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Control of Boilers

Control Strategies

There are basically five fundamental control strategies that are used in process control. They are: simple feedback control, feedforward plus feedback control, cascade control, ratio control, and feedforward control. In the control of boilers, all five of the fundamental control strategies are used. Many companies show all controllers on drawings as PID controllers. This is because vendor algorithms/function blocks for control are defined as PID controllers. Most control loops are PI only, therefore that format is used in this book.

Bumpless Transfer

The NFPA 85 Code requires bumpless transfer from manual to automatic. Before the development of the DCS (distributed control systems or digital control systems) and electronic systems, it was the responsibility of the operator to line up the set point and the process variable before transferring to automatic control. These systems have the capability of the set point tracking the process variable so they are aligned when control is transferred to automatic control.

Simple Feedback Control

With simple feedback control, changes in the primary variable feedback to a control function, as shown in Figure 2-1. The process variable is compared to the set point of the controller. The differential between the set point and process variable generates an output signal to the manipulated variable and adjusts the variable to bring it back to set point. The function can be proportional-plus-integral (as shown), proportion-only, proportional-plus-derivative, integrally-only, or proportional-plus-integral-plus-derivative.

In all these cases, the controller includes an error detector function, which measures the error between the primary variable and the set point. Other terms are used such as process variable or measured variable. The controller output is determined by a combination or summation of the effects of the different control action capabilities that are built into the controller. This can be gain, reset, derivative, or any combination of the three. These are the proportional or gain multiplication of the error magnitude, the difference between the measured amount and the set point, the integral action based on incremental time away from set point multiplied by error magnitude, and the derivative or rate of change of the measured variable.
Derivative action is not represented in the functional diagram/symbol drawing examples, although it may be used. Derivative action should only be used when there is dead time or a slow responding process such as temperature control. A change in the controller output changes the manipulated variable, which through action of the process, changes the process output selected as the primary variable. The manipulated variable may also be referred to as the process variable. For drum level control, the manipulated variable is the water flow. On draft control, the manipulated variable is typically the ID fan vane or damper and may be ID fan speed control or a combination of vane or damper and speed.

More detail on how proportional, integral, and derivative action function is covered in controller tuning.

Feedforward plus Feedback Control

In feedforward-plus-feedback control, a secondary variable that has a predictable relationship with the manipulated variable is connected (Figure 2-2). In this case, a change in the secondary variable causes the manipulated variable to change in anticipation of a change in the primary variable. This reduces the magnitude of the primary variable change due to the more timely control action that originates from the secondary variable. The feedback portion of the loop contains the set point and can contain any of the controller functions of the basic feedback loop. The feedforward gain is adjustable.

Basically, the feedforward portion of the control loop minimizes upsets and keeps the process at the desired set point.
Cascade control consists essentially of two feedback control loops connected together with the output of the primary loop acting as set point for the secondary loop (Figure 2-3). Cascade control is applied to stabilize the manipulated variable so that a predictable relationship between the manipulated variable and the primary variable can be maintained.

To avoid control instability due to interaction between the two feedback control loops, it is necessary that the response time constants be substantially different. Process response of the seco-
secondary control loop should be the faster of the two. A general rule is that the time constant of
the primary loop process response should be a minimum of 5 to 10 times that of the secondary
loop. The longer time constant of the primary loop indicates a much slower response. Because
of this, a normal application would be temperature control (a normally slow loop) cascading
onto flow control (a normally fast loop). Other suitable candidates for cascade control are tem-
perature cascading onto pressure control and level control cascading onto flow control.

**Ratio Control**

Ratio control consists of a feedback controller whose set point is in direct proportion to an
uncontrolled variable (Figure 2-4). The operator of the process can set the proportional rela-
tionship, or another controller, or a feedforward signal can automatically adjust it. When boilers
burn multiple fuels, air requirements for the different fuels may vary. Ratio control is used to
to ratio the quantity of air required for different fuels.

![Figure 2-4 Ratio control.](image)

As shown, the mathematical function is a multiplier. If the ratio is set, the set point of the con-
trolled variable changes in direct proportion to changes in the uncontrolled variable. If the
multiplication is changed, the direct proportional relationship, or ratio between the controlled
and the uncontrolled variable, is changed.

Most boiler control applications will consist of an overall control system in an interconnected
matrix of the five types of control.

**Feedforward Control**

Feedforward control is used in a number of configurations to improve process control. In feed-
forward control, a measured variable is used to detect a process change in the system. The
measured variable sends this information to a feedforward controller. The feedforward controller determines the required change in the manipulated variable, so that when the effect of the change is combined with the change in the manipulated variable, no change occurs in the controlled variable. This perfect correction is difficult to accomplish. Feedforward control has some significant problems. The configuration of feedforward control assumes that the changes are known in advance, that the changes will have transmitters associated with them, and that no important undetected changes will occur. Steam flow is used as a feedforward signal for the set point of an O₂ analyzer, or the signal from a fuel flow can be used to set a fuel air ratio (Figure 5-3 in Chapter 5). Feedforward can be used to add derivative to increase pulverizer coal feed.

**Controller Tuning**

There are a number of procedures for tuning controllers. There is Default Tuning, S.W.A.G. tuning, Ziegler Nichols, Lambda, and self tuning. Some startup engineers still use the trial and error or S.W.A.G. method.

Self-tuning controller algorithms are now available for insertion into control systems. Such controllers automatically compensate the controller tuning as process or boiler conditions change. Adaptive tuning can also be implemented from load or some other variable of the process.

“Lambda tuning was originated in the synthesis design method whereby the controller must cancel out the process dynamics. In more technical words, given the transfer functions of the components of a feedback loop, synthesize the controller required to produce a specific closed-loop response (loop in automatic). The simplest achievable closed-loop response is a first-order lag. This response was originally proposed by Dahlin (1968), who defined the tuning parameter with the Greek letter Lambda, to signify the time constant of the control loop in automatic, hence the name Lambda Tuning. Lambda Tuning produces a first order, non-oscillatory response to a set point change. This is done by selecting the desired time constant on automatic. Loops tuned using Lambda Tuning will minimize (or eliminate) over-shoot, have great flexibility, and present repeatable results. This method is becoming more popular as more uniform products are required, minimum variability is demanded, and stable processes are needed.”

To demonstrate the various tuning modes the Ziegler Nichols method is used. In 1942, Ziegler and Nichols were the first to propose a standard method for tuning feedback controllers. After studying numerous processes, they arrived at a series of equations that can be used for calculating the gain, reset, and derivative values for feedback control loops. They developed two methods. One is referred to as the ultimate method because it requires the determination of the ultimate gain (sensitivity) and the ultimate period for the control loop. The ultimate gain is the maximum allowable value of gain for a controller with only a proportional mode in operation for which the closed loop system shows a stable sine wave response to a disturbance.

The second method developed by Ziegler and Nichols for tuning control loops was based on data from the process reaction curve for the system under control. The process reaction curve is simply the reaction of the process to a step change in the input signal. This process curve is the reaction of all components in the control system (excluding the controller) to a step change to the process.

The ultimate method is also referred to as the quarter decay tuning (see Figure 2-5 and Table 2-1 for the equations). This method requires defining the Su and the Pu (Figure 2-6). Su is ultimate sensitivity and is the gain or proportional band that creates a continuous sine wave, steady-state output as indicated on the center graph in Figure 2-6. This is determined with the reset/integral turned off. Pu is the ultimate period or time between the peaks of the steady-state sine wave in Figure 2-6.

![Process response curve 1/4 decay](image)

**Figure 2-5 Ziegler Nichols tuning.**

The ultimate method is used in the examples because it is easy to understand and demonstrates the difference between proportional/gain, reset/integral, and derivative control by using PC-ControlLAB 3, a software training program developed by Harold Wade Associates and sold by ISA. The top diagram in Figure 2-6 demonstrates an unstable response. In this diagram the output variations become larger and larger. The bottom diagram demonstrates dampened response. In this diagram the outputs become smaller and smaller. With this method there is overshoot. In some cases, it is important to tune the system so that there is no overshoot.

The center diagram demonstrates a stable response. From this diagram we can determine the Su and the Pu. In these equations, gain is used and the integral is in minutes/repeat. Some vendors use repeats/minute instead of minutes/repeat, or proportional band, instead of gain.

For any feedback control system, if the loop is closed (and the controller is on automatic), one can increase the controller gain, during which time the loop will tend to oscillate more and more. If the gain is further increased, continuous cycling, or oscillation in the controller variable, will be observable. This is the maximum gain at which the system can be operated before it becomes unstable; therefore, this is the ultimate gain. The period of these sustained oscillations is called the *ultimate period*. If the gain is increased further still, the system will become unstable. These three situations are illustrated in Figure 2-6.
Determining Gain, Reset, and Derivative

To determine the ultimate gain and the ultimate period, remove the reset and derivative action from the controller by setting the derivative time to zero and the reset time to infinity, or turn the reset off. PC-ControLAB 3 provides the ability to turn off the reset by going to tune options and turning off reset.

With the controller in the automatic mode, the loop closed, and the gain set at 12, an upset is imposed on the control loop and the response observed. The easiest way to impose an upset is to change the set point by a small amount. If the response curve produced does not dampen out and is unstable (top of Figure 2-6 - unstable response), the gain is too high.

With the gain set to 3, an upset is created. If the response curve dampens out (bottom of Figure 2-6 - dampened response), the gain is too low. The gain was increased and upsets repeated until a stable response was obtained.

### Table 2-1 Tuning terms/equations

<table>
<thead>
<tr>
<th>Terms are:</th>
<th>Equations are:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_c = \text{gain}$</td>
<td>Proportional only Figure 2-6 a</td>
</tr>
<tr>
<td>$T_i = \text{integral, reset (Time integral)}$</td>
<td>$K_c = 0.5 \text{ Su}$ 0.5 x 9 = 4.5 gain</td>
</tr>
<tr>
<td>$T_d = \text{derivative (Time)}$</td>
<td>Proportional-plus-reset Figure 2-6 b</td>
</tr>
<tr>
<td></td>
<td>$K_c = 0.45 \text{ Su}$ 0.45 x 9 = 4.05 gain</td>
</tr>
<tr>
<td></td>
<td>$T_i = \text{Pu/1.2 min/rpt}$ 7.5 / 1.2 = 6.25 reset</td>
</tr>
<tr>
<td></td>
<td>Proportional-Plus-Derivative Figure 2-6 c</td>
</tr>
<tr>
<td></td>
<td>$K_c = 0.6 \text{ Su}$ 0.6 x 9 = 5.4 gain</td>
</tr>
<tr>
<td></td>
<td>$T_i = 0.5 \text{ Pu min/rpt}$ 0.5 x 7.5 = 3.75 reset</td>
</tr>
<tr>
<td></td>
<td>$T_d = \text{Pu/8}$ 7.5 / 8 = 0.94 derivative</td>
</tr>
<tr>
<td>$K_c, K_i, K_d$</td>
<td>Using the equations $\text{Su} = 9$ and $\text{Pu} = 7.5 \text{ minutes}$ from Figure 2-6.</td>
</tr>
</tbody>
</table>

Using the equations $\text{Su} = 9$ and $\text{Pu} = 7.5 \text{ minutes}$ from Figure 2-6.

**Determining Gain, Reset, and Derivative**

To determine the ultimate gain and the ultimate period, remove the reset and derivative action from the controller by setting the derivative time to zero and the reset time to infinity, or turn the reset off. PC-ControLAB 3 provides the ability to turn off the reset by going to tune options and turning off reset.

With the controller in the automatic mode, the loop closed, and the gain set at 12, an upset is imposed on the control loop and the response observed. The easiest way to impose an upset is to change the set point by a small amount. If the response curve produced does not dampen out and is unstable (top of Figure 2-6 - unstable response), the gain is too high.

With the gain set to 3, an upset is created. If the response curve dampens out (bottom of Figure 2-6 - dampened response), the gain is too low. The gain was increased and upsets repeated until a stable response was obtained.
When a stable response is obtained, the values of the ultimate gain ($S_u$) and the ultimate period ($P_u$) of the associated response curve should be noted. The ultimate period is determined by the time period between successive peaks on the stable response curve. The ultimate gain (also called the ultimate sensitivity or $S_u$) is the gain setting of the controller when a stable response is reached (center of Figure 2-6 – stable response).

Using PC-ControLAB 3, the stable response is achieved with a gain of 9, and the time from peak to peak is approximately 7.5 minutes. The 7.5 minutes is the peak to peak time on Figure 2-7. The cycle is generated with a gain of 9 and no reset (reset turned off).
**Gain vs. Proportional Band (PB)**

Gain and proportional band are used as tuning terms. Gain is the reciprocal of proportional band. Proportional band (PB) is in percent.

\[
\text{Prop Band} = \frac{100}{\text{Gain}} \\
\text{Gain} = \frac{100}{\text{Prop Band}}
\]

Examples:  
If Gain is 2, PB = \(\frac{1}{2} = 0.5 \times 100 = 50\%\) PB or \(100\% / 2 = 50\%\)  
If Gain is 0.5, PB = \(1 = 2 \times 100 / 0.5 = 200\%\) PB or \(100\% / 0.5 = 200\%\)

Repeats per minute vs. minutes per repeat:

Integral Action is minutes per repeat or repeats per minute. Repeats per minute is the reciprocal of minutes per repeat.

Example: \(0.5 \text{ Min/Repeat} = \frac{1}{0.5} = 2 \text{ Repeats/Min}\)

Figure 2-7 demonstrates a typical output variable.

**Figure 2-7** Typical output variable.  
*Note: Only a small output cycle is required to determine the Su and Pu values.*

**Controller Actions**

**Gain/Proportional Action**

When gain/proportional control only is used, there is a one-time step change based on deviation from set point. A feedback controller with gain/proportional control only, may not stabilize the set point (Figure 2-8). Note the difference between the process variable (PV) and set point (SP). For gain/proportional only control, the gain is 4.5 (Table 2-1).
Figure 2-8 Deviation between setpoint and process variable.

Integral/Reset Action
Integral action is time-based change in minutes and repeats the gain change until the loop stabilizes at set point. The tuning setting is in repeats per minute or minutes per repeat. Note in Figure 2-9 with gain/proportional and integral/reset action, the measurement lines out at set point in approximately 30 minutes. Also note the recovery on the second cycle is one quarter of the first cycle. For gain/proportional plus reset control, the gain is 4.05 and reset is 6.25 (Table 2-1).

Figure 2-9 Upset and return to recovery with reset.
**Derivative Action**
When there is dead time or a slow reacting process, derivative can be added to improve control. Derivative time action contributes an immediate valve/output change proportional to the rate of change of the error. As the error increases, the proportional action contributes additional control valve movement. Later, the contribution of the proportional action will have equaled the initial contribution of the rate action. The time it takes for this to happen is called the derivative time. Derivative action is applied to a process that is slow or has dead time. Note in Figure 2-10, with the addition of derivative, the measurement lines out at set point in approximately 10 minutes for gain. As was noted in Figure 2-7, only a small output cycle was required to determine the Su and Pu values.

![Figure 2-10 Upset and return to recovery with derivative action and reset.](image)

The Ziegler Nichols method can be used on most process control loops; however, no one method can be used on all control loops.

Figure 2-11 is an example of control of a process with randomly varying load and with PID control and the tuning determined by using Ziegler Nichols tuning parameters.

![Figure 2-11 Steady process variable with randomly varying load.](image)
Controller Actions Setup

There are many different functions required in design and configuration and/or programming a control system. Controller functions need to be determined. Controller functions can be direct or reverse acting. A direct acting controller output increases as the PV (Process Variable) increases, and a reverse acting controller output decreases as the PV increases. If the control system is programmable, the systems engineer must make the selection. The failure mode of the control valve or damper determines whether the controller is a direct or reverse acting controller. Units of measurement are in percent or engineering units. When we think of the various control signals such as the process variable or set points, we can define them as a percentage or assign engineering units.

The Effects on Tuning

There are numerous things that affect the tuning of control loops. Some examples are: reaction time of process, process noise (furnace pressure, air flow), calibration of transmitter (span of the transmitter), linearity of process (pH loop), linearity of final element, speed of response of final element (valves, dampers), valve sizing and valve hysteresis. The addition of a valve positioner can improve control by providing valve position repeatability for a specific input.

Temperature control would be an example of a slow responding process. Flow control would be an example of a fast responding process.

Calibration Effect on Gain

Example: Span of transmitter

\[
\begin{align*}
\text{0-2000 psi 4-20 ma} & = 125 \text{ psi/ma} \\
\text{1000 to 2000 psi 4-20 ma} & = 62.5 \text{ psi/ma}
\end{align*}
\]

Note, the span is one number and calibration range is two numbers.

Using engineering units in this example, the span of 0-2000 is two times that of the span 1000-2000. Therefore, the gain would be two times greater than when calibrated with a span of 0-2000 psi. This is a common problem particularly on high pressure boilers. With a wide span, a control output may cycle and yet the process appears to be steady.

There is no one method of control tuning that is best for all process loops. Different types of processes, control valves or dampers, vendor control algorithms or function blocks can make this impractical.

Transmitters

Each control loop should be reviewed by a risk analysis to determine if a redundant transmitter or switch is required. Field transmitter or switch device redundancy should be provided to the extent necessary to achieve desired system reliability. When two transmitters or switches are employed, excessive deviation between the devices must be alarmed and the associated control
loop transferred to manual. When three transmitters are employed, excessive deviation between the transmitters must be alarmed. A median select signal is required by the NFPA 85 Code for furnace pressure measurement and is commonly used when there are multiple transmitters.

When writing specifications for transmitters or switches, it is important to include calibration range and span. Also include materials of construction, especially the wetted parts. For transmitters consider the effect on tuning control loops. If the span is significant, the gain on the controller may be difficult to set.

**Redundancy**

When two transmitters or switches are employed, it may be configured as 1-o-o-2 – one out of two. This is called redundancy. Two protective circuits are operating essentially in parallel. A single point failure will disable one of the two circuits while the redundant circuit continues to provide the needed protection. A failure detection mode such as no output must be defined.

When two transmitters or switches are employed, it may be a 2-o-o-2 – two out of two. This is not redundancy, because a single point failure in either circuit will cause an output tripping action. This allows no fault tolerance, yet has two circuits required to hold. Where 1-o-o-2 might be a parallel circuit (normal operation energized with de-energize to trip), 2-o-o-2 would be a series circuit. If two flame detectors are required to see flame, or the boiler will trip, this is 2-o-o-2. This demonstrates that it is possible to have a 1-o-o-1 circuit with a 2-o-o-2 portion, a 1-o-o-2 circuit with a 2-o-o-2 portion, or a 2-o-o-3 circuit in which a critical portion is 2-o-o-2.

When three transmitters or switches are employed, it could be configured as 2-o-o-3 voting. This could be called triple redundancy. In this type of interlock system, the output of two out of three individual interlock circuits must agree to hold in a circuit in monitoring normal operation. If two out of three agree to trip, tripping action will trip the process equipment device. Any single point failure involving the interlock devices will not trip the operating equipment. A maximum of two such failures will trip, just as a minimum of two good circuits will allow continued operation.

Three transmitters or switches 2-o-o-3 could be configured voting with fault tolerance. While this type of system requires two out of three voting to keep process equipment operating, more than two single point failures in separate circuits can be tolerated. For example, if the total circuit is made triple redundant and each circuit broken into three sequential parts, 27 separate potential pathways in 9 circuit segments exist.

**Interlock Circuitry**

One, two, or three transmitters may be required. When only one transmitter is employed, it is referred to as 1-o-o-1 – one out of one. In this configuration, a single circuit with a single point failure in the system will cause an output action. The circuit itself should be designed so that any output action is always safe (e.g., shutdown the equipment). ASME recommends median select. The NFPA 85 Code requires median select for furnace pressure measurement.
Final Control Elements

All final control elements are to be designed to fail safe on loss of demand signal or motive power, i.e., open, close, or lock in place. The fail safe position must be determined by the user and based upon the specific application.