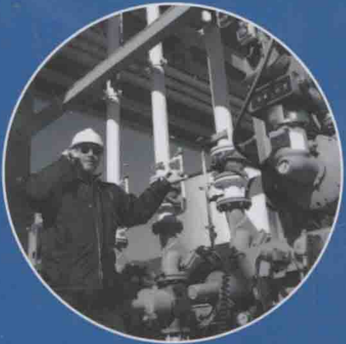
ADVANCED PROCESS CONTROL

Beyond Single Loop Control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ADVANCED PROCESS CONTROL

Beyond Single-Loop Control

Cecil L. Smith

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ADVANCED PROCESS
CONTROL

PREFACE

Exactly what is advanced process control? My favorite definition is from an attendee to a continuing education course: Advanced control is what we should be applying in our plants but are not applying, for whatever reason. This definition lacks specificity, but it does reflect the reality that what seems advanced to some does not seem advanced to others.

To be categorized as advanced, a control configuration must have at least one of the following attributes:

- It relies on more than one measurement.
- It drives more than one final control element.
- It incorporates a process relationship of some form (which may be as simple as a characterization function).
- It incorporates functions such as constraint control that are intended to optimize process operations.
- It addresses interaction between process variables.
- It is beyond the capabilities of a technician (or at least all but the best of them).

One possible definition is anything other than simple feedback control, which is understood to be a configuration consisting of three elements:

- A final control element
- A PID controller that generates the output to the final control element
- A measurement device that provides the process variable input to the PID controller

If simple feedback control provides the required performance, it should definitely be used. Going beyond simple feedback control always incurs costs that must be justified by the returns from the improved performance. Advanced control should be pursued only when the improved performance translates into enhanced process performance.

Cascade is a good example of the difficulty of defining advanced process control. To most, a level-to-flow cascade is only slightly above simple feedback control on the scale of sophistication. Few would consider these to be advanced control. But consider a temperature-to-temperature cascade applied to a process consisting of interacting stages (as are most temperature processes). Most find these quite challenging and beyond the capabilities of all but the most experienced technicians. Given the importance of temperatures to process operations, arguments can be made to include such cascades in the advanced control category.

The term *advanced control* is sometimes used to refer to some form of model predictive control (MPC) technology. Model predictive control is definitely advanced control; however, other control technologies deserve to be included in the advanced control category.

The focus of this book is process control, not process safety. Process control must operate the process in the most effective manner, which often leads to considerable complexity. Process safety must avoid unsafe process operating conditions, usually by initiating a shutdown or trip. Although these two are largely separate issues, one requirement must be imposed on the process controls: The process controls must not take any action that would necessitate a reaction from the safety system. Such trips are unnecessary trips and must not happen.

In the process industries the P&I diagram is used almost universally to present the control configuration. This representation encompasses all normal control functions. But for smooth operations, the following requirements must be addressed:

Bumpless transfer. For control configurations that generate multiple outputs, an "all or none" option is not acceptable. The operators must be able to assume control of an individual output at any time. This must not in any way disrupt the other functions being provided by the control configuration. When the manually controlled output is returned to automatic control, there must be no abrupt change in the value of the output (or in any other output from the controls).

Windup protection. When the output of a PID controller ceases to affect its measured variable, the reset mode will drive the controller output to a limit. This is windup. Subsequently, the controller must "unwind," and this is where the consequences appear. A common cause of windup is when a limiting condition has been attained. Limits apply to all process control applications, the simplest manifestation being a fully open or fully closed valve. However, limits can arise within the process, a common example being heat transfer limiting conditions.

Addressing these issues is often as challenging as developing the configuration for the normal control functions. This book gives such topics appropriate attention.

What if these issues are ignored? Consequences that surface during periods of normal control activities are usually considered to be nuisances that the operators can easily handle (we say that the control configuration has some "warts"). Unfortunately, consequences are most likely to appear during process upsets when the operators are very busy. What would otherwise be a nuisance becomes a distraction that takes the operator's attention away from more pressing matters. Given the "right sizing" of operations staffs, such distractions become serious matters.

This is one aspect that commercial model predictive control packages generally address quite well. Most permit operators to assume control of any output without disrupting the remaining functions. Limiting conditions can be imposed on the outputs, on dependent variables, and so on. That such factors have received appropriate attention has certainly contributed to the success of these packages.

This book also reflects the "You have to understand the process" philosophy that dates from my early years in this business. Process control is appropriately a part of chemical engineering, and those with a process background have made important contributions to the advancement of process control. Even though model predictive control relies on certain principles of linear systems theory, those who pioneered the initial applications were firmly rooted in the process technology.

I am a firm proponent of the time domain. Absolutely no background in Laplace transforms is required to understand the presentations in this book. The word "Laplace" is not mentioned outside this preface, and the Laplace transform variable s is not used anywhere. I firmly believe that Laplace transforms should not be taught in a process control course that is part of the undergraduate chemical engineering curriculum.

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Taos, NM
September 24, 2009

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1

INTRODUCTION

The vast majority of the control requirements in the process industries can be satisfied with a simple feedback control configuration that consists of three components:

- A measurement device for the controlled variable or process variable (PV)
- A proportional-integral-derivative (PID) controller
- A final control element, usually a control valve

The performance of any control configuration can be quantified by the variance in the control error, which is the difference between the set point (SP) and the PV. Control configurations more sophisticated than simple feedback offer the promise to reduce (or narrow) this variance. However, proceeding in this direction requires an incentive, the following two being the most common:

- The simple feedback configuration performs so poorly that it affects process operations negatively. Narrowing the variance in the control error translates directly into more consistent process operations.
- A significant economic incentive exists to operate the process more efficiently. Usually, this entails improving the control performance so that the process can be operated closer to a limiting condition. This is summarized as "narrow the variance, shift the target."

In this book we examine several control methodologies that can be applied to enhance the performance of the controls. The user has two options:

Advanced Process Control: Beyond Single-Loop Control By Cecil L. Smith

- Replace the PID controller, usually with some version of model predictive control. Few regulatory control systems provide model predictive control as a standard feature, but the technology is readily available and easily purchased.
- Retain the PID controller, but incorporate additional logic to enhance the control performance. Most digital systems implement the PID controller as a function block. Numerous additional function blocks are supplied as part of the basic offering, making this approach relatively easy to pursue.

The choice is often dictated by economics. Significant benefits are required to justify model predictive control, so such controllers are often used in conjunction with optimization efforts. Otherwise, the capabilities of the controls must be enhanced by using other function blocks in conjunction with the PID controller.

1.1. IMPLEMENTING CONTROL LOGIC

As used in control systems, a *block* may encompass the following:

Input or measurement block. This block accepts a signal of some type from a field measurement device and converts the input to a numerical value of the measured variable in engineering units (°C, psi, lb/min, etc.).

Output or valve block. This block provides a signal of some type to a final control element. Most final control elements in process facilities are control valves, hence the term *valve block*.

Control block. Each block is described by an equation or algorithm that relates the output(s) of the block to its input(s). Some control systems provide a large number of very simple control blocks; others provide a smaller number of more complex control blocks, each with numerous options. Either approach is possible.

The processing of inputs and outputs can be implemented by other means, but for the control functions, the use of blocks is almost universal.

Input or Measurement Block. Although technically incorrect, the term *analog* is commonly used within digital systems. Prior generations of process controls were based on either electronic or pneumatic technology, and the term *analog* was appropriate. To ease the transition to digital controls, the initial versions of microprocessor-based process controls were designed specifically to closely emulate their analog predecessors. Hence, it should not be surprising that the term *analog* would be applied to corresponding signals within digital systems, and it is also used herein.

The correct term is *digital*. A digital signal is a finite arithmetic approximation to an analog signal. All digital values have a finite resolution: specifically, a change of 1 in the least significant number used in the representation. Here are two examples:

Decimal. A four-digit decimal representation with the format xxx.x has a resolution of 0.1. There are 10,000 possible values (0.0 through 999.9), so the resolution is often stated as 1 part in 10,000.

Binary. A 16-bit binary integer value (short integer) has a resolution of 1 bit. The number of possible values is 64,536 ($= 2^{16}$), either 0 through 64,535 for unsigned integers or −32,768 through 32,767 for signed integers. The resolution is 1 part in 64,536 or less, depending on the range of values that can occur.

In processing inputs from room-temperature devices (RTDs) and thermocouples, a common approach is for the input card to convert the input to engineering units in either °C or °F (this is specified via an option on the input card). The result is a short integer value (16 bits) but with the format understood to be xxxx.x. That is, 1074 is understood to be either 107.4°C or 107.4°F. Considering the accuracy of RTDs and thermocouples, a resolution of 0.1°C or 0.1°F is reasonable. But for narrow spans on displays and trends, the finite resolution will be evident. Some address this issue by smoothing or filtering the input value, but this adds undesirable lag to a control loop.

In all examples presented herein that involve temperature measurements, a resolution of either 0.1°C or 0.1°F is imposed. The objective is to illustrate the impact of finite resolution on the performance of various control configurations.

Output or Valve Block. Some control valves fail closed; others fail open. For an output of 0%, a fail-closed control valve is fully closed; for an output of 0%, a fail-open control valve is fully open. If the output to a fail-closed control valve is 60%, the control valve is 60% open. If the output to a fail-open control valve is 60%, the control valve is 60% closed or 40% open.

The failure behavior of the control valve is not really a control consideration. A control configuration that outputs to a fail-open control valve will perform just as effectively as a control configuration that outputs to a fail-closed control valve, and vice versa. The behavior of the control valve on failure is appropriately a decision for those doing the hazards analysis. Those that configure the controls need to know how the control valve is to behave on failure, but they have no reason to prefer a fail-closed valve to a fail-open valve, or vice versa.

In the past, the failure behavior of the control valve was reflected within the control configuration in various ways, depending on how the supplier implemented certain features. But with digital systems, the trend is to configure the controls to generate all outputs as percent open, that is, as if the controls always output to a fail-closed control valve. Herein it is assumed that the input to the valve block or its equivalent will always be percent open. The valve block will address the issues pertaining to fail-open or fail-closed. Consequently, the output of the controls will be referred to routinely as *valve opening*. In effect, the controls determine the output in terms of valve opening and then let the valve block do the rest.

For a fail-closed valve, the valve block merely transfers the value of its input to the final control element. But for a fail-open valve, the percent open value of the input must be converted to a percent closed value for the final control element. Where this is done depends on the physical interface to the control valve:

Current loop. A current flow of 4 mA or less must cause the control valve to be in the desired failure state. Therefore, the conversion from percent open to percent closed must be done before the current loop output is generated. It will be assumed herein that this is done by the valve block, but if not, one need only insert a $Y = 100 - X$ computation into the control configuration to convert input X as percent open to output Y as percent closed.

Fieldbus. When the output is transmitted to a smart valve via a network or communications interface, the output can always be transmitted as percent open. If the control valve is fail-open, the smart valve converts to percent closed. On loss of communications with the controls, the smart valve can be configured to drive the valve to its failure or "safe" state (equivalent to 4 mA or less from a current loop).

With time, fieldbus interfaces will replace current loops within industrial control systems.

Control Block. The configuration of a control block involves three categories of specifications:

Options. For example, the PID is either direct or reverse acting.

Parameters. For the PID, the parameters include the tuning coefficients, the controller output limits, and others.

Inputs. Each input to a control block is usually the output of another block. Some inputs are optional in the sense that designating a source for such an input is not mandatory.

Why configure by designating the source of each input to the control block? Why not configure by designating the destination of each output? For each input to a control block, there can be only one source. However, a given output from a block may be an input to more than one other block.

For configuration purposes, each output of a block must have a unique designation. This designation has two components:

Tag name. Each block is assigned a unique tag name, such as FT101 for a flow measurement and TC4011 for a temperature controller. The numerical designation is always site specific; however, the use of FT for flow transmitters, TC for temperature controllers, and so on, is widespread. For many of the examples in this book, the numerical designation is not needed to identify a function block uniquely; often, only "FT," "TC," and so on, suffices as the tag name.

Attribute. Each output of a control block has a unique designation that depends on the type of the control block. For the PID control block, the attribute "SP" designates the current value of the set point. Every PID control block provides an output for the current value of the set point, and this output is designated by "SP."

Herein these two components are combined into a single mnemonic <Tag Name>.<Attribute>, with the decimal point or period serving as the separator. That is, TC4011.SP is the current value of the set point of control block TC4011.

Some systems also use attributes to designate the inputs to a function block. Using the PID controller as the example, "PV" designates the process variable input, "RSP" designates the remote set point input, and so on. This approach is used herein.

Process and Instrumentation (P&I) Diagram. Figure 1.1 presents the P&I diagram for a level-to-flow cascade configuration for controlling the level in a vessel. The output of the level controller is the set point for the discharge flow controller. This is conveyed explicitly in the P&I diagram, with the output of the vessel level controller connected to the set point [actually, the remote set point (RSP) input] of the discharge flow controller.

P&I diagrams such as in Figure 1.1 convey the requirements for normal operation of the controls. For the level-to-flow cascade in Figure 1.1, these requirements are as follows:

- The vessel level transmitter provides the PV input to the vessel level controller.
- The discharge flow transmitter provides the PV input to the discharge flow controller.

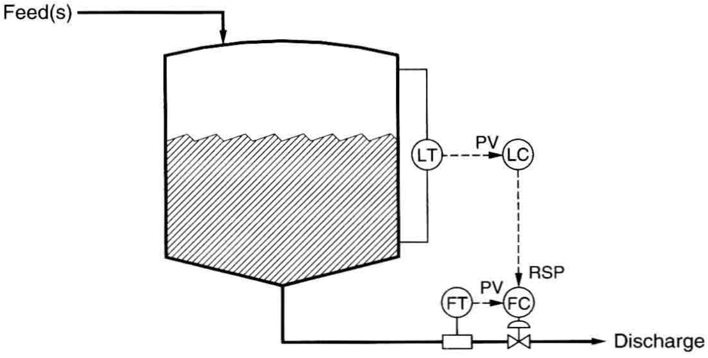

Figure 1.1 P&I diagram of a level-to-flow cascade.

- The output of the vessel level controller is the set point for the discharge flow controller.
- The output of the discharge flow controller is the opening of the control valve on the vessel discharge.

But for smooth operation, other requirements must be incorporated into the control configuration.

Bumpless Transfer and Windup Protection. When implementing the control configuration for an application, the requirements for normal operation of the controls take precedence. However, capabilities are also required to address the following:

- *The transition from manual to automatic must be smooth or "bumpless".* The PID block provides for bumpless transfer from manual to automatic. But what about switching the discharge flow controller in Figure 1.1 from automatic to remote? To achieve a smooth transition, functions in addition to those illustrated in Figure 1.1 are required. Similar requirements apply to all control configurations and usually increase in complexity with the complexity of the control configuration.
- *The PID controller must not be allowed to wind up.* Windup is a phenomenon associated with the reset mode and is often referred to as *reset windup*. The PID block invokes windup protection when the controller output is driven to either of the controller output limits. However, there are external factors that can result in windup. The condition for windup to occur is stated as follows:

  > *Reset windup occurs in a controller when changes in the controller output have no effect on the process variable.*

  This statement will be used repeatedly in subsequent chapters. Using the cascade control configuration in Figure 1.1 as an example, suppose that the measurement range of the discharge flow controller is 0 to 100 gpm, but when the control valve is fully open, the discharge flow is 70 gpm. Does increasing the set point above 70 gpm have any effect on the flow? Once the control valve is fully open, additional increases have no effect on the variable being controlled. The condition for windup exists in the vessel level controller. There are three capabilities for avoiding such windup:

  - Integral tracking
  - External reset
  - Inhibit increase/inhibit decrease

  Implementations of the PID block must provide at least one of these, but configuring such features is not normally represented on P&I diagrams such as Figure 1.1.

The logic required to address these issues can easily exceed the logic for the normal control functions. Ignoring the requirements for bumpless transfer and windup protection will have consequences. Rarely do consequences arise during normal production operations, but commonly arise when situations such as the following occur:

- During startup and shutdown.
- The process is driven to a limiting condition, such as maximum heat transfer in an exchanger or operating a fired heater at the minimum firing rate.
- Temporary disruptions to production operations, such as operating a column on total reflux (feed is stopped, but boil-up and reflux continue).
- Switching between modes of operation, such as regenerating the catalyst in a fluidized bed.

The importance of addressing the consequences depends on how frequently such events occur. If they arise only during startup and shutdown, the consequences can be addressed by incorporating appropriate actions into the operating procedures for startup and shutdown. But if they occur routinely during process operations, the controls must cope with any consequences without depending on intervention by the operators.

One approach is to switch the controls to manual should conditions arise where windup would occur. The operator must subsequently return the controls to automatic when such conditions no longer exist. This approach is certainly preferable to permitting windup to occur. To use this approach, bumpless transfer from manual to automatic is essential. However, the burden imposed on the process operators would be acceptable only when such conditions arise infrequently. Instead of switching the PID controller to manual, emphasis herein is placed on approaches that initiate appropriate windup protection via the inputs to the PID block.

Softwiring. In single-loop controllers, hardware terminals are provided for each input and output. For a PID controller, the signal from the measurement device is connected to the terminals for the PV input. The controller output is available via the terminals for the controller output. The control configuration is determined by the physical wiring for these terminals. Softwiring involves using an analogous approach in software, specifically, software emulation of hardwiring. Instead of physical connections, the source of each input is specified in the software configuration for each block. Graphical development facilities permit these connections for softwiring to be specified on the graphical representation of the control logic.

Figure 1.2 presents the configuration for a level-to-flow cascade. Two liberties have been taken:

- The customary P&I diagram representations are used for the controllers. Subsequently, a rectangular representation for the PID block is presented with all inputs on the left and all outputs on the right. Older configuration