WATLOW

PRACTICAL PID GUIDE
FOR PROCESS CONTROL

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1.0 Introduction

This Guide is written for users of Proportional, Integral, and Derivative controllers, especially those who are not trained as control engineers. It is the writer's intent to attempt to eliminate the mystery sometimes associated with this subject matter and make it easier for the user to acquire a better understanding of what makes it work so well.

Although the field of industrial controls has changed significantly over the years, the principals of Proportional, Integral, and Derivative (first commercially introduced in the 1930's) has not changed much, if at all. The material contained in this guide is written using terminology and concepts as deployed in Watlow Proportional, Integral, and Derivative controllers. Watlow makes no claims that this is the definitive study of Proportional, Integral, and Derivative control; different companies may or may not use different terminology and concepts in their implementations.

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2.0 Proportional, Integral, and Derivative Overview

In the industrial process control field there are many written explanations of Proportional, Integral, and Derivative control and yet, after reading the theory, many users are still mystified. What is Proportional, Integral, and Derivative and why do you need it? How do you tune it? These are some of the most asked and most unanswered questions by users.

The following text is an attempt to provide answers to these questions from the user's viewpoint. The answers are meant to be clear uncomplicated instructions for effectively using Proportional, Integral, and Derivative as well as defining some of the most common terminology used in the control industry today.

2.1 Basic Elements of Proportional, Integral, and Derivative Control Systems

A control loop may consist of four or five elements and it may control in an open loop or a closed loop form.

- **Primary Element**: senses the Process Variable. A thermocouple measuring temperature is an example.

- **Controller Element**: may or may not be able to accept the signal from the Primary Element without signal conditioning. If the controller element is not electrically designed to receive the input directly, a signal Conditioner Element is needed (See below).

- **Signal Conditioner Element**: when a Signal Conditioner Element is needed, another element is added to the control loop. This element transduces the Primary Element signal into a signal that is acceptable to the Controller Element. Example: PSI into 4-20 mAdc.

- **Final Control Element**: the Controller Element sends the control signal to the Final Control Element. The Final Control Element controls the Manipulated Variable Element.

  The Final Control Element may be a motor positioning valve used to control the delivery of natural gas into a burner system, or a Solid State Relay controlling voltage into an electric load.

- **Manipulated Variable Element**: the energy of the process such as Electrical Power, Steam, Natural Gas, etc. needed by the process for the process variable to reach the set point.

2.2 Output Configuration

The output configuration is sometimes confused with the control mode. Outputs can be configured in various ways (i.e., heat, cool, alarm, etc…) and in various combinations; the combinations are limited only by the control type. The output configuration has no impact on how the controller will respond to the difference between the process variable and the set point.

2.3 Control Modes

Settings that allow changes to the control mode (closed loop / open loop) determine how the controller will respond to an input signal in reference to a set point.

- **Open Loop (Manual)** - also known as manual control, uses no feedback from the process, so the control output is preset to produce a desired effect. This assumes that the process is slow enough for corrective action due to information from another source other than the Primary Element, or the process characteristics are such that open loop control will hold the set point within desired limits.

- **Closed Loop (Auto)-** also known as Automatic Control, uses feedback from the process, comparing the process variable to the set point, thus providing automatic control to the process.

2.3.1 On/Off

On/off control is the simplest way to control a process; a controller using on/off control turns an output on or off when the process variable reaches a certain limit below or above the set point. On/off control will cycle the process variable around the set point. The process variable deviation from the set point is primarily due to the process dynamics rather than the controller gain.

Watlow controllers provide an adjustable spread or hysteresis for on/off control loops. If the spread or hysteresis is set to 5 and the set point is 200°F the output will be turned off when the process variable is equal to the set point. In most heating applications the process variable will continue through and above the set point due to thermal dynamics. When the process variable has cycled back down through the set point - 5 (195°F) the output will then be turned back on. Typically, it is more critical as to when the heat is turned back on below the set point as to how close the control cycle will be to the set point. Occasionally, this adjustable spread or hysteresis is too narrow for the process and an undesirable and intermittent chattering of the final control element may be present. By monitoring the process the user can then readjust the spread or hysteresis to eliminate this disturbance.

The main output element form used with Watlow on/off control is the electromechanical relay. It is used for electrical heating loads, solenoid valves and two-position motor control as well as other two state control elements. An analog output normally used for proportioning outputs such as 0-5 Vdc may also be operated as on/off.

2.3.2 Proportional

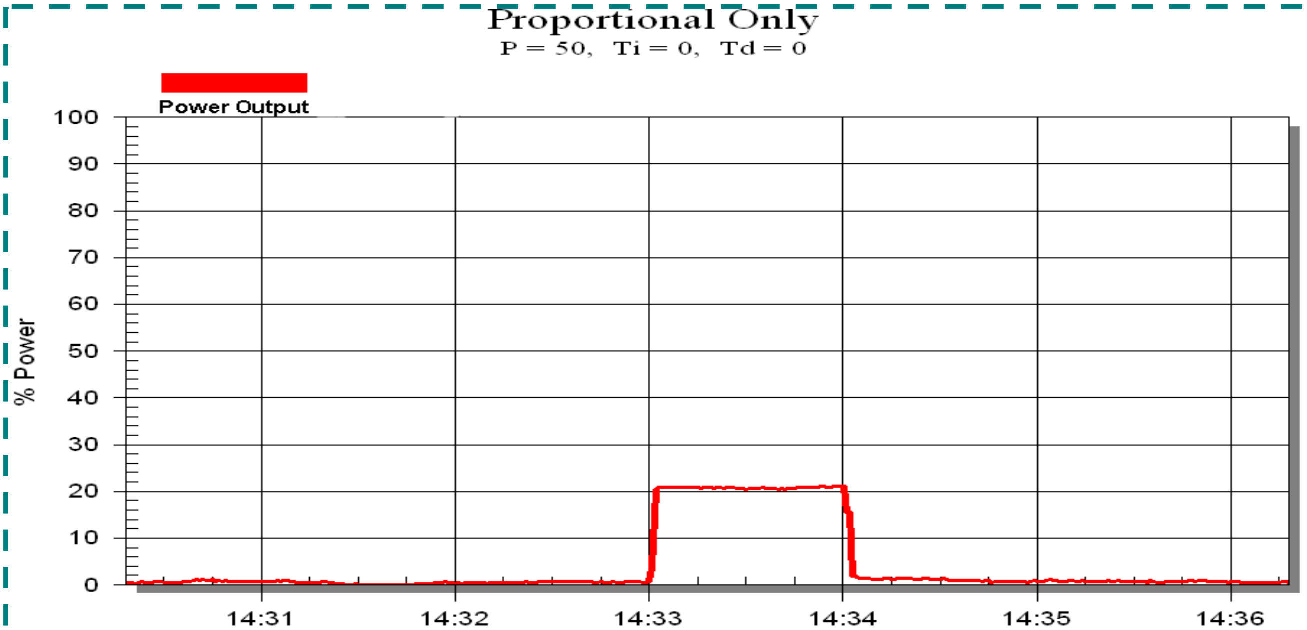
Proportional control sometimes referred to as gain, is the first mode in the control algorithm. The proportional control mode is the proportional change of the control output to a change in the input signal. The proportional mode coefficient is expressed in a unit known as proportional band . This band, in engineering units of the input range, is the amount of change over which the input process variable must change to effect a 0% to 100% or 100% to 0% change in the output of the controller.

Example:
A proportional band of 50 will have a change of 100% in the output when the process variable has changed by 50°F/C from the set point. Anything greater than 50° is known as "outside the proportional band", thus there is no further change of the output.

Because the normal dynamic response of Proportional, Integral, and Derivative control is an ever-changing process variable and output signal, it can be difficult to get a handle on what exactly is happening without capturing a specific moment in time. The graph below does this well in that there is a specific step change applied to the proportional band where the error from the set point is clearly defined and static. With this known error we can then calculate what the output should be and then actually confirm the calculation by monitoring the control output over time.

The graph below shows an increase in the output of 20% for a known step change in the process variable. With the current settings for Integral and Derivative equal to zero the output will remain at 20% unless there is another step change in the process variable.

Figure 2.0



A small proportional band can cause the process variable to oscillate around the set point; on the other hand, a proportional band that is too high may keep the process variable from ever reaching the set point. Since cycling of the process variable can be the result of a small proportional band (high gain), increasing the proportional band (lower gain) is one way to reduce cycling of the process variable. As a result of this increase, the reduced controller output will become proportional to a change in the input. Because of this proportional response to the input most refer to this function as the proportional band. The proportional function of the control is to control the overall process gain.

2.3.3 Suggestions for Initial Proportional Settings

The general rule for proportional control is that the smaller the change of the output for a given change of the input, the finer the resolution of control; and thus a more proportional control is achieved. A high amount of change in the output will result in a high change in the process variable and unwanted output oscillations will occur. The optimum proportional band is selected to give the highest amount of output change (smallest proportional band) without causing output oscillations. This is determined by the actual process physical characteristics, such as the primary energy source, the thermal loading, and the response of the primary as well as the final control element.

Again, as a general rule, a good initial setting for the proportional band is approximately 10% of the set point below 1000°F, and 5% above 1000°F. Through process observation these initial settings will likely need to be modified. As an end result, the output should not deviate more than 2-3% of the output average. For a 1° change of the input most temperature control systems will produce an output change of between 1 to 5%. This correlates to a proportional band range of 20 to 100°F. To obtain the power output change for a given change in the process variable, divide the output range of 100% by the degrees of the proportional band. A proportional band of 25 will give a 4% change of output power per degree change of the input. Keep in mind, there are processes requiring other proportional band settings.

The table below shows the practical range of proportional band with the resultant change in the output. A proportional band outside of this range is not useful in most temperature applications.

PB°F	Out %/°F	PB°F	Out %/°F	PB°F	Out %/°F	PB°F	Out %/°F	PB°F	Out %/°F
5	20.0	30	3.3	55	1.8	80	1.25	125	0.80
10	10.0	35	2.8	60	1.6	85	1.17	150	0.66
15	6.6	40	2.5	65	1.5	90	1.11	175	0.57
20	5.0	45	2.2	70	1.4	95	1.05	200	0.50
25	4.0	50	2.0	75	1.3	100	1.00	250	0.40

Using a Proportional only control mode will not normally bring the process variable to the set point. Process dynamics will ensure an offset due to the amount of energy required to hold the process variable to set point as it changes the controller output level to meet the process requirements for the amount of energy required to hold to the process variable to the set point.

2.3.4 Integral

Temperature is a function of time. The reaction time of the system or process may be short or long depending on its particular physical characteristics. The Integral action uses the time element as a control function (commonly, but not exclusively, identified as I, or T_i).

Some Watlow controllers present the Integral coefficient as seconds (R/M = 60/T_i) and expresses the amount of time over which the control action repeats the Proportional error from set point. A T_i value of 120 would be .5 repeats per minute. Other controls provide a choice where if the units are set to SI (International System of Units) the Integral contribution is measured in minutes per repeat and conversely, if the units are set to US (Reset) the contribution is measured in repeats per minute. When the proportional band is above or below the set point, the deviation from the set point is known as offset, sometimes referred to as droop. Throughout the remainder of this document this deviation will be referred to as offset. Regardless of what you call it or how you define the Integral parameters the bottom line functionality of the Integral action corrects for the offset by increasing and or decreasing the output over time so that the proportional band and set point are equal.

Whenever the process variable is away from set point (offset), there's a proportional error signal, which is the first response of the Proportional, Integral, and Derivative control function. If the proportional error signal is not reduced to zero, the Integral mode will repeat the proportional error signal to the output, at the rate specified by the Integral value. It will continue this function until the proportional error has been reduced to zero or the output has increased to 100%. When the process variable is at set point with no proportional error, the output will remain at the level that the Integral action has reached. The Integral contribution is not only changing the output of the controller by the amount of the proportional band change, but at the rate of change of its setting; remember, the Integral contribution is a function of time. We can see now that if using seconds per repeat, a lower entry will deliver more repeats of the Proportional correction to the output in a shorter period of time, thus the output will be faster in response. A practical useful range for this setting would be between 30 to 1200 seconds per repeat and 2.0 to 0.05 repeats per minute for Reset. A setting below 30 seconds will normally cause output oscillations, and a setting above 1200 seconds is normally too slow.

The general rule for setting T_i is that the faster the process, the lower the T_i, the slower the process, the higher the T_i. A process that comes to a new control point after a step change in 20 minutes is considered fast; after 1 hour, it is considered slow. Settings below 60 seconds are considered fast; settings above 600 seconds are considered slow. Settings of 60, 120, 180, and 240 seconds handle most processes.

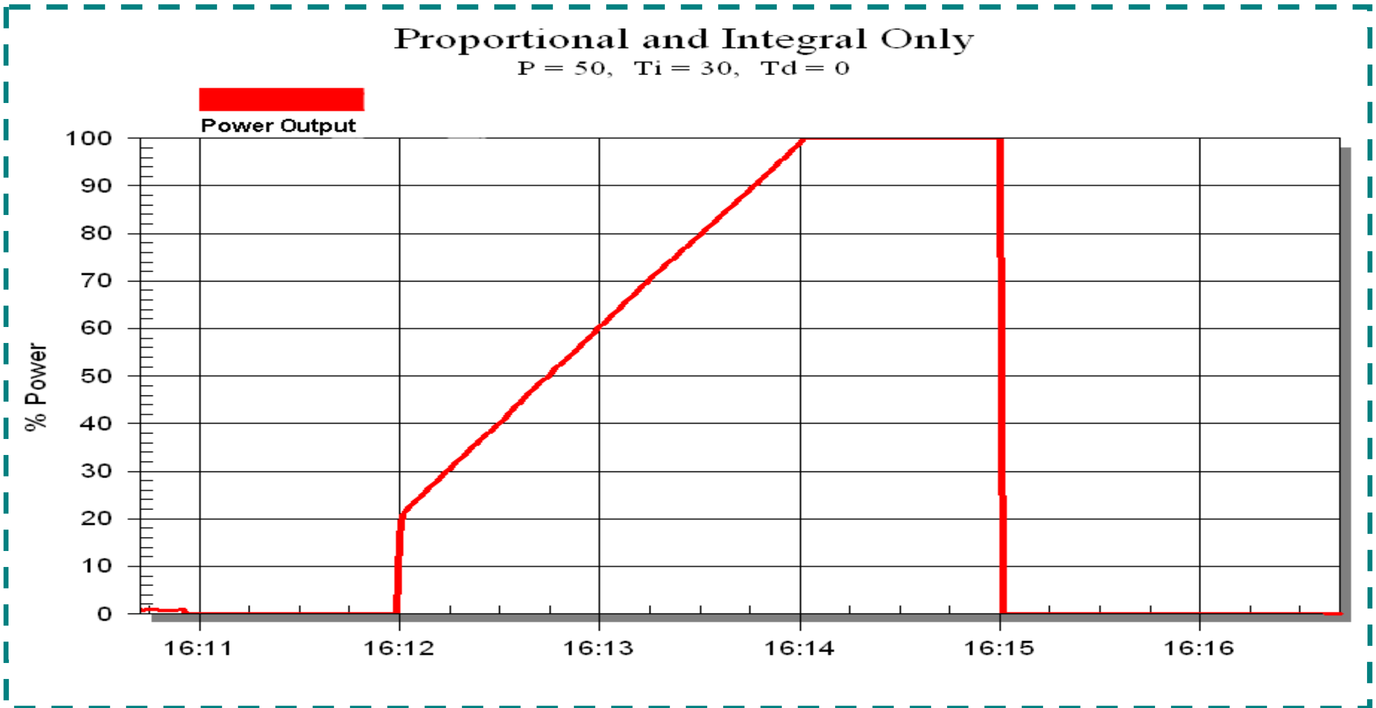
To produce a 100% change in the output, with a proportional band of 20 and a Integral value equal to 60, a 1° change in the process variable would result in a 5% change in the output. The Integral setting would result in a 95% change in the output in a time frame of 19 Minutes.

100% output - 5% proportional band = 95%/5% (1 R/M) = 19 minutes

An Integral value, which is too high, will not allow the process variable to come to set point within a reasonable amount of time. A low Integral value will cause the output to oscillate, thus causing the process variable to cycle at a slow rate. This is called Reset cycling.

To bring more clarity to the discussion above, the graph below (figure 2.1) clearly depicts the response of a control with the PB set at 50. Introducing a 10° change in the process variable from the set point causes the first response to be that of the Proportional contribution. Due to the fact that every degree change on the process variable translates to a 2% rise in the output we can clearly see an overall jump of 20% immediately after the step change occurs. Thereafter, we can also see the Integral contribution repeating the 20% Proportional response to the output at the rate of 30 seconds a repeat.

Figure 2.1



In controlling a process to a set point, process engineering must allow the controller to be within its control capability. In most processes, the controller element is the fine control, while the process itself is the course control. The ideal range of the control output should be 40-60%, however this is determined more by the process characteristics than it is by the controller.

When sizing control valves, electrical loads or other final elements, the correct sizing will allow the controller output to be in the 40-60% range when the process variable lines out at set point while also being at mid-range of the process control span. Normal Proportional, Integral, and Derivative control levels range from 20-80% with extreme ranges from 10-90%. Anything below 10% or greater than 90% normally will have control problems. With 2-mode PI control overshooting the set point is typical as the Integral sum cannot be reduced until the process variable exceeds the set point. The control mode to reduce the Integral sum before reaching set point is known as the Derivative Mode.

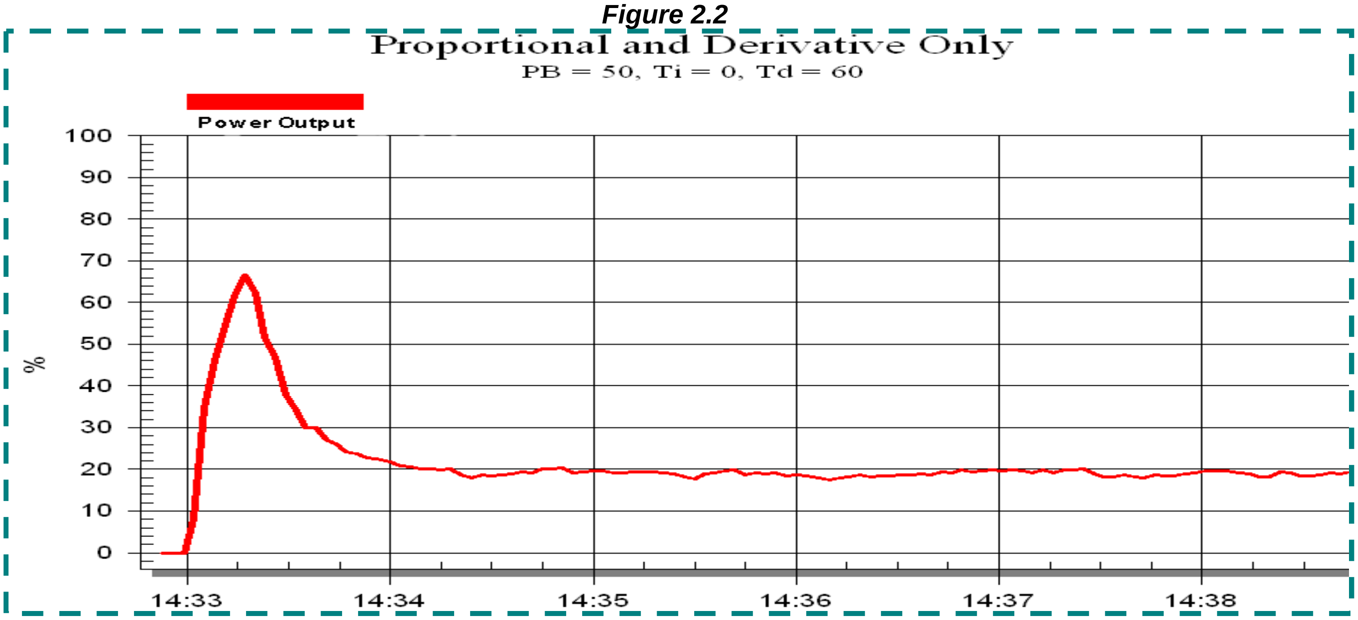
2.3.5 Derivative

As stated above, with proper settings for both Proportional and Integral, the process variable may still overshoot or undershoot the set point. This is to be considered normal control characteristics of Proportional and Integral or two-mode control. The occurrence and magnitude of such swings above and below the set point is dependent to a great extent on the process characteristics. In most processes this condition of over/undershoot is not a problem. In the event that it is, the Derivative or Rate mode should be used.

The Derivative (commonly, but not exclusively, identified as D, or T_d) mode also known as Rate, anticipates the rate of change of the process and will then compensate to minimize this over/undershoot. Some Watlow controllers provide an option as to whether the Derivative coefficient is represented in either seconds (Derivative mode) or minutes (Rate mode). Derivative control is the instantaneous change of the control output level above and beyond the P contribution and in the same direction as the Proportional error. The amplitude of the T_d contribution to the output level is derived from value of change of the Proportional error. When the specified T_d time has expired, the output will have reduced to the value of only the PB change to the output level. The result of the T_d mode contribution is to reduce or increase the output much more quickly than when using the PB mode only.

As was the case in the previous graphs, the initial output response to the 10° step change of the process variable is the 20% P contribution. Beyond the 20% we see the Derivative action taking the output to approximately 68%. With no change in the process variable, we see that one minute (D = 60 seconds) later the Derivative time has expired and the output reduced back to the 20% P contribution only. The D mode coefficient is in seconds and the Rate coefficient is in Rate Minutes.

Figure 2.2



The Derivative mode is only active upon a change in the PB error or when the process variable is changing. The D mode coefficient is derived from the I mode coefficient by dividing the T_i constant by six. This would be the typical value used for the T_d constant.

Example: T_i = 180 seconds/6=30. T_d = 30. The higher the number the greater the D mode action. Setting the rate too high will cause undershooting of the process variable and possible cycling of the process variable above the set point.

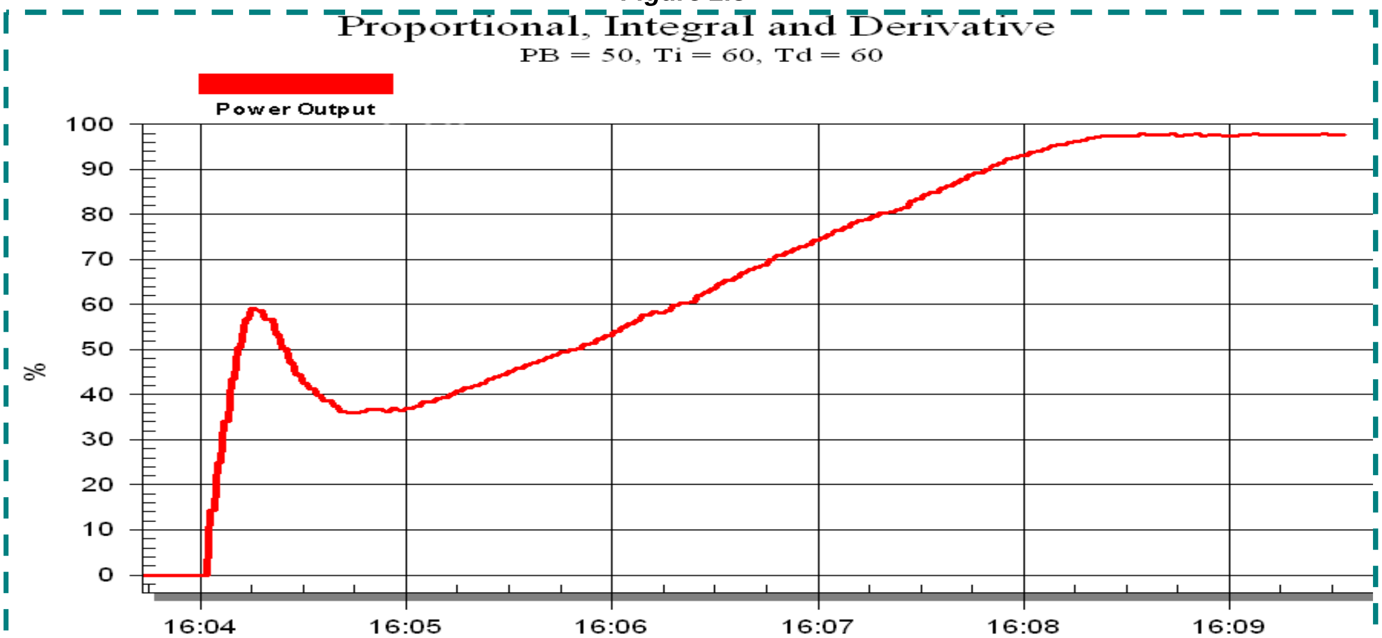
2.3.6 Proportional, Integral, and Derivative Control Mode

With three-mode control the output signal is a composite of the three control functions (see figure 2.3 below) and will vary, as process dynamics require, holding the process variable to the set point. Proportional, Integral, and Derivative, or 3-mode control, is used when on/off control is not sufficient for the control requirements of the process; if cycling the process variable cannot be tolerated, if process loading is variable, or if the set point is changeable, Proportional, Integral, and Derivative should replace on/off control.

As was stated earlier there are those in the industry that use different terminology in describing Proportional, Integral, and Derivative. For instance, some will refer to Proportional as Gain, Integral as Reset, and Derivative as Rate. The control action is the same, but the engineering units used for the Proportional, Integral, and Derivative adjustments are not.

Proportional, Integral, and Derivative is based upon the amount of difference between the process variable to the set point. This is known as the process error. This process error can be either a positive value or a negative value. When the process variable equals the set point the process error is zero. The basic Proportional Integral and Derivative equation is P + I + D = controller output level.

Figure 2.3



3.0 Tuning Proportional Integral and Derivative Loops

Proper tuning is critical to acquiring peak performance from any Proportional, Integral, and Derivative controller. It involves learning and understanding the process characteristics of the particular thermal system and then applying appropriate Proportional, Integral, and Derivative parameters. Generally speaking, there are three ways to tune a Watlow Proportional, Integral, and Derivative controller.

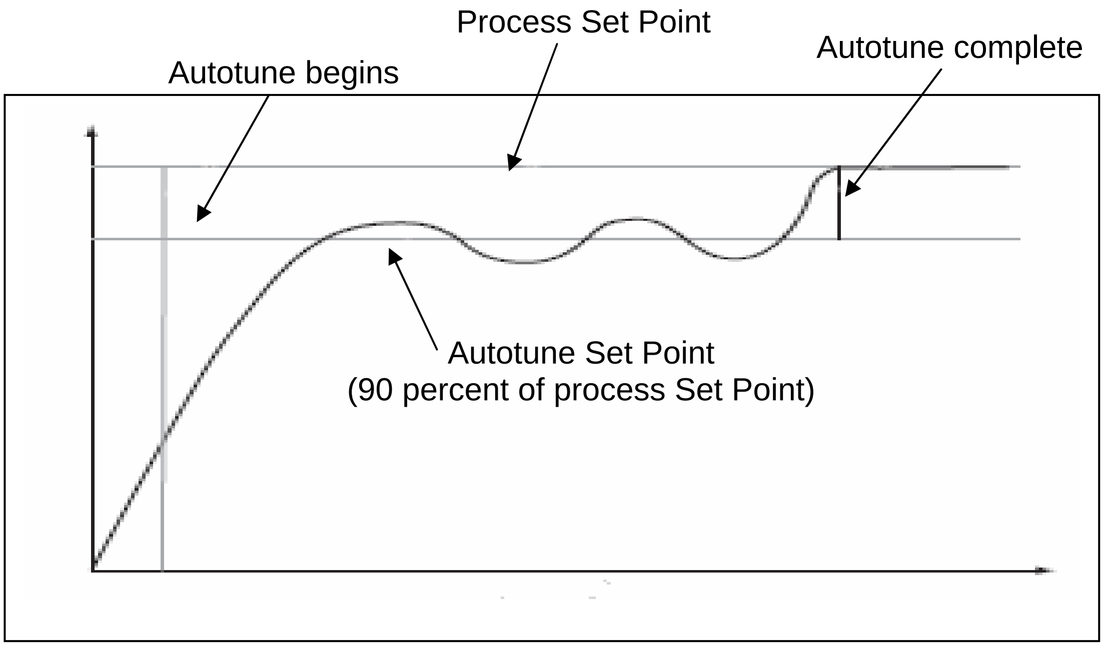
1) AutoTune *
2) Adaptive Tune (TRU-TUNE+) *
3) Manual Tune

* Not available on all Watlow controls

3.1 Auto Tune

The autotuning feature allows the controller to measure the system response to determine effective settings for Proportional, Integral, and Derivative control. When autotuning is initiated the controller reverts to on-off control. The temperature must cross the Autotune Set Point four times to complete the autotuning process. Once complete, the controller controls at the normal set point, using the new parameters.

Figure 3.1



3.2 Adaptive Tune (TRU-TUNE+™)

This feature is best used when an application requires frequent set point changes over a large processing or temperature range. It should also be used where load variations (i.e., increased material flow or variations in flow demand) are common. These disturbances modify the thermal loading characteristics and therefore require modifications to the tuning parameters in order to maintain superior controllability of the system. TRU-TUNE+™ utilizes a set of proprietary expert tuning rules to calculate and adjust the Proportional, Integral, and Derivative parameters without further user intervention. This feature can be viewed as a dynamic (while the control is actively controlling) fine tuning mechanism for the parameters already established in the initial auto-tuning.

TRU-TUNE+™ offers other advantages as well in that it can tune loops more precisely (plus or minus 0.1 degree Fahrenheit) than controls utilizing auto-tune or manual tune procedures. While TRU-TUNE+™ can also tune both heating and cooling Proportional, Integral, and Derivative parameters, it will also reduce or eliminate overshoot when approaching Setpoint as well.

3.3 Manual Tune

In some applications, the autotune process may not come up with appropriate tuning parameters (process characteristics you desire) for Proportional, Integral, and Derivative. If the autotune does not provide satisfactory results, you will have to perform a manual tune on the process. Manual tuning allows the user to set each parameter individually for Proportional, Integral, and Derivative. Below, the reader will find recommended steps to take in the process of manually tuning a Watlow control. Although these steps have been followed many times on various applications with much success it is important to keep in mind that all applications do not produce the same results. Use this procedure as a baseline to get started and modify as your application demands.

Place the control in manual mode to avoid upsetting the process when changing Proportional, Integral, and Derivative coefficients. After changing the coefficients, place the loop back into auto. If a small upset of the output is not important, Proportional, Integral, and Derivative constants may be tuned while in auto. Time is a factor in temperature processes. Allow time between adjustments, for most thermal processes wait 20 minutes before making new changes.

3.3.1 Manual Tune - Proportional

When using single mode Proportional band for control set the Integral and Derivative to off. Using only Proportional mode for control requires a smaller Proportional band than using Proportional and Integral or Proportional, Integral, and Derivative. A range of 3-10% of the SP is a useful range for this form of control.

Manual Tune - Proportional

Step	**Description**
1	Set P to 30% of SP; I and D Modes to 0. Place in Auto. Wait until PV is close to SP and as stable as it can get.
2	Set Control Mode to Manual
3	Set P to ½ of current setting
4	Set Control Mode to Auto
5	Check to see that the output is stable (look at output % not PV)
6	If output is stable at less than a 2% delta change, go to step 2
7	When output is **NOT** stable with more than 2% delta change
8	Set Control Mode to Manual
9	Increase P by 25%
10	Set Control Mode to Auto
11	Check to see that the output is stable (look at output % not PV)
12	If output is **NOT** stable go to step 8
13	When output is stable leave Control Mode in Auto and tune the I Mode

3.3.2 Manual Tune - Proportional and Integral

Two-mode, Proportional and Integral, is the most common control mode in the industry. The Proportional band must be tuned first before the Integral. Preset values may be used to accomplish a faster tuning. Integral below 30 seconds will most likely cause cycling and is not recommended for most thermal applications.

Manual Tune - Integral

Step	**Description**
1	Set I to 60
2	Set Control Mode to Auto

3	Check to see that the output is stable (look at output % not PV)
4	If output is stable with less than a 2% delta change
5	Set I to 50% of current setting
6	Check to see that the output is stable (look at output % not PV)
7	If output is stable go to step 5
8	When output is **NOT** stable with a greater than a 2% delta change
9	Increase I by 50% of current setting
10	If output is still not stable increase I by 50% of current setting until stable
11	When output is stable leave Control Mode in Auto and tune the D Mode

3.3.3 Manual Tune - Proportional, Integral and Derivative

Three-mode, Proportional, Integral, and Derivative control is used primarily when overshoot of the process variable cannot be tolerated. Proportional and Integral must be tuned before attempting to tune the Derivative mode.

To determine the Derivative coefficient simply divide the Integral coefficient by 6.

3.4 Summary - Manual Mode Tuning

In most processes, the tuning parameters acquired through following the above steps should not have to be changed or retuned. On the other hand, the user may want to consider retuning if one or more of the changes identified below were to occur:

- Large variance in operational Setpoint from the tuning Setpoint.
- Process material loads have changed in size
- Process load changes due to exothermic reaction

The Integral and Derivative values will usually remain the same. In the event that the Integral value is changed the Derivative should also be changed as well.