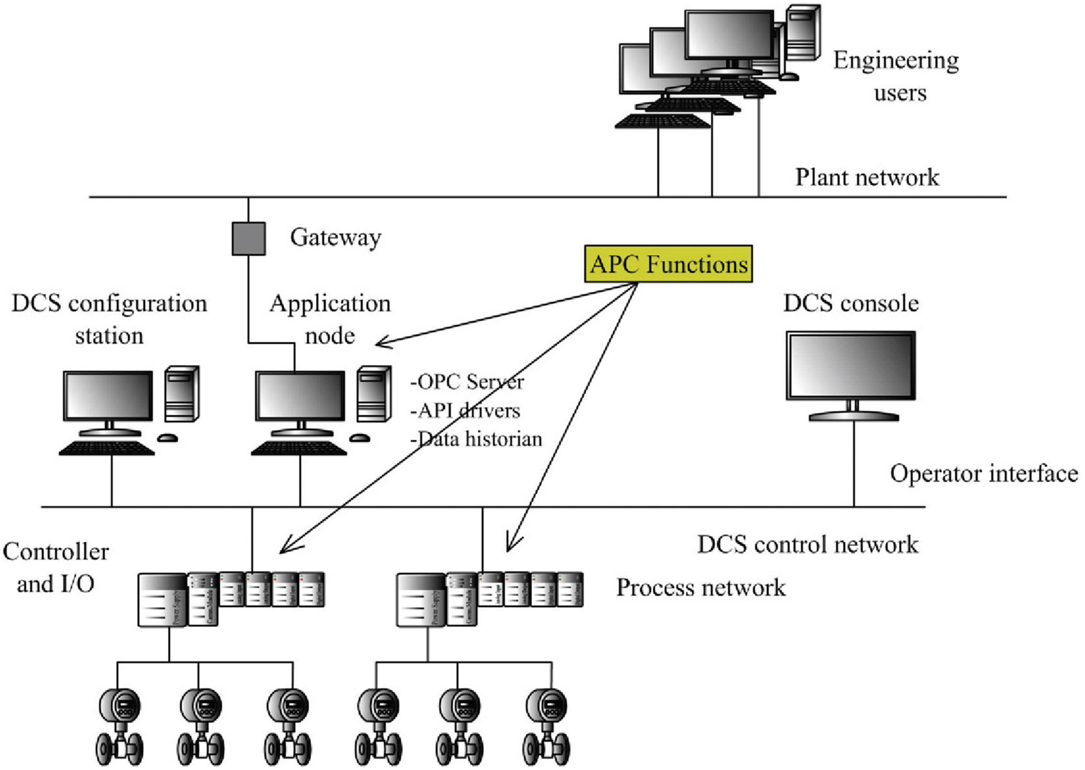

FIGURE 19.5 Embedded APC in new architecture

As a result, the effort to implement and maintain these applications is dramatically reduced. With these new systems, there are:

- No extra databases to maintain on the supervisory system.
- No database synchronization issues as points are added, changed, or recalibrated.
- No watchdog times required to confirm that the APC application is still working.
- No controller fail/shed logic design to automatically handle failure of an APC application.
- No interface configuration or programming to communicate between the DCS and the supervisory computer.
- No separate operator interface monitors or custom graphics for the APC functions.

A few vendors offer embedded APC tools that can run entirely in automation system controllers, in a high-speed, robust, and redundant environment. This architecture opens the technology to a whole new class of control problems, including those with very high-speed dynamics or applications that need to output directly to a valve instead of a PID controller set point.

FURTHER READINGS

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