PID Loops - Demystified

What is a PID Loop

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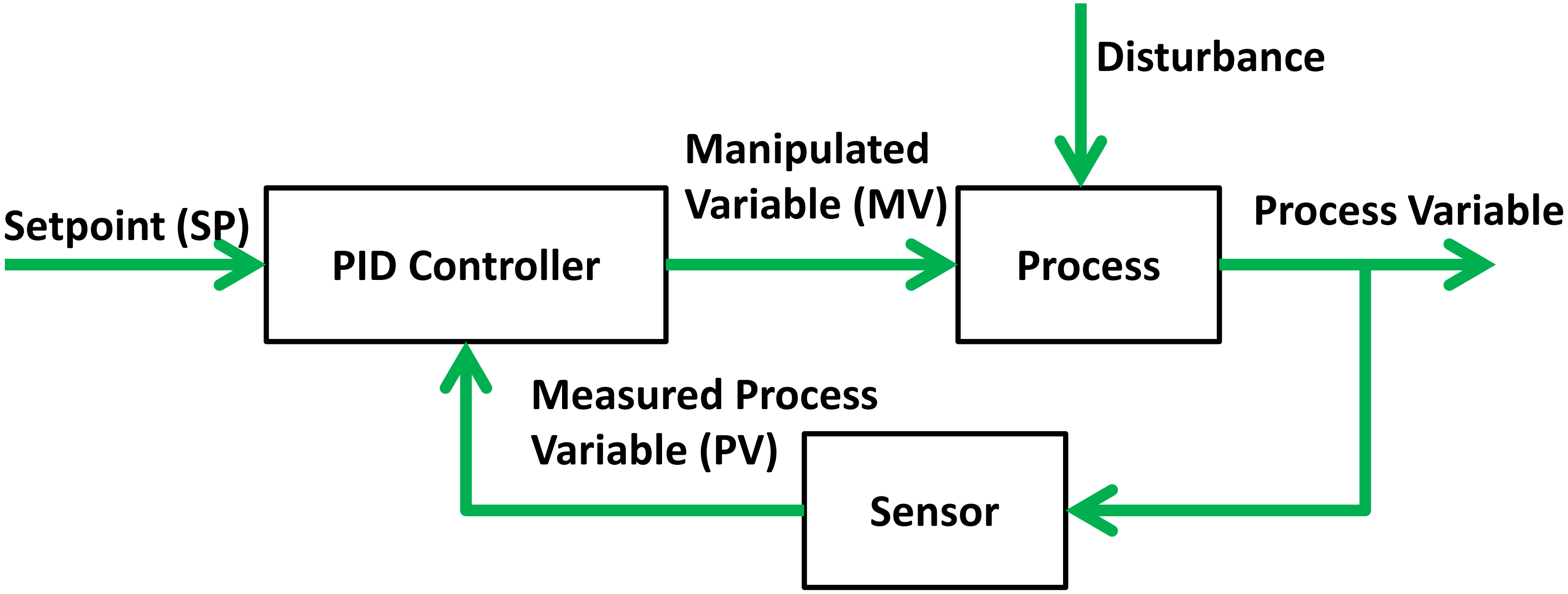
LT Software Solutions, Inc.
WORLD-CLASS AUTOMATION PROVIDER

Outline of discussion

- **What is a PID Loop**
- **Process Reaction**
- **Why Tuning is Important**

What is a PID Loop

A PID loop is an algorithm that provides continuous adjustments to a process so that the end control goal can be met.

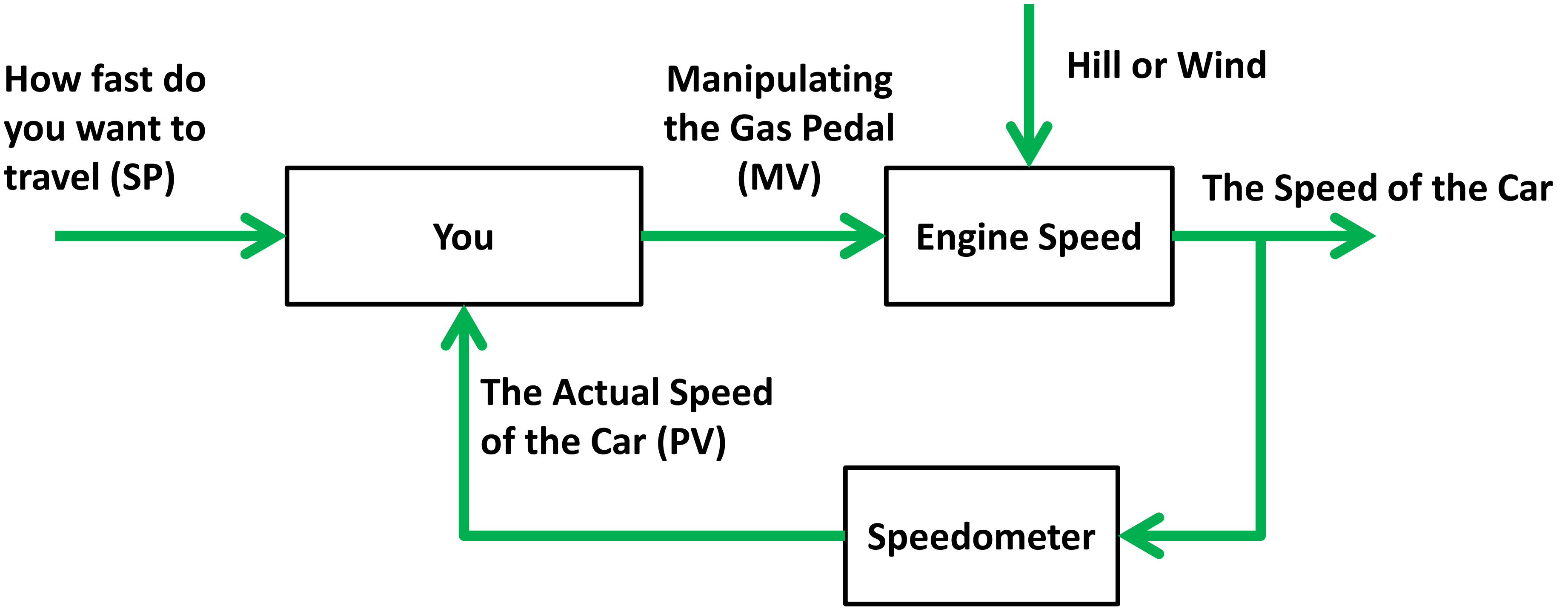


Classic block diagram of a PID Loop

What is a PID Loop

An Everyday example of a You as a PID Loop

Cruise Control



Classic block diagram of a PID Loop – Cruise Control

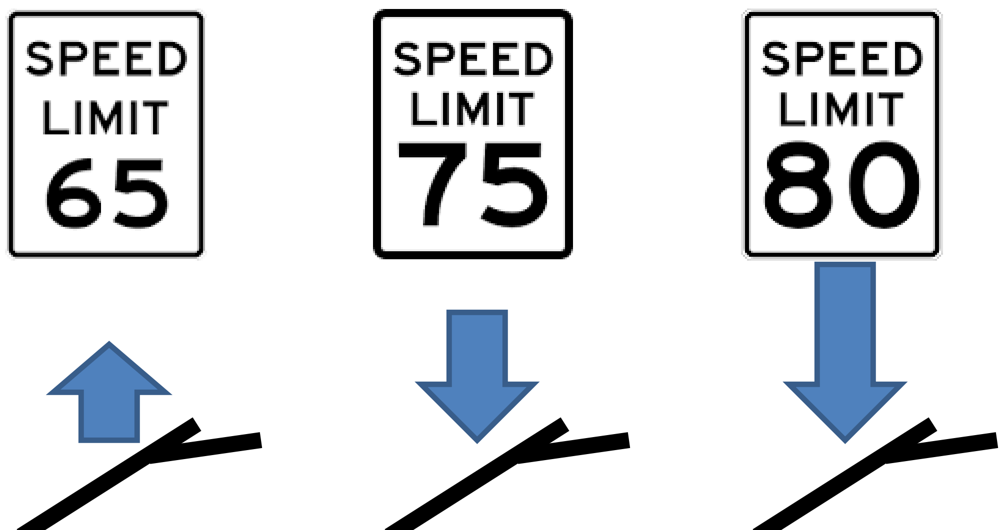
What is a PID Loop

An Everyday example of a PID Loop

Cruise Control

What you need to know

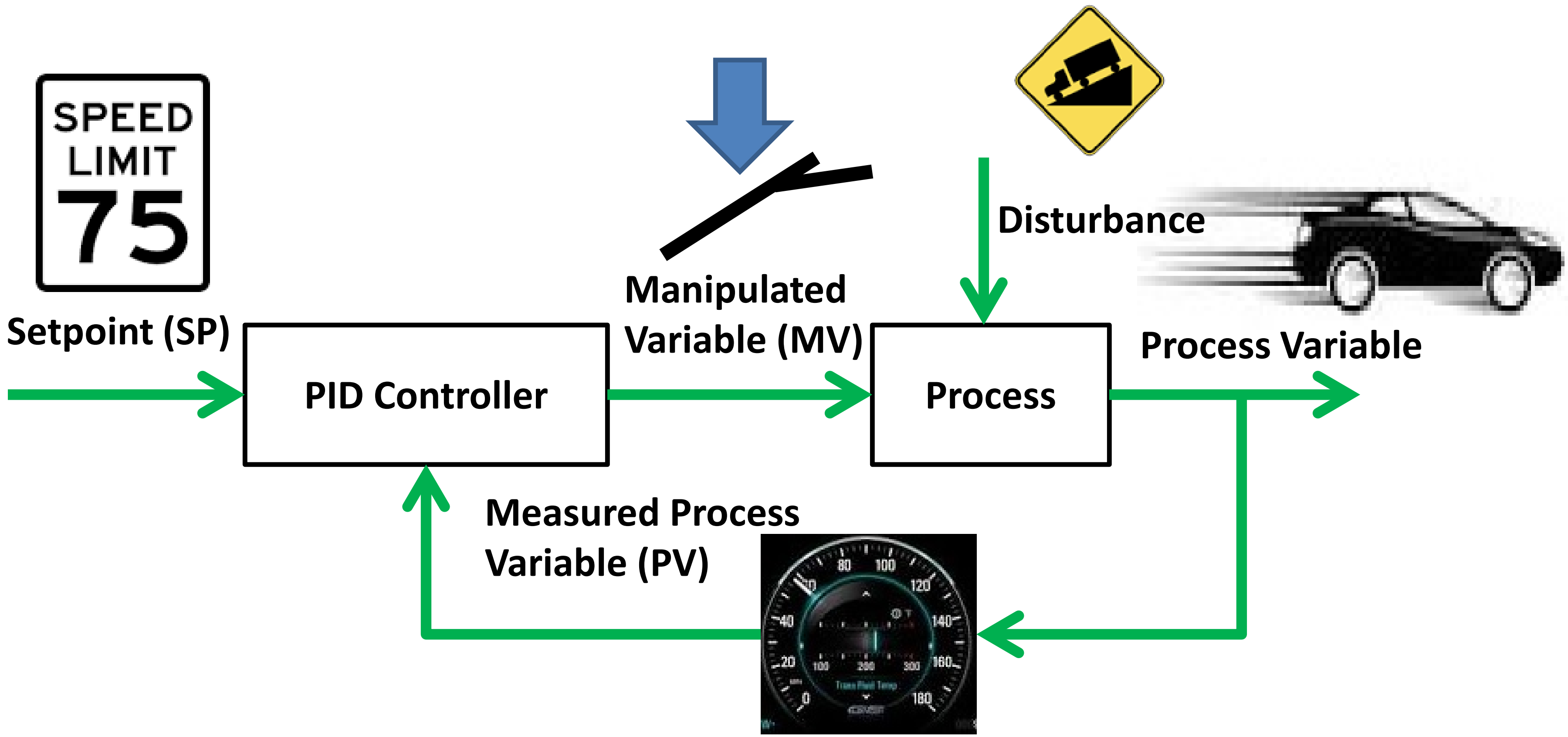
- (PV) How fast are you traveling
- (SP) How fast do you want to travel
- (MV) Do you need more or less gas to meet your goal
- (P Gain) How Soon do you want to reach your goal



What is a PID Loop

Cruise Control Applied to the Classic PID Block Diagram

Cruise Control



Block diagram of a Cruise Control PID Loop

What is a PID Loop

A PID loop is comprised of several parts that work together to achieve the end goal.

SP – Setpoint (Where you want to be)

PV – Process Variable (Where you are)

Error – Difference between the SP and the PV

MV - Manipulated Variable

P – Proportional Gain [Kc] (How much of the instantaneous error to apply to the correction)

I - Integral [*T*i] (How much of the error to integrate over time)

D - Derivative [*T*d] (Correction based on Predicted Rate of Change)

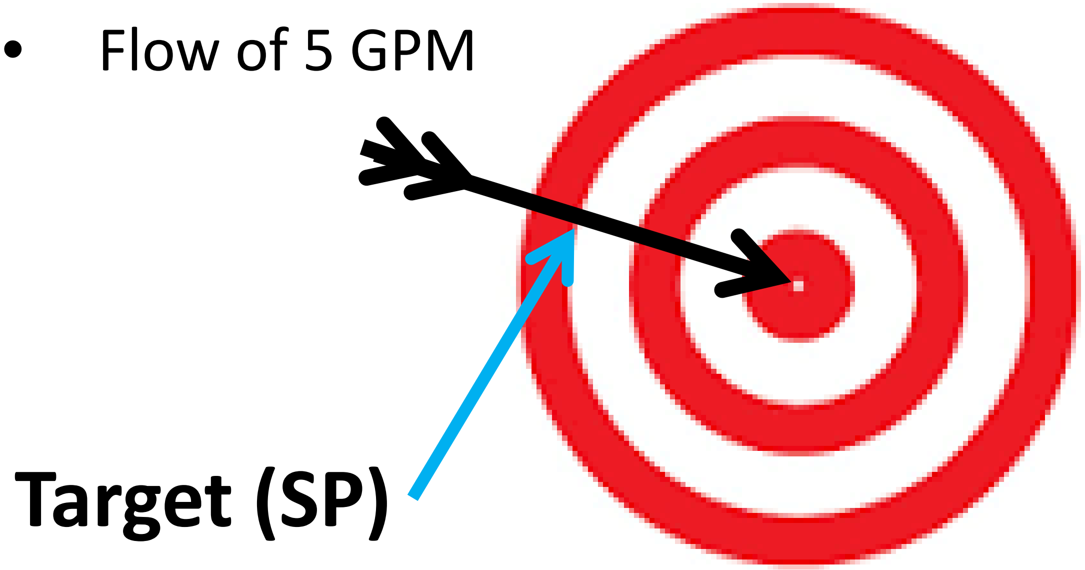
What is a PID Loop

Setpoint (SP)

The setpoint is the end goal of where you want your process to be.

Examples of Setpoints

- Temperature of 130 Deg F
- Level of 75% Full
- Flow of 5 GPM



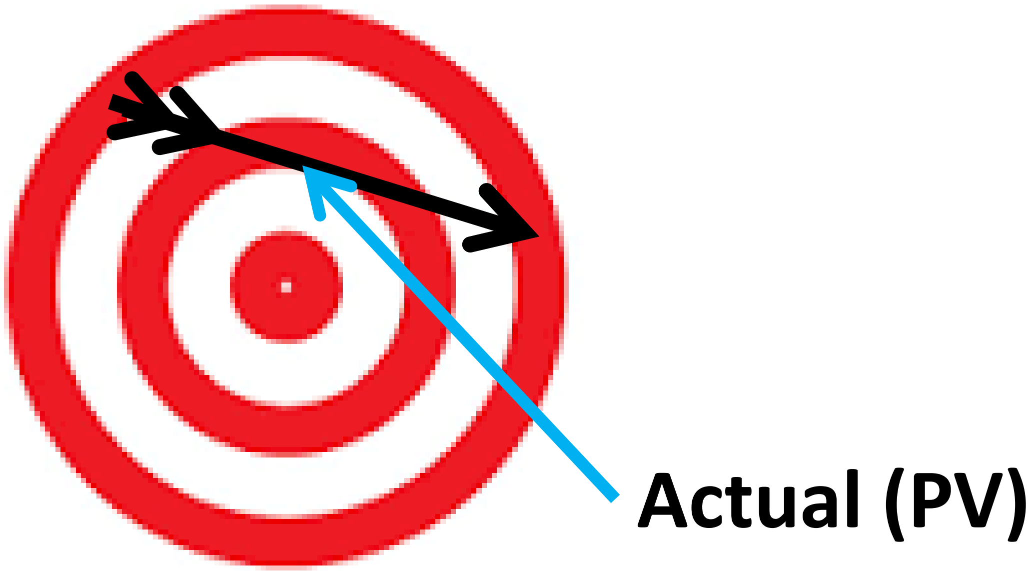
What is a PID Loop

Process Variable (PV)

The Process Variable is the instantaneous measurement of where the process is now.

Examples of Process Variables

- Temperature of 130 Deg F
- Level of 75% Full
- Flow of 5 GPM

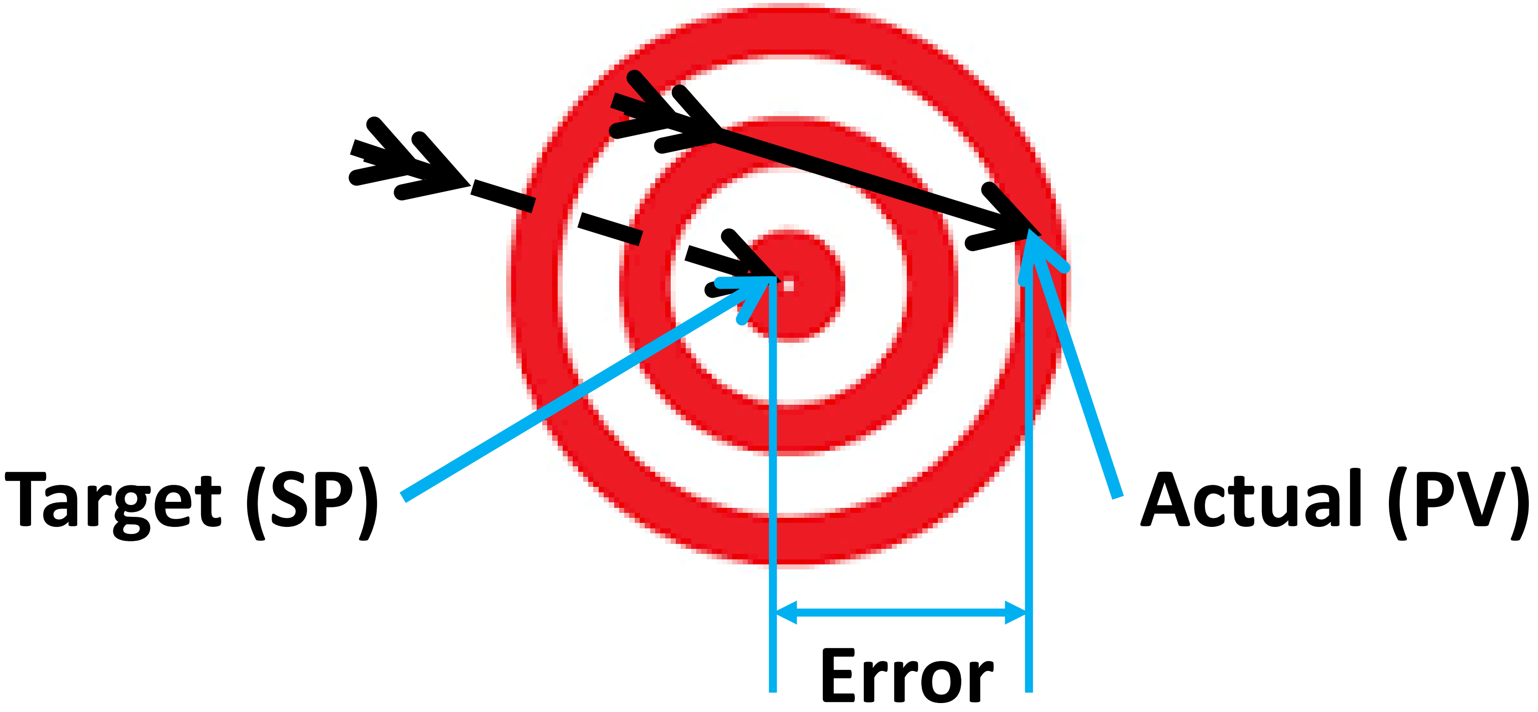


What is a PID Loop

Error

The Error is simply the difference between the Setpoint and the Process Variable.

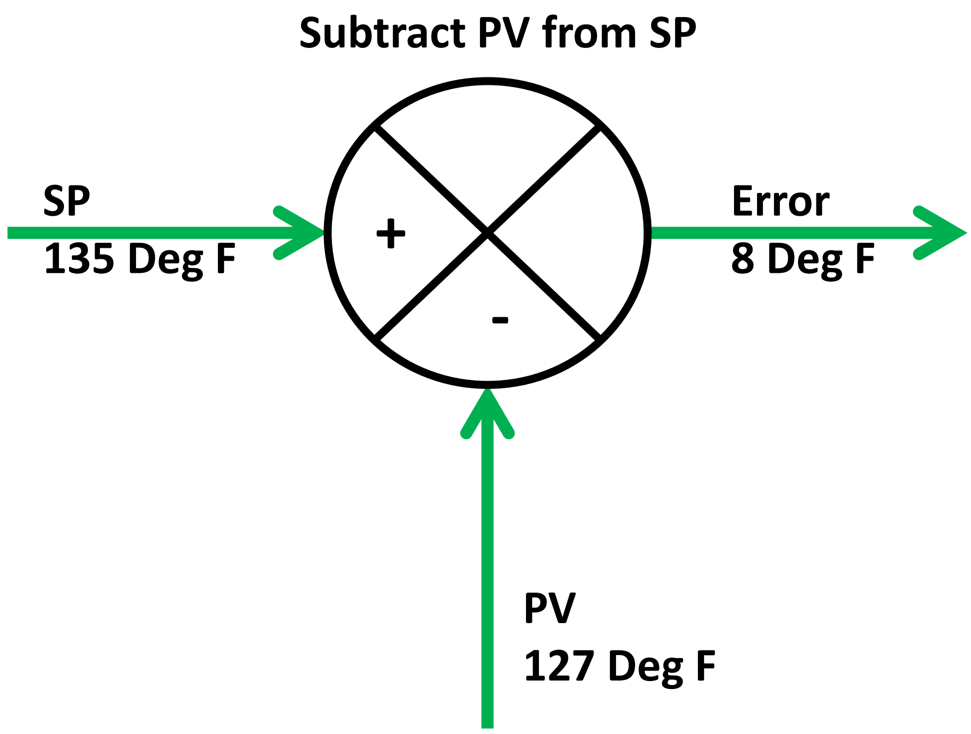
In the world of PID the **error** is what drives the loop.



What is a PID Loop

Error

The Error is simply the difference between the Setpoint and the Process Variable. Remember the **error** is what drives the loop.

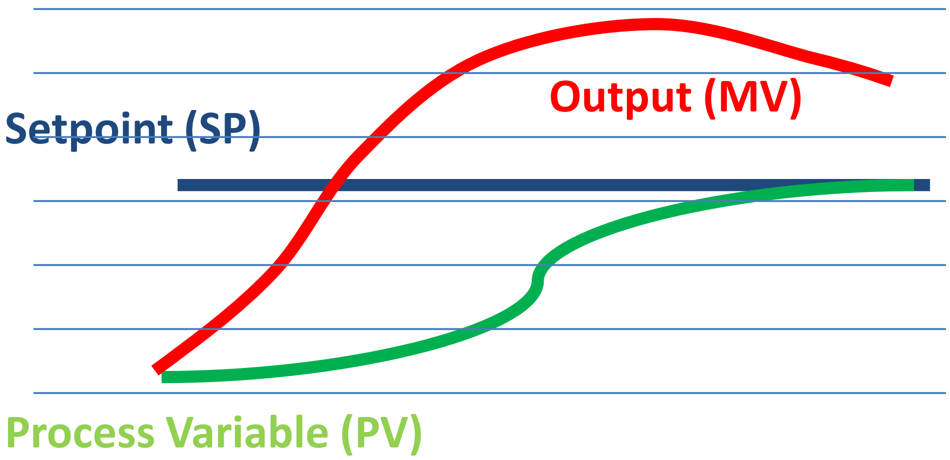


Manipulated Variable (MV)

The Manipulated Variable or the output of the controller is the amount of force or energy that is being put into (Or taken away from) the process and is usually not on the same scale as the SP or the PV. The MV is typically represented in terms of 0 – 100% or On / Off.

Examples of a Manipulated Variable value

- 0%
- 47%
- 100%
- On
- Off



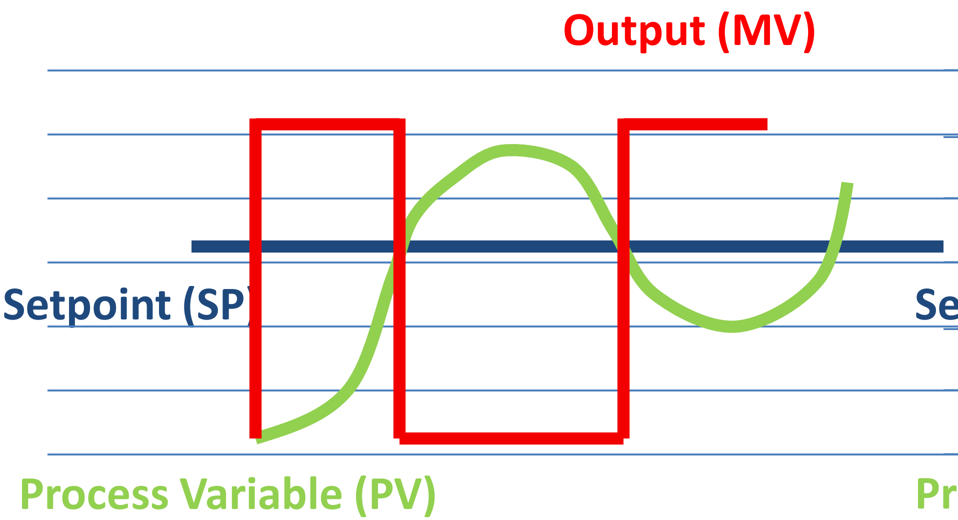
What is a PID Loop

Difference Between On/Off Control and PID Control

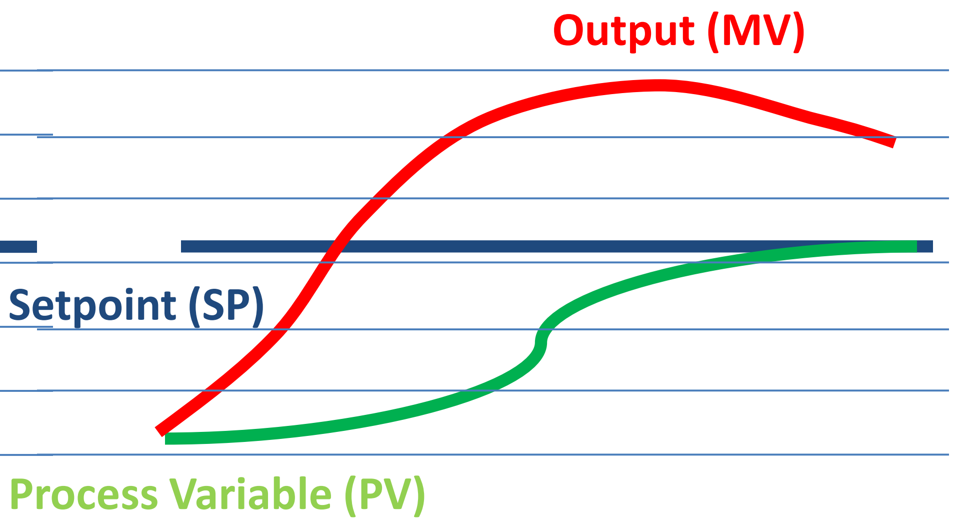
On/Off Control - Apply Energy (Flow, Pressure, Heat, Cooling, etc) until the PV (Actual Value) is **AT** the Setpoint.

PID Control - Apply Energy (Flow, Pressure, Heat, Cooling, etc) so that the PV (Actual Value) **APPROACHES** the Setpoint.

On/Off Control



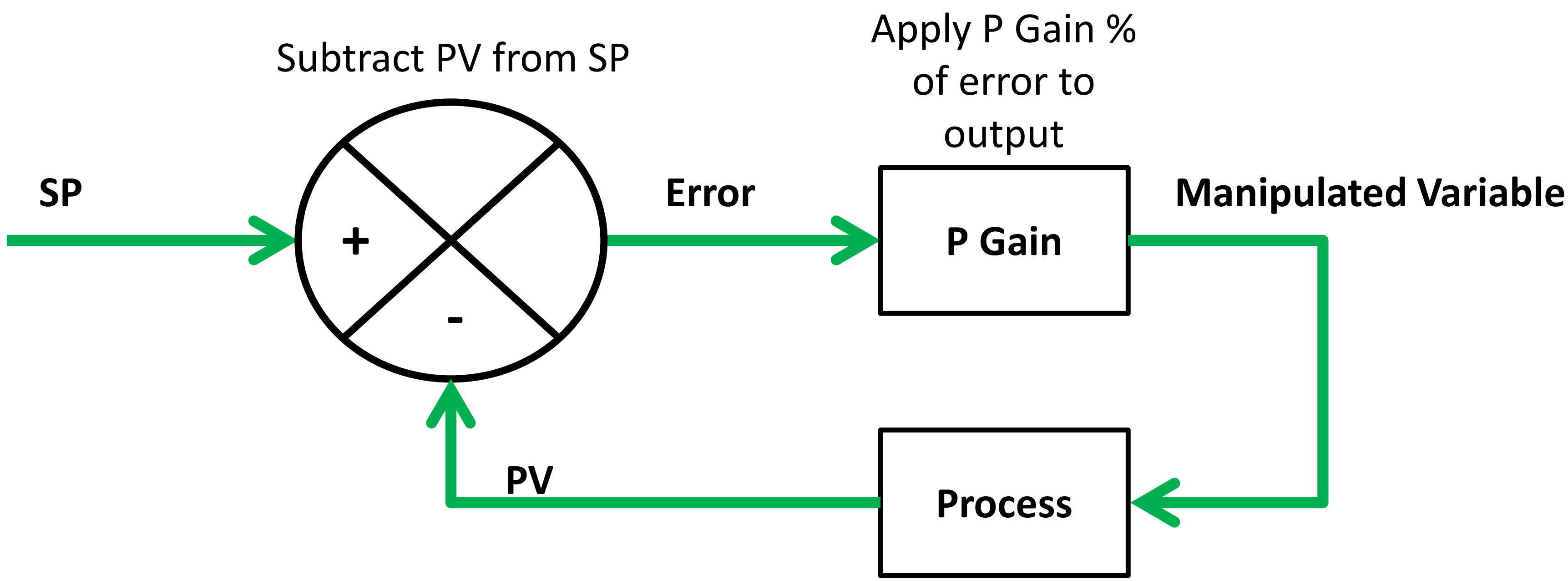
PID Control



Proportional Control Mode

P Gain

The Proportional Gain or Kc is the percentage of the instantaneous error to be applied to the correction of the output. The higher the P Gain the more aggressive the loop corrections, and the faster the loop responds.



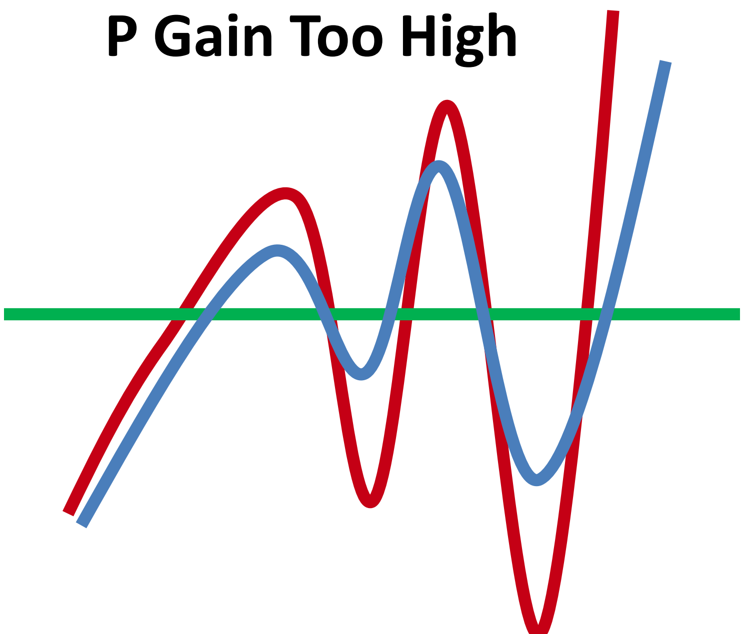
Proportional Control Mode

P Gain

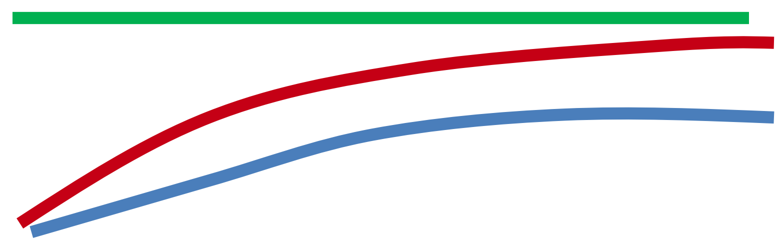
A P Gain that is too high will cause the loop output to become unstable due to over correction.

A P Gain that is too low will cause the loop output to lag behind the target.

P Gain Too High



P Gain Too Low



MV

PV

SP

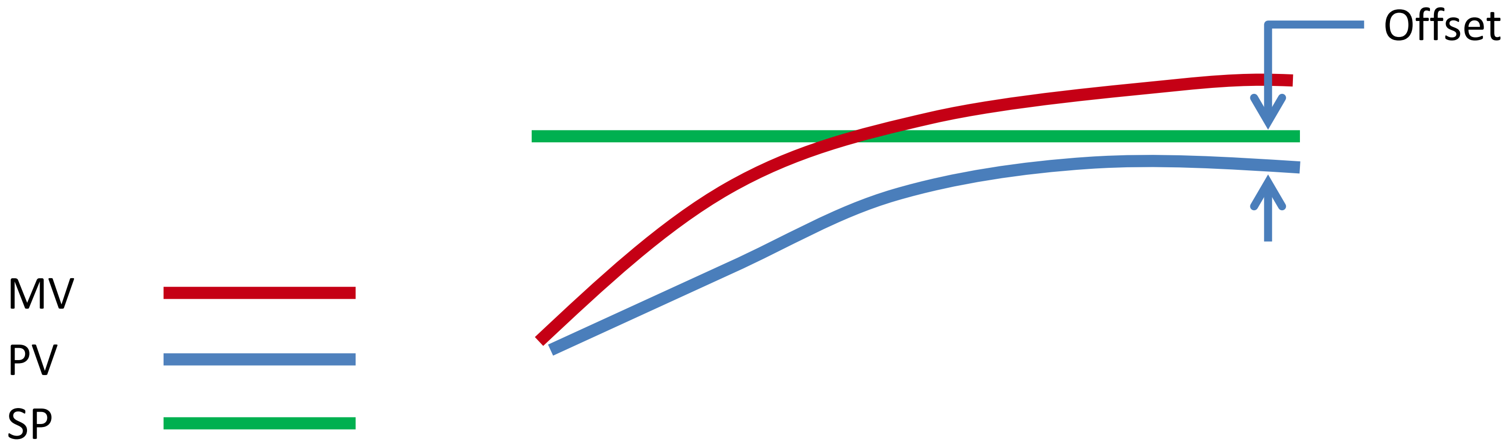
Proportional Control Mode

Proportional Only Control

Under proportional-only control, as the error approaches 0 the effect of proportional control only is generally too marginal to push the PV to reach the setpoint.

This will leave what is called an **offset** which will remain until the operator intervenes and manually changes the controller's output to increase the MV to remove the offset.

When this is done it is said that the operator has manually **"Reset"** the controller.



Proportional + Integral Control Mode

When the Error is TOO Small

When the error becomes so small that the electronics or mechanical components of the system that is being controlled begin to not respond to the changes that are commanded from the PID loop. This is because they either fall in between the resolution points of an Analog Output module or because the inertia of the controlled system is too great to be overcome by such a small difference in the loop output.

Error Gain Adjustment

0.00001 **X** 0.05 = 0.0000005

Process

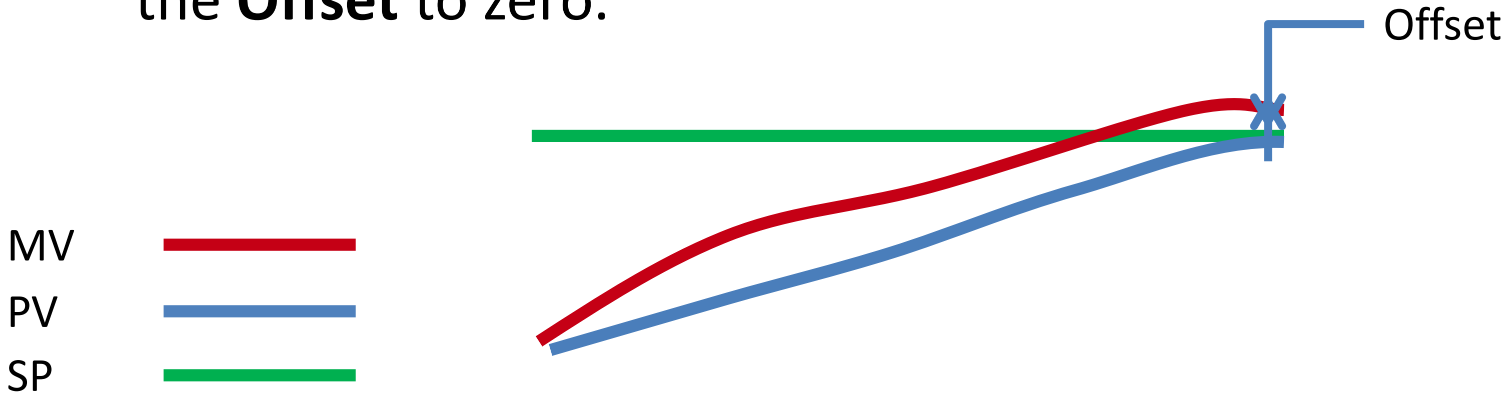
Proportional + Integral Control Mode

Automatic Reset or Integral Control Mode

The need for manually resetting the output of a loop as described in the previous two slides led to the development of Automatic Reset or the Integral Control Mode.

As long as there is an error present the integral control mode will continuously increment or decrement the controller's output to attempt to reduce the error to 0.

Given enough time, and with minimal disturbance the addition of integral action to proportional control will drive the controller output to a point that will reduce the **Error** and thus the **Offset** to zero.



Proportional + Integral Control Mode

Automatic Reset or Integral Control Mode

The effect of the Integral change is based on the size of the error. Large error = fast changes, small error = slow changes .

For any given error, the speed of the integral action is set by the integral time setting of the controller.

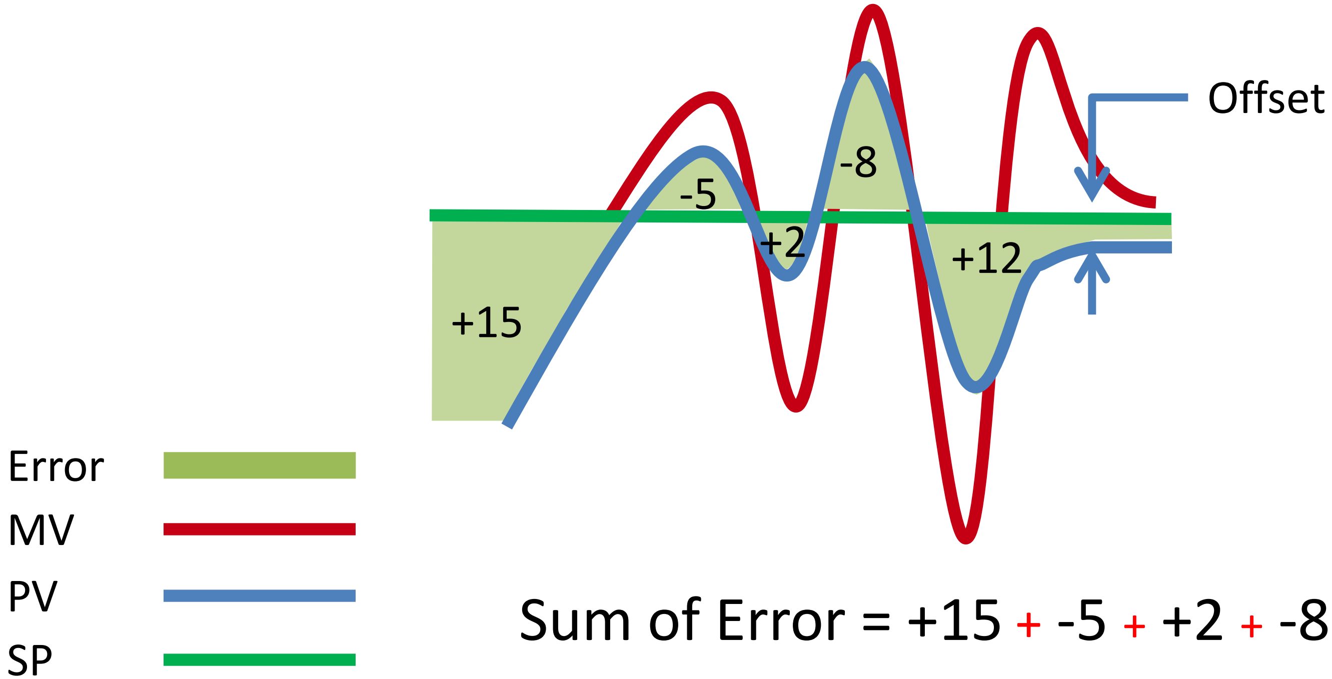
$$\frac{Kc}{Ti} \text{ X Sum of Error} = \text{Integral Action}$$

Proportional + Integral Control Mode

Integral

The Integral Term or *Ti* is used to integrate the sum of the error over time into the output of the control loop.

Without the I Term as the Error approaches 0 the MV will settle at an offset position from the setpoint and be unable to make the last transition to setpoint.



Sum of Error = +15 + -5 + +2 + -8 + +12

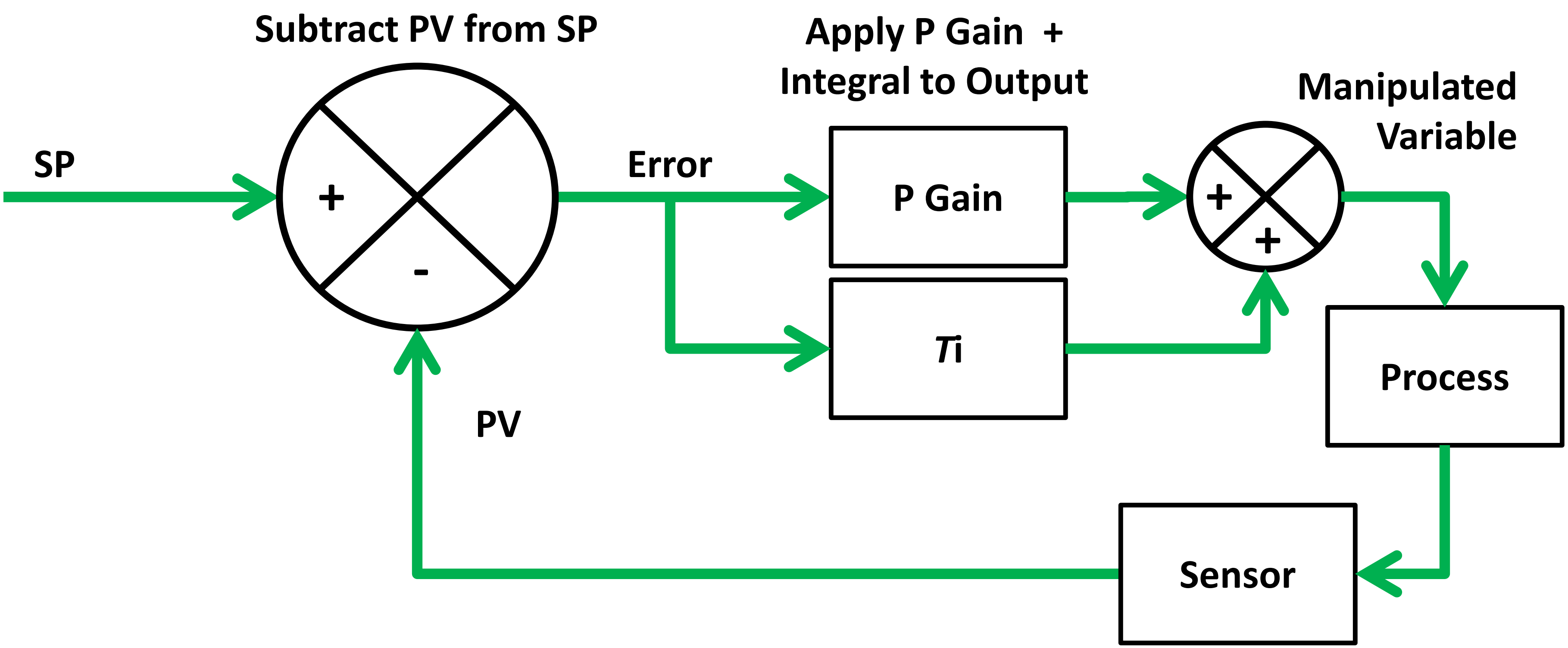
Proportional + Integral Control Mode

I Term (*Ti*)

The Integral Term or *Ti* is used to integrate the sum of the error over time into the output of the control loop.

Adding the *Ti* term to P control results in the classic PI controller.

Almost all of the temperature or pressure control applications in use in modern breweries today only require PI control.



Proportional + Integral + Derivative Control Mode

D Term (*T*d)

The Derivative Term or *T*d is most often used in motion control and is rarely used in Process Control.

*T*d is used to change the output (MV) based on the predicted **rate of chang**e of the error.

The Derivative mode produces more control action if the error changes at a faster rate. If there is no change in the error, (Steady State) the derivative action is zero.

Using Derivative allows larger P and *T*i terms to be used and can provide for much more aggressive control loops.

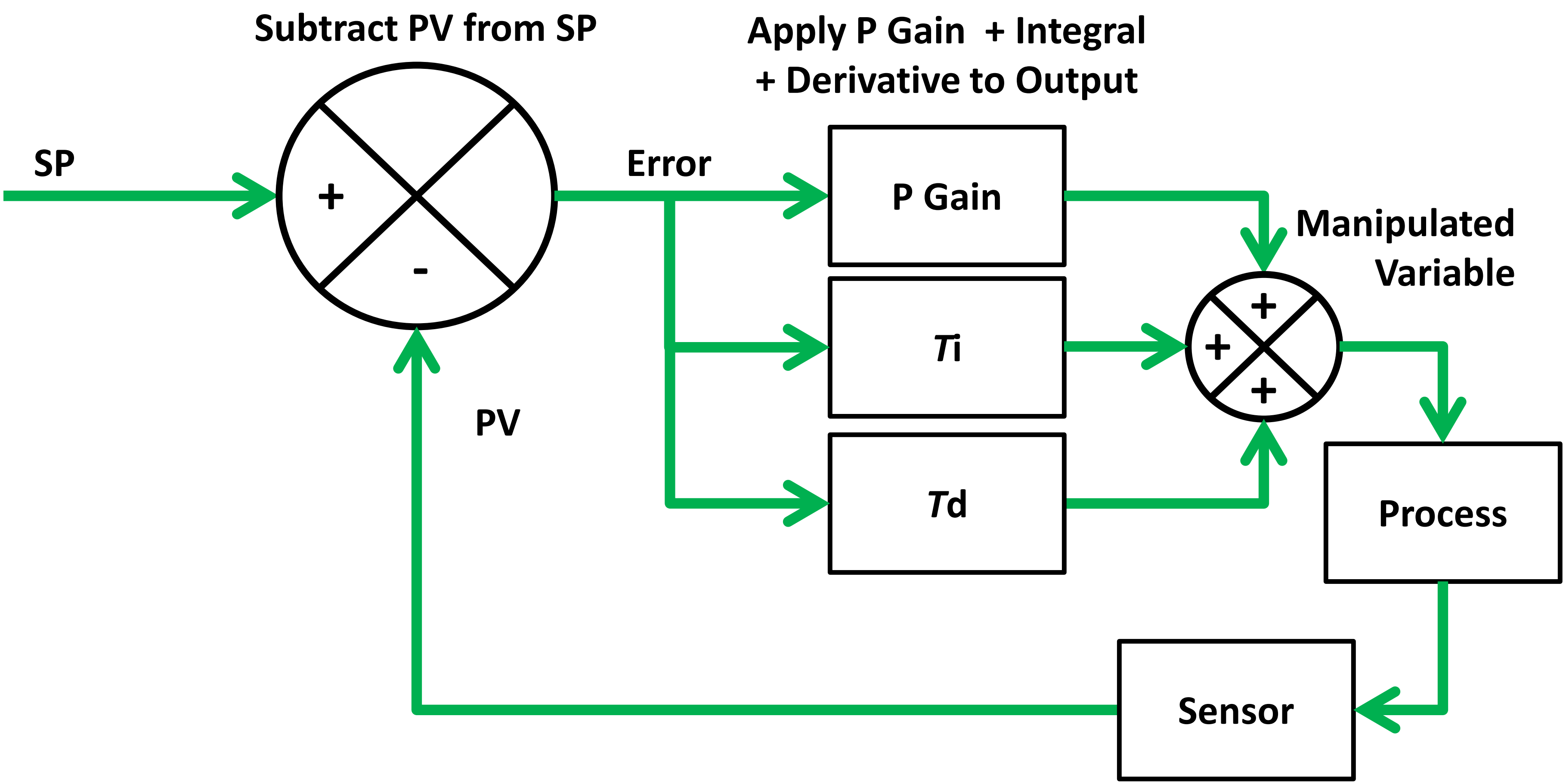
As with P and *T*i, if the *T*d time is set too long, oscillations may occur and the control loop will become unstable.

If the PV has a high noise level Derivative is not recommended as this will tend to make the loop unstable.

Proportional + Integral + Derivative Control Mode

D Term (*T*d)

The Derivative Term or *T*d is used to change the output (MV) based on the predicted **rate of change** of the error.



PID Application

Applications

Practical applications of PID loops in a modern brewery typically include:

- Temperature control of large tanks of liquid.
  - Fermentation, Utility Hot Water, Brew Kettle
- Temperature control of small volumes of liquid
  - Knockout Temperature, Strike or Underlayment water
- Flow control of liquid
  - Wort Flow, Strike Rate
- Pressure control
  - Brew Kettle Pressure, CO_2 Pressure

Process Reactions

Process Reactions

Each of the processes under PID control will have different reaction times primarily due to the mass of product involved and the differential between the **Process** being controlled and the **Energy Source** being used.

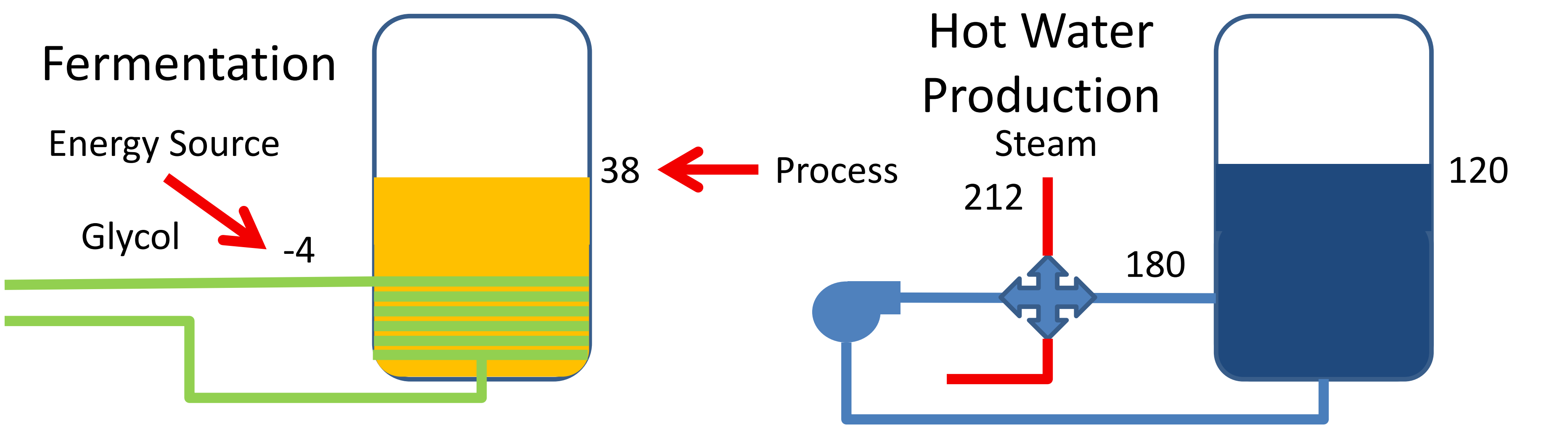
In most cases the **Energy Source** will be Steam, Differential Water Temperature, or Differential Pressure.

Process Reactions

Process Reactions – Temperature Control in Large Volumes

Temperature control of large tanks of liquid.

- Glycol vs Fermenter - Typically changes very slowly
  - Low differential between process and energy source
  - Large mass that is fairly resistant to temperature change
- Hot Water vs Water Tank - Typically changes very slowly
  - Low differential between process and energy source
  - Large mass that is fairly resistant to temperature change



Process Reactions – Proper Tuning

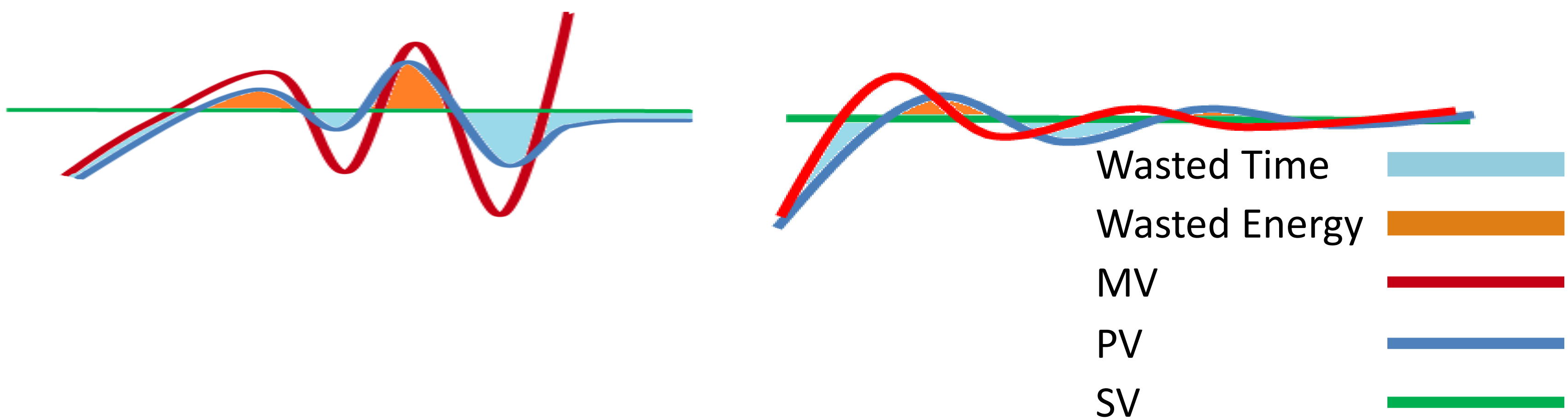
The Effects of Proper Tuning on Process Reactions in Large Volumes

In large volumes a poorly tuned PID loop may be masked by the large inertia of the system that is being controlled.

You can see that there is not much difference between the two examples but there is still waste in the poorly tuned loop, Multiply that waste by 24 hours a day and 365 days a year and it adds up.

Improperly Tuned Loop

Properly Tuned Loop

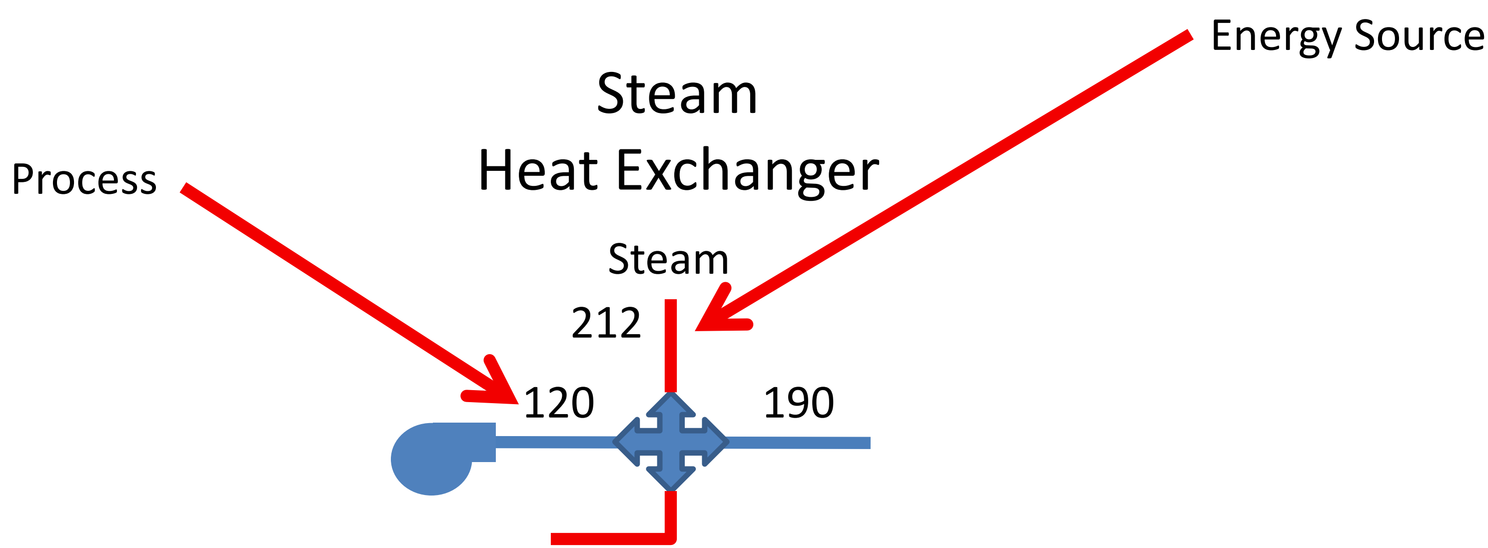


Process Reactions

Process Reactions – Temperature Control in Small Volumes

Temperature control of small volumes of liquid.

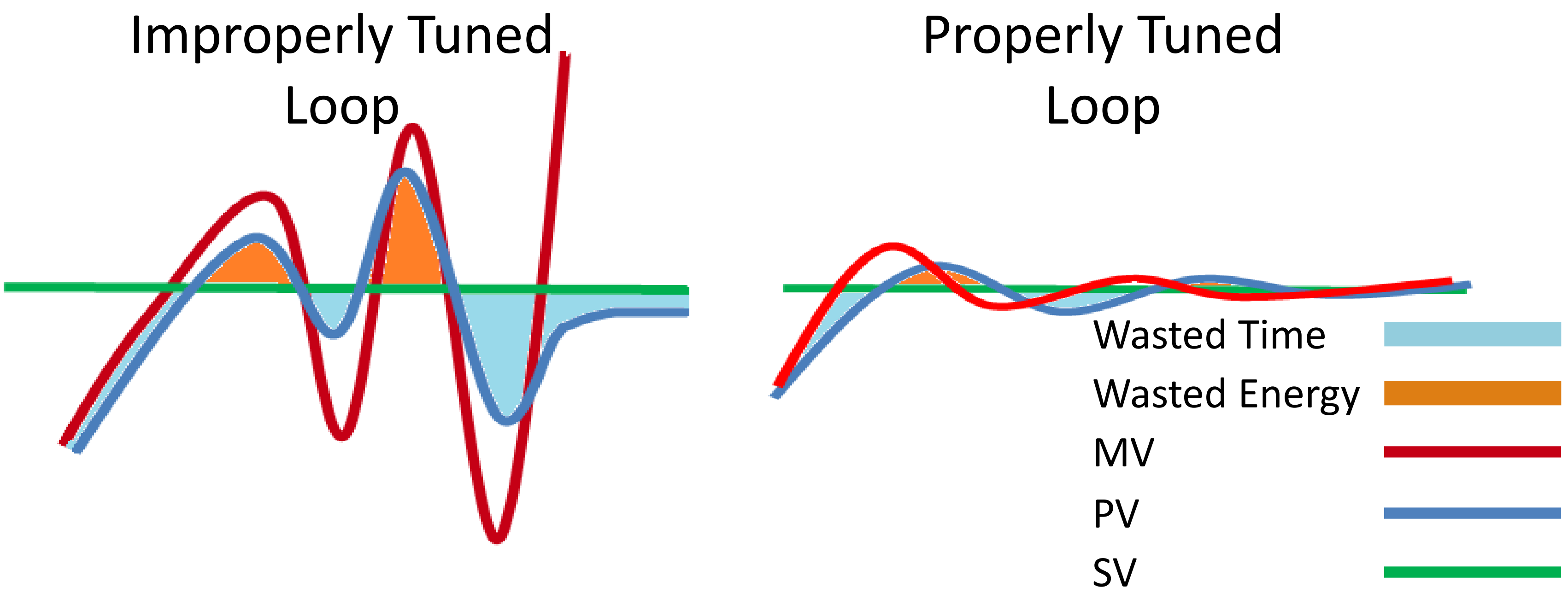
- Steam vs Water - Typically changes very quickly
  - High differential between process and energy source
  - Small mass that changes temperature fairly quickly



Process Reactions – Proper Tuning

The Effects of Proper Tuning on Process Reactions in Small Volumes

In small volumes a poorly tuned PID loop will result in erratic control and will not produce the required temperature or pressure. There is quite a bit of difference between the two examples and there is a great deal of wasted energy and time in the poorly tuned loop. This will result in poorly controlled temperature and a delay in getting the process under control.

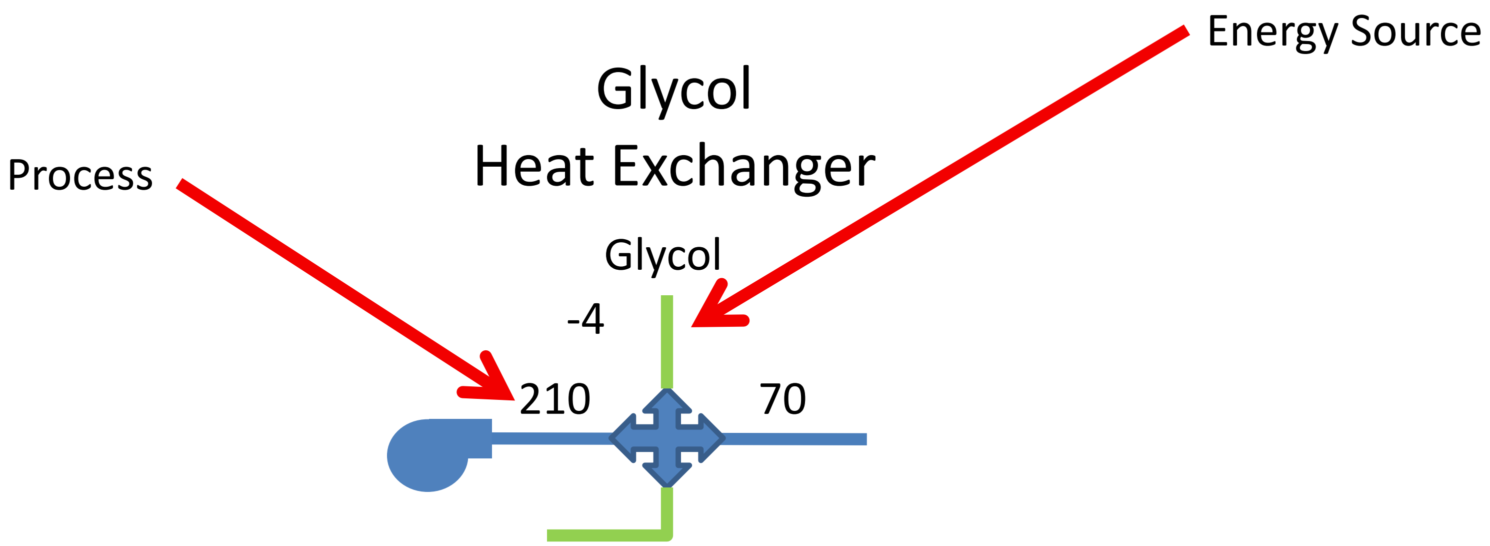


Process Reactions

Process Reactions – Temperature Control in Small Volume

Temperature control of small volumes of liquid.

- Glycol vs Wort - Typically changes very quickly
  - High differential between process and energy source
  - Small mass that changes temperature fairly quickly



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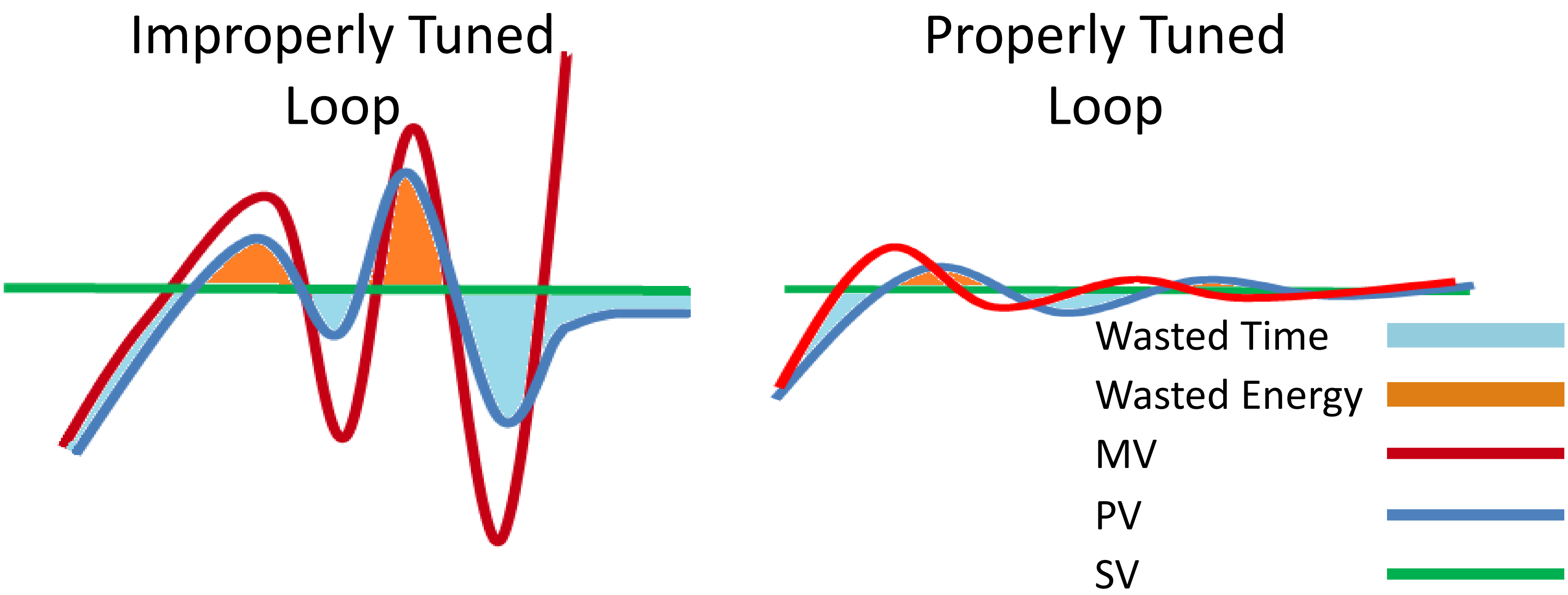
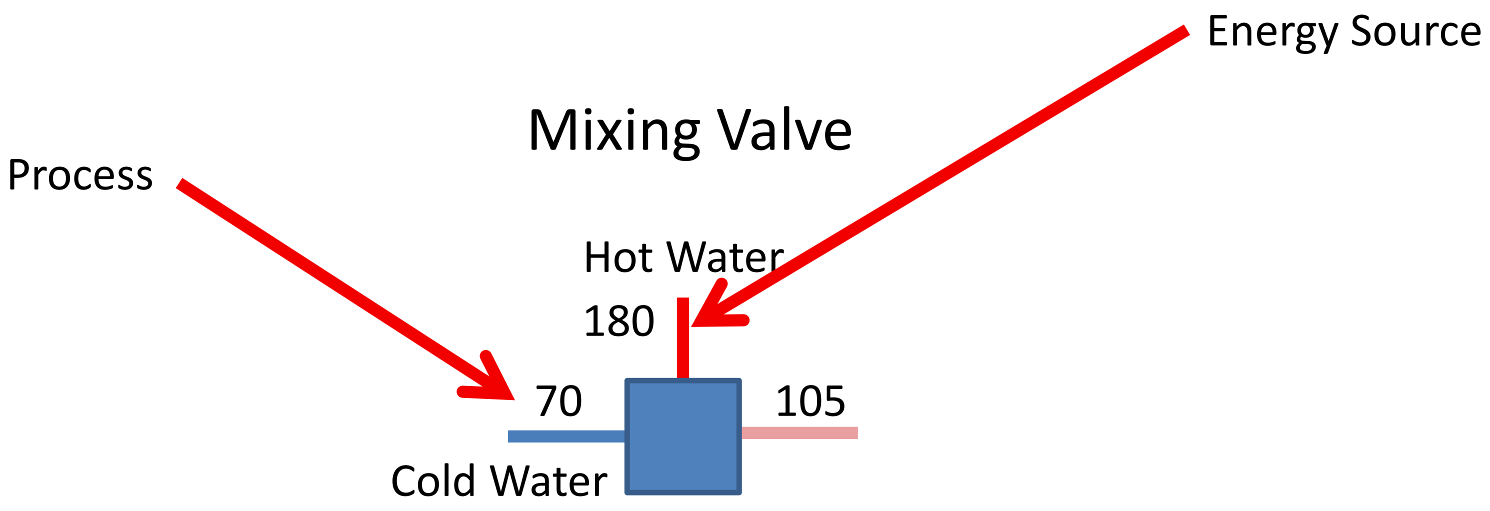


Process Reactions

Process Reactions – Temperature Control in Small Volume

Temperature control of small volumes of liquid.

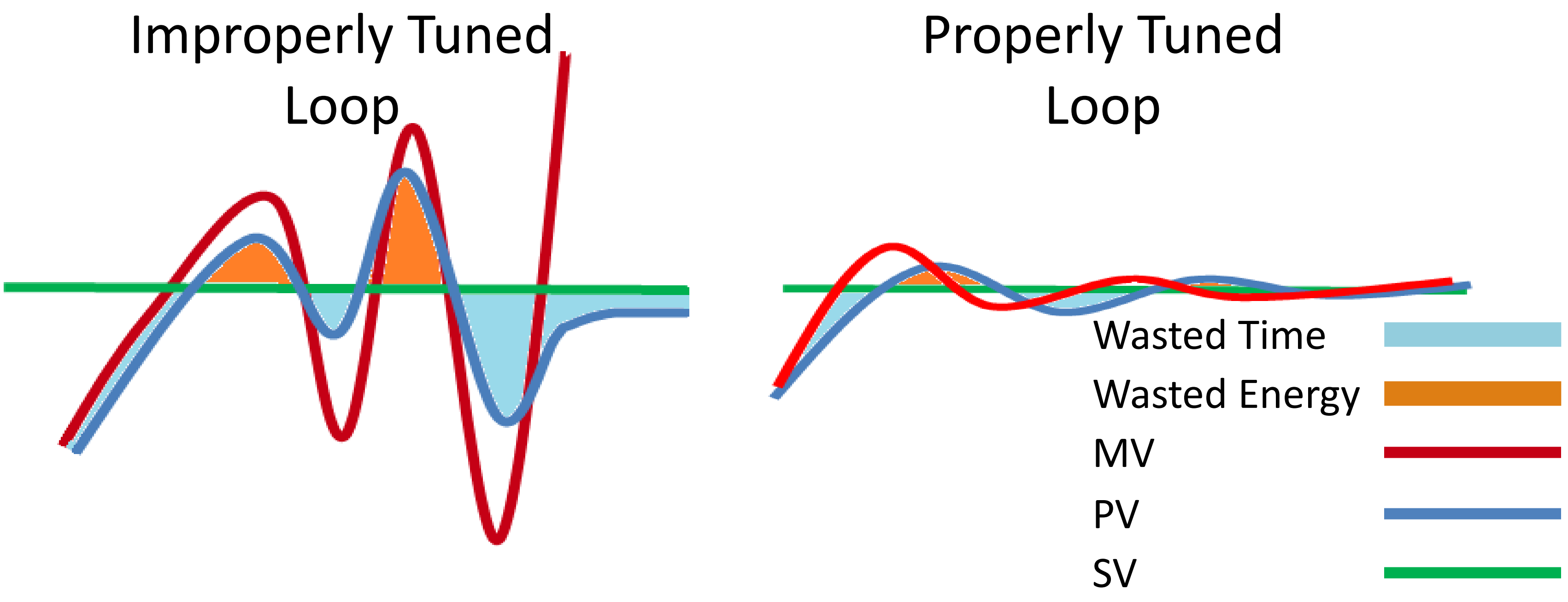
- Mixing Valve vs Water Temp - Typically changes moderately
  - Low differential between process and energy source
  - Small mass that changes temperature fairly quickly
  - May not be linear due to characteristics of actuator



Process Reactions – Proper Tuning

The Effects of Proper Tuning on Process Reactions in Small Volumes

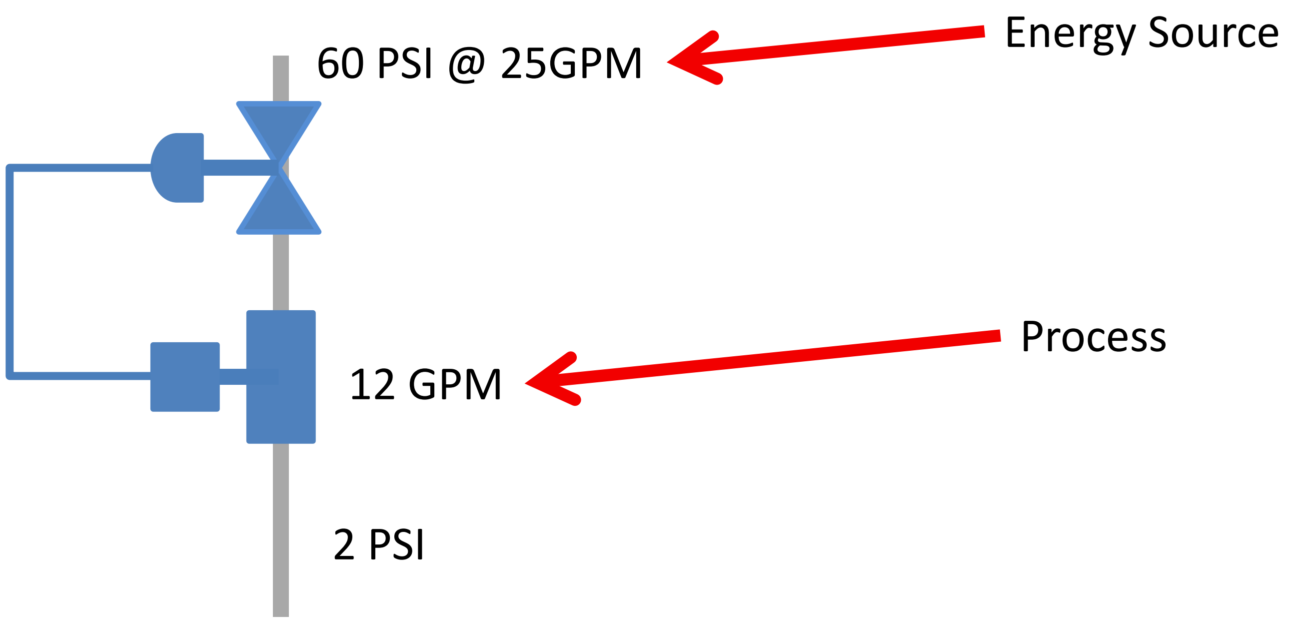
In small volumes a poorly tuned PID loop will result in erratic control and will not produce the required temperature or pressure. There is quite a bit of difference between the two examples and there is a great deal of wasted energy and time in the poorly tuned loop. This will result in poorly controlled temperature and a delay in getting the process under control.



Process Reactions – Flow Control

Flow control of liquid.

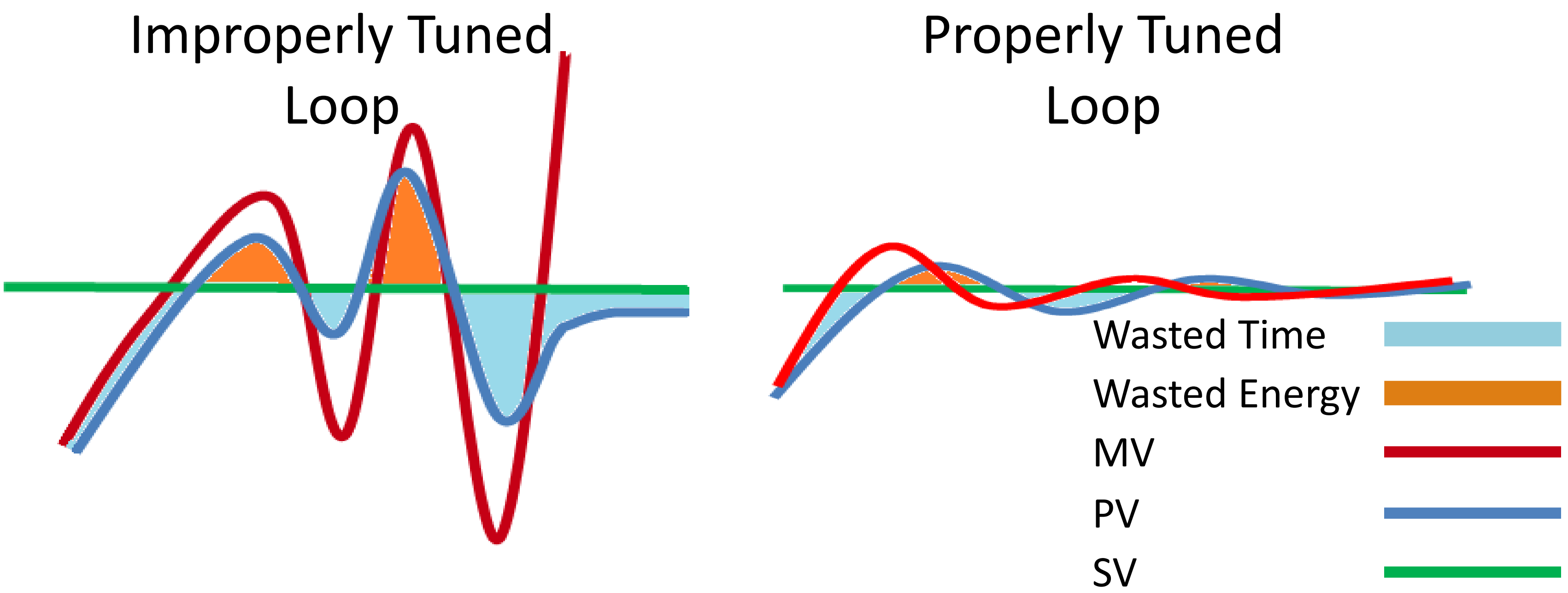
- Control Valve vs Water Flow - Typically changes moderately
  - Medium differential between Process and Energy Source
  - Small mass that changes rate fairly quickly



Process Reactions – Proper Tuning

The Effects of Proper Tuning on Process Reactions in Flow Control

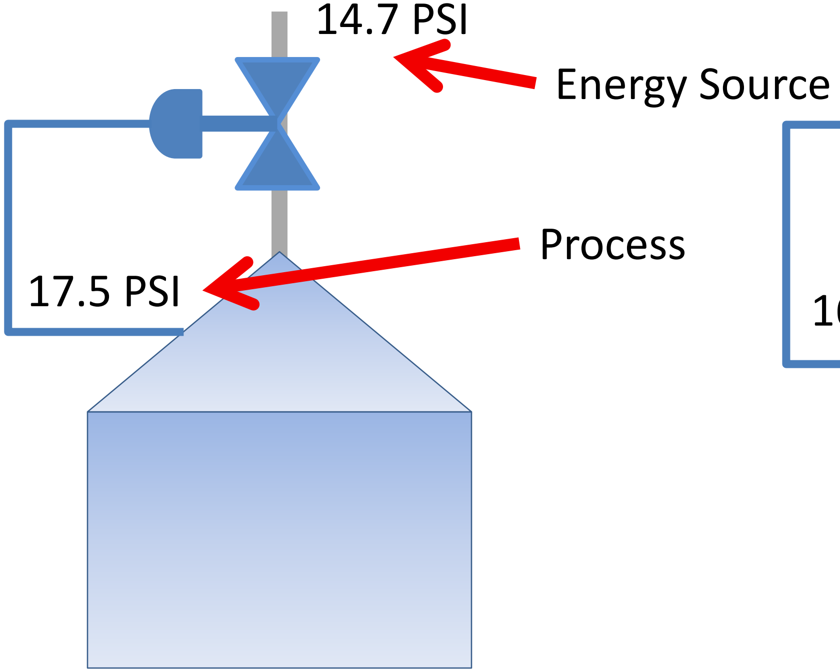
When applied to Flow Control a poorly tuned PID loop will result in erratic control and will not produce the required Flow Rate. There is quite a bit of difference between the two examples and there is a great deal of wasted time in the poorly tuned loop. This will result in poorly controlled Flow Rate and a delay in getting the process under control.



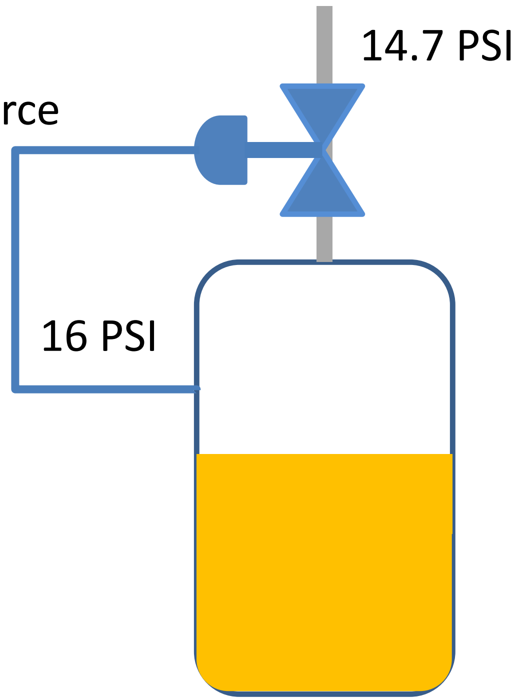
Process Reactions – Pressure Control

Pressure control of gas.

- Control Valve vs Pressure - Typically changes moderately
  - Low differential between process and energy source
  - Small mass that changes rate fairly quickly



Brew Kettle Pressure



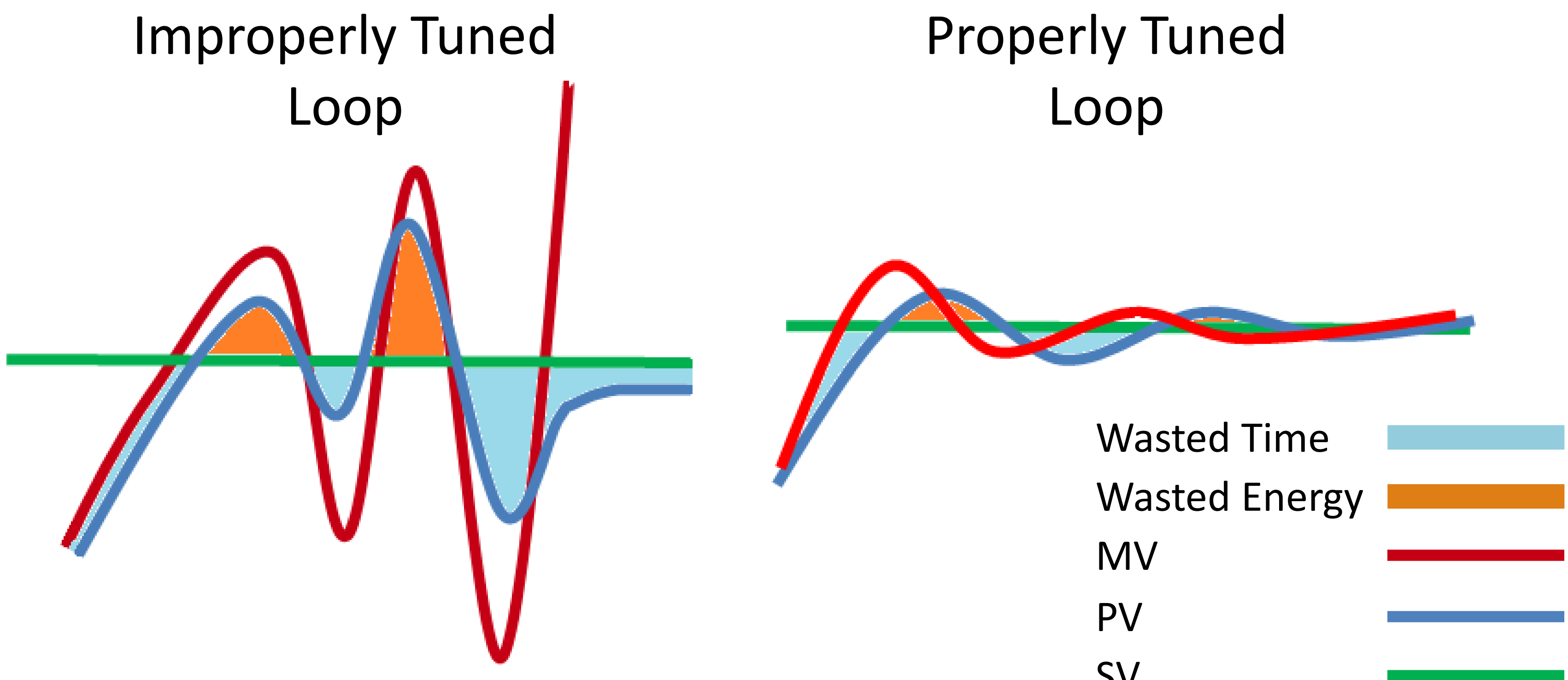
CO2 Pressure

Process Reactions – Proper Tuning

The Effects of Proper Tuning on Process Reactions in Pressure Control

In general a properly tuned PID loop will require less energy and will provide a higher throughput for your process.

Improperly tuned PID loops waste energy and will increase the amount of time required for a process to settle and become stable.



PID Tuning – The Basics

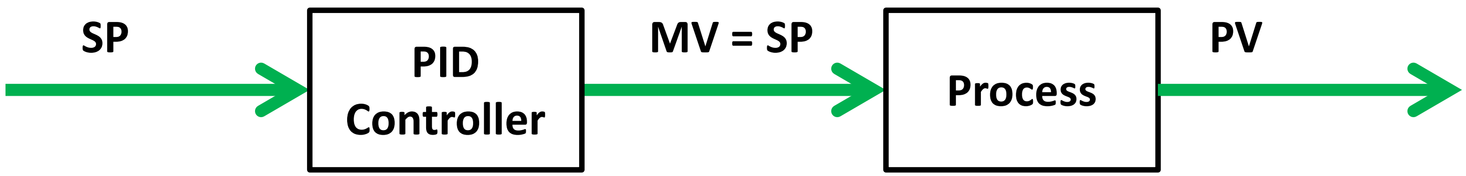
The Basics

Before we can attempt to tune any PID loop we first need understand the type of process that is being controlled. The type of process is generally defined by its dynamic characteristics. Which is, how does the process variable (PV) react when the process is put into manual mode and the Manipulated Variable (MV) is stepped up or down.

PID Tuning – The Basics

Manual Mode

Putting the process into manual removes the feedback from the process and the controller simply sets the MV to the value of the SP. Your particular PID controller may have a mechanism of setting the MV directly without changing the SP.



Loop placed in Manual

PID Tuning – The Basics

Process Types

PID loops in a modern brewery the process types fall into these two areas:

- Self Regulating
- Integrating

Self Regulating Process

If you step your SP in open loop and this causes the PV to start rising or falling, but the gradient quickly starts to decrease until it has leveled off to a flat slope then your process is Self Regulating.

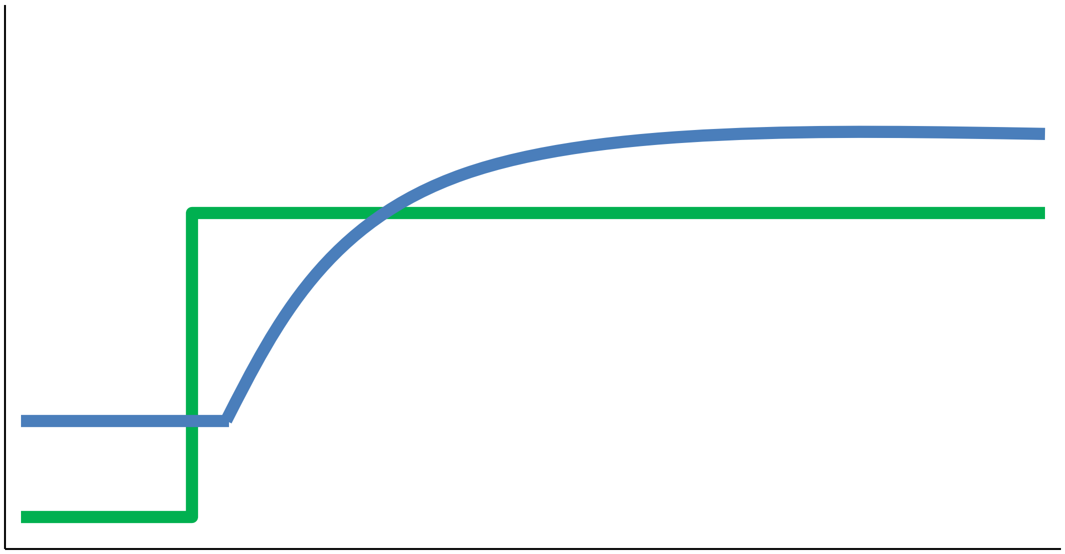
Integrating Process

If you step your SP in open loop and this causes the PV to start rising or falling and it keeps moving in that same direction in a mostly linear fashion then your process is an Integrating Process.

PID Tuning – Self Regulating Process

Self Regulating Process

A Self Regulating Process can be identified by the flat slope of the PV after an initial rise or fall in response to a change in the MV in Manual Control.

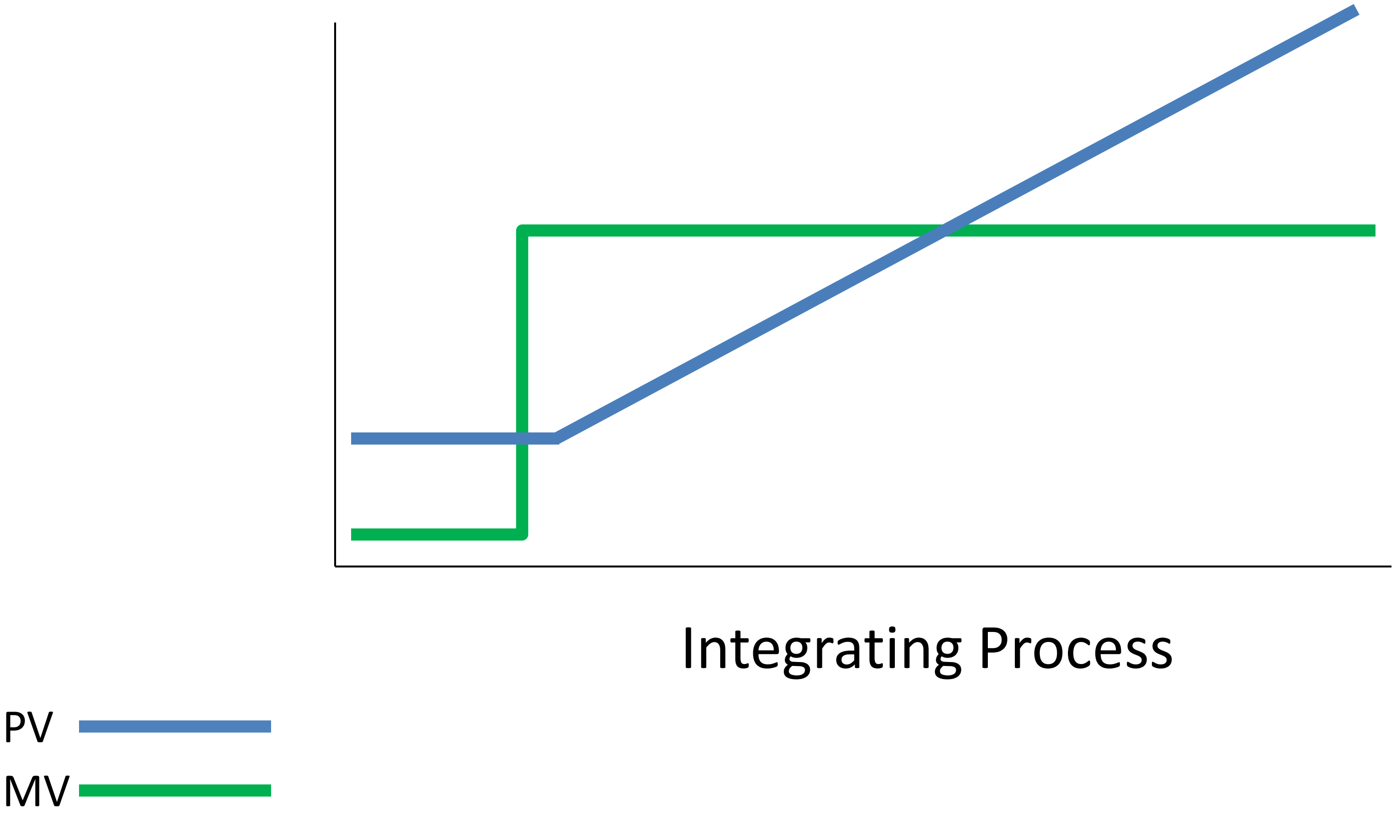


Self Regulating Process

PID Tuning – Integrating Process

Integrating Process

An Integrating Process can be identified by the linear slope of the PV in response to a change in the MV in Manual Control.



Integrating Process

PID Tuning – How will your Process React

Warning

Think about what will happen to your process when it is stepped in manual open loop. You need to be aware that some processes may be too reactionary for this procedure to be performed safely.

PID Tuning – Identifying Your Process Type

Identification Process

To identify the type of process you are to be dealing with you can follow these basic steps:

1. Place the PID controller in Manual.
2. Once in Manual the MV will be set to the SP or you may need to manipulate the MV directly.
3. Making sure that you stay within safe limits, Step the SP (MV) plus or minus a few percentage points.
4. Look at the slope of the PV and identify the type of process.
5. If you find that the process is Integrating make sure to set the SP (MV) back to its original setting to arrest the change in PV.

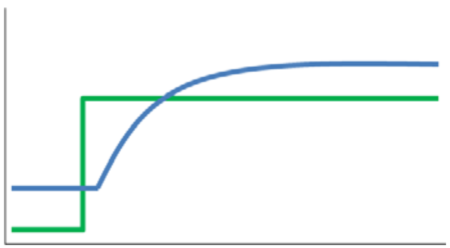
Note: Keep in mind that hysteresis in actuator(s) and the process itself may require an SP (MV) that is on the other side of the original value to completely arrest the PV.

PID Tuning – How will your Process React

Process Types

These diagrams show how you would expect to see a Self Regulating Process and an Integrating Process react.

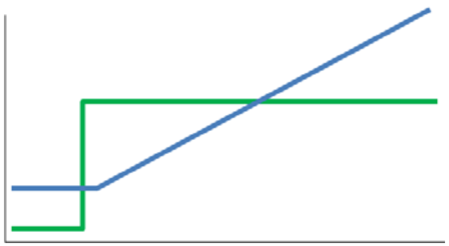
Self Regulating Process



Self Regulating Process Examples

- Water Flow
- Tank Pressure with fixed exhaust orifice
- Fermentation Temperature
- Brew Kettle Heat

Integrating Process



Integrating Process Examples

- Tank Level Control
- Steam Heat Exchanger

PID Tuning – How will your Process React

Process Types

Note: An Integrating Process may appear as a Self Regulating Process if enough external force (i.e. Heat Loss, Pressure Relief Valve, or Vessel Overpressure) is applied to the process.

Ziegler – Nichols PID Tuning Method

Tuning Procedure

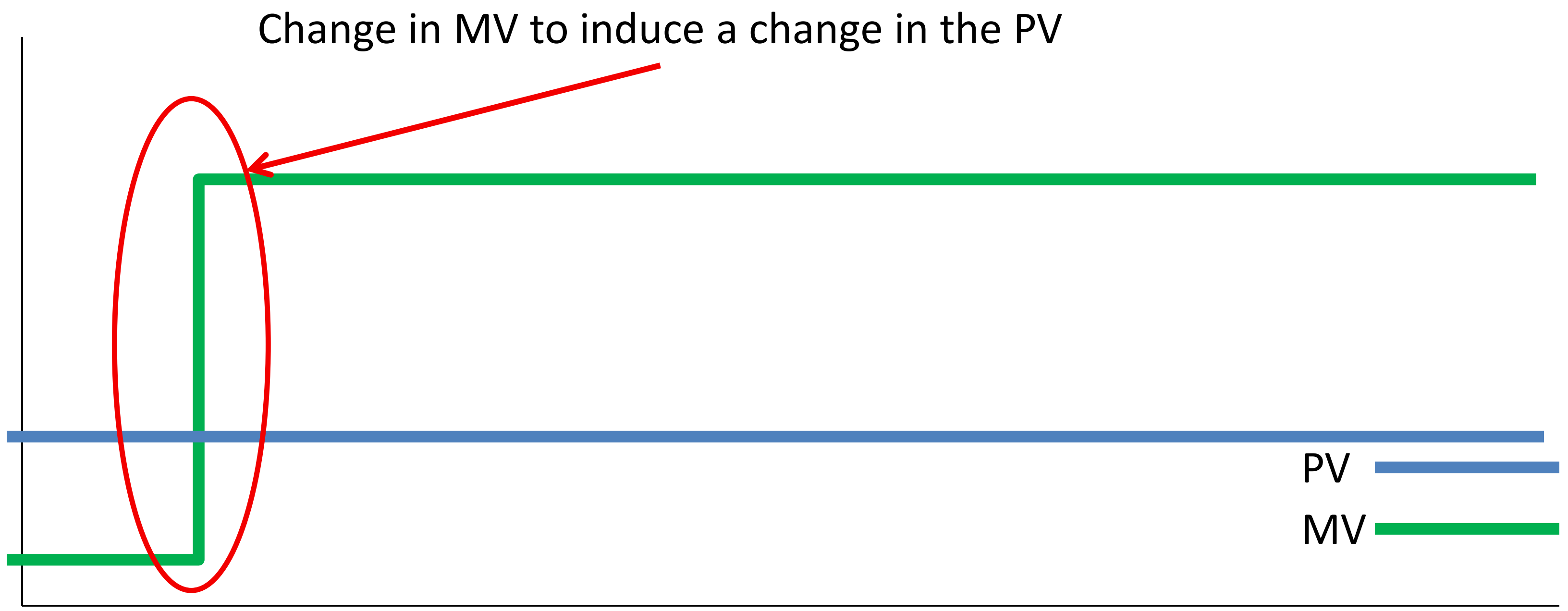
Assuming the control loop is linear and the final control element is in good working order you can use the Ziegler-Nichols open loop tuning method.

The Ziegler-Nichols open-loop tuning rules use three process characteristics: Process Gain (pg), dead time (t_d), and Differential Time (tau). These are determined by performing an open loop step test and analyzing the results.

Ziegler – Nichols PID Tuning Method

Self Regulating Tuning Procedure

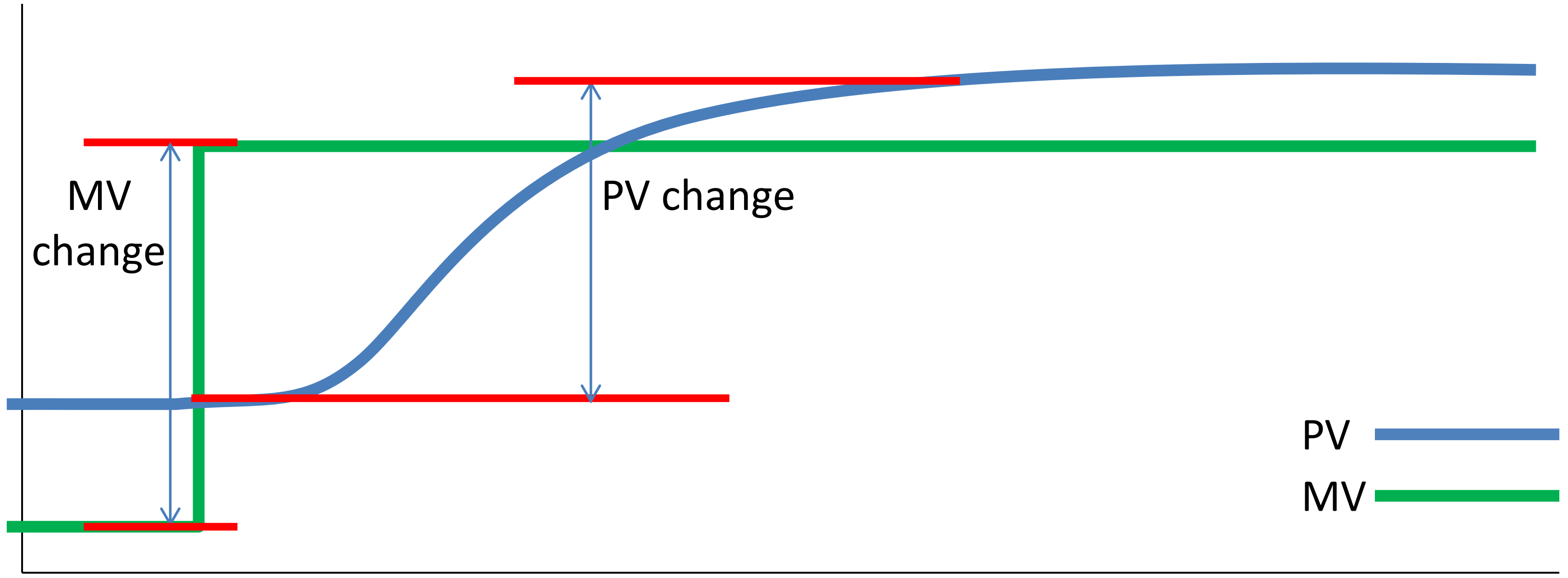
- Place the controller in manual and wait for the process to settle out.
- Make a step change of a few percent in the Manipulated Variable (MV) and wait for the process variable (PV) to settle out at a new value.



Ziegler – Nichols PID Tuning Method

Self Regulating Tuning Procedure

- Convert the total change obtained in PV to a percentage of the span of the measuring device.
- **gp** (Process Gain) = Change in PV [in %] / Change in MV [in %]
- This step tells us how **much change** is produced in the PV by a known change in the MV

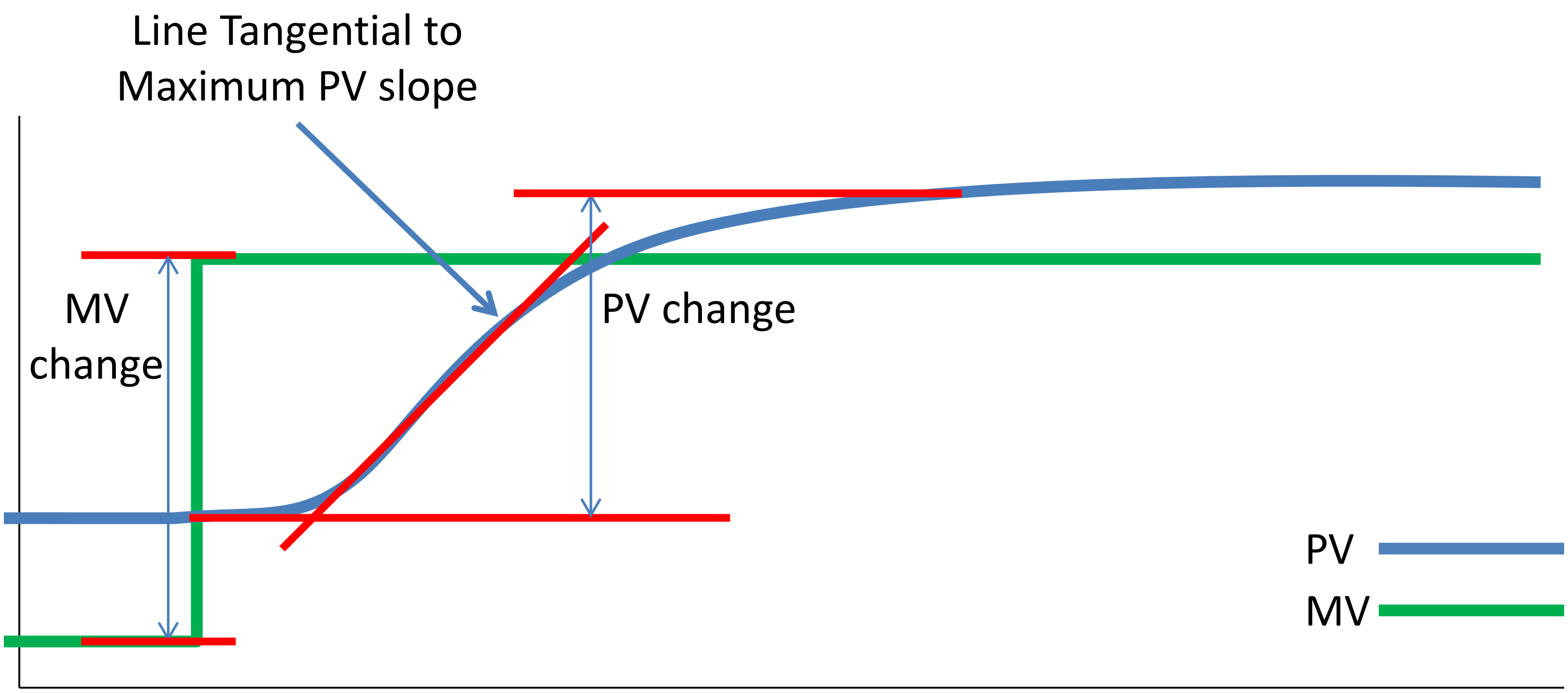


Ziegler – Nichols PID Tuning Method

Self Regulating Tuning Procedure

Find the maximum slope on the PV response curve. Draw a line tangential to the PV response curve through the points of inflection.

This tells us the **Rate of Change** of the PV for a known change in the MV



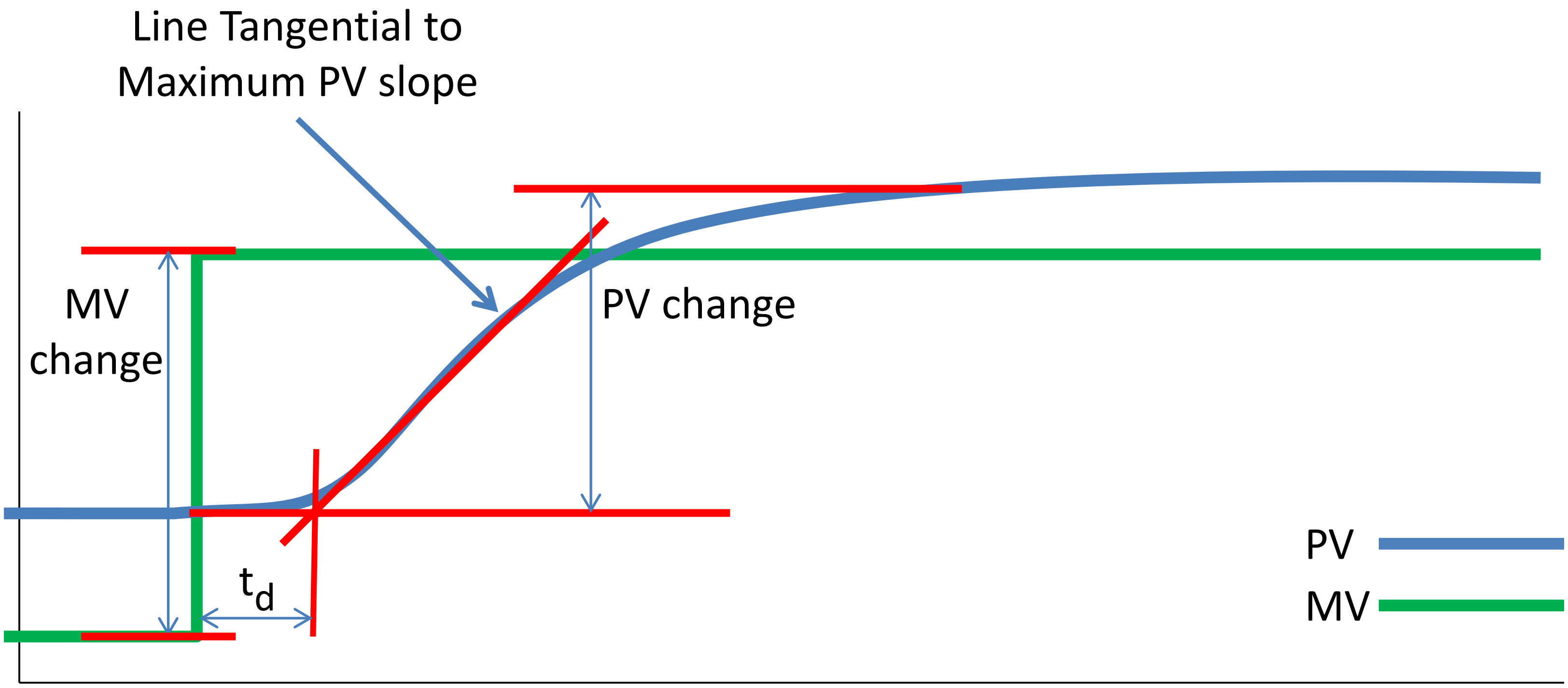
Ziegler – Nichols PID Tuning Method

Self Regulating Tuning Procedure

Measure the dead time (td) as follows:

- **td** = time difference between the step-change in MV and the upward intersection of the PV.

This tells us the **Delay** in the change of the PV after a known change in the MV



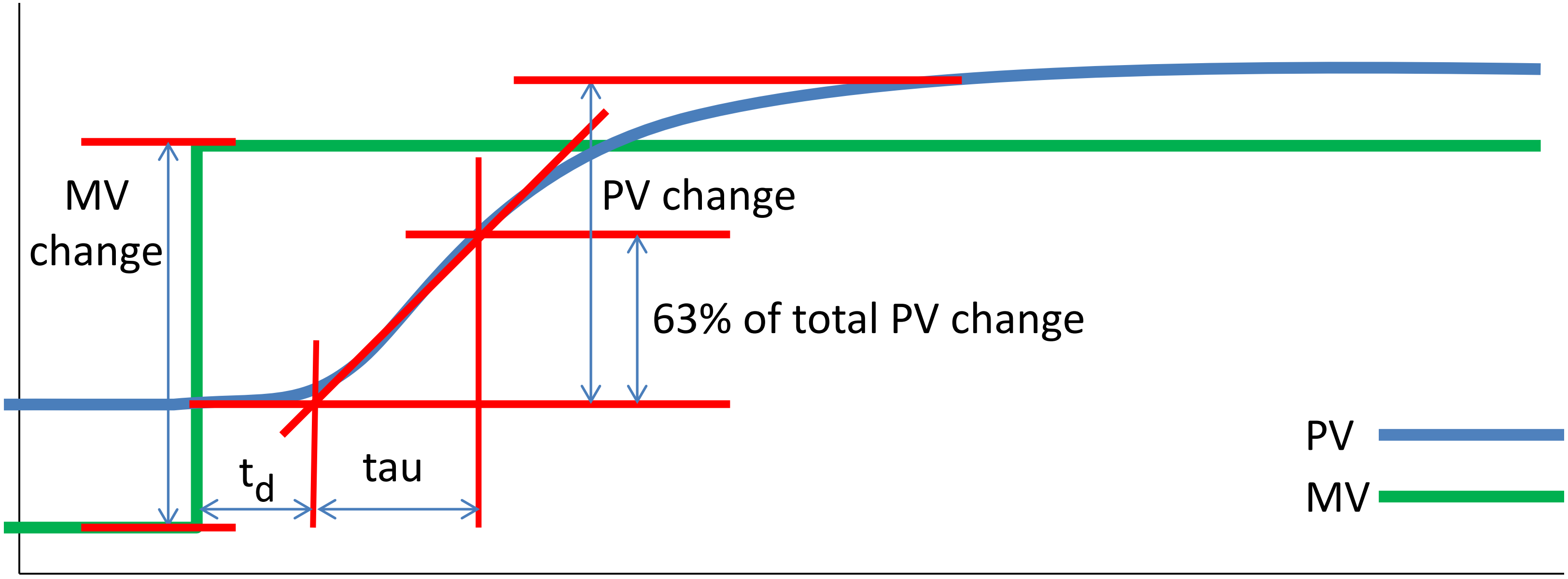
Ziegler – Nichols PID Tuning Method

Self Regulating Tuning Procedure

Calculate the value of the PV at 63% (0.63) of its total change. On the PV reaction curve, find the time value at which the PV reaches this level.

Measure the time constant (tau) as follows:

- **tau** = time difference between the upward intersection of the PV at the end of dead time, and the PV reaching 63% of its total change.



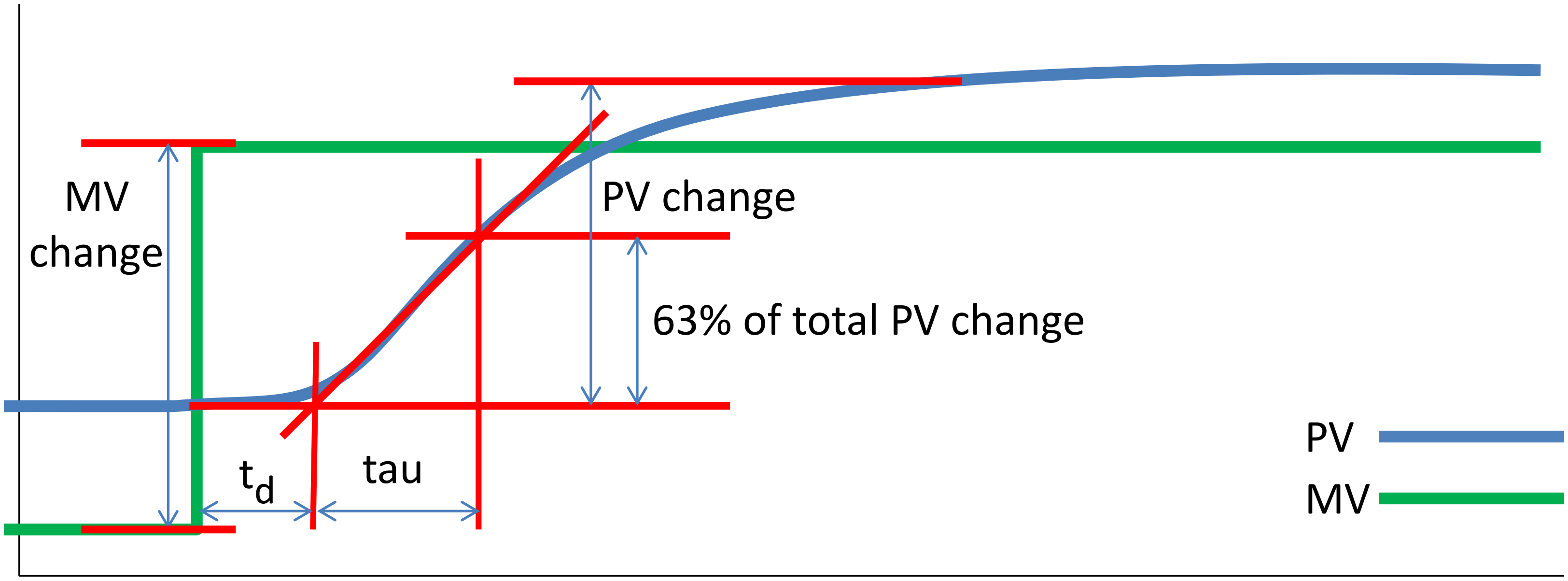
Ziegler – Nichols PID Tuning Method

Self Regulating Tuning Procedure

gp (Process Gain) = Change in PV [in %] / Change in MV [in %]

t_d = time difference between the step-change in MV and the upward intersection of the PV.

tau = time difference between the upward intersection of the PV at the end of dead time, and the PV reaching 63% of its total change.



PID Tuning – Self Regulating

Self Regulating Tuning Procedure

Convert your measurements of dead time and time constant to the same time-units your controller's integral mode uses. (e.g. if your controller's integral time is in minutes, use minutes for these measurements).

Do two or three more step tests and calculate process gain, dead time, and time constant for each test to obtain a good average of the process characteristics.

PID Tuning – Self Regulating

Self Regulating Tuning Procedure

Calculate settings for Controller Gain (Kc), Integral Time (Ti), and Derivative Time (Td), using the tuning rules below. Note that these rules produce a quarter-amplitude damping response and the calculated controller gain values should be divided by two.

- For P: Kc = tau / (gp * t_d)
- For PI: Kc = 0.9 * tau / (gp * t_d); Ti = 3.33 * t_d
- For PID: Kc = 1.2 * tau / (gp * t_d); Ti = 2 * t_d; Td = 0.5 * t_d

IMPORTANT: If you have not already done so, divide the calculated controller gain (Kc) by two to reduce overshoot and improve loop stability.

PID Tuning – Integrating Process

Integrating Tuning Procedure

The Loop tuning procedure for an Integrating Process is much like that of a Self Regulating process with a small exception.

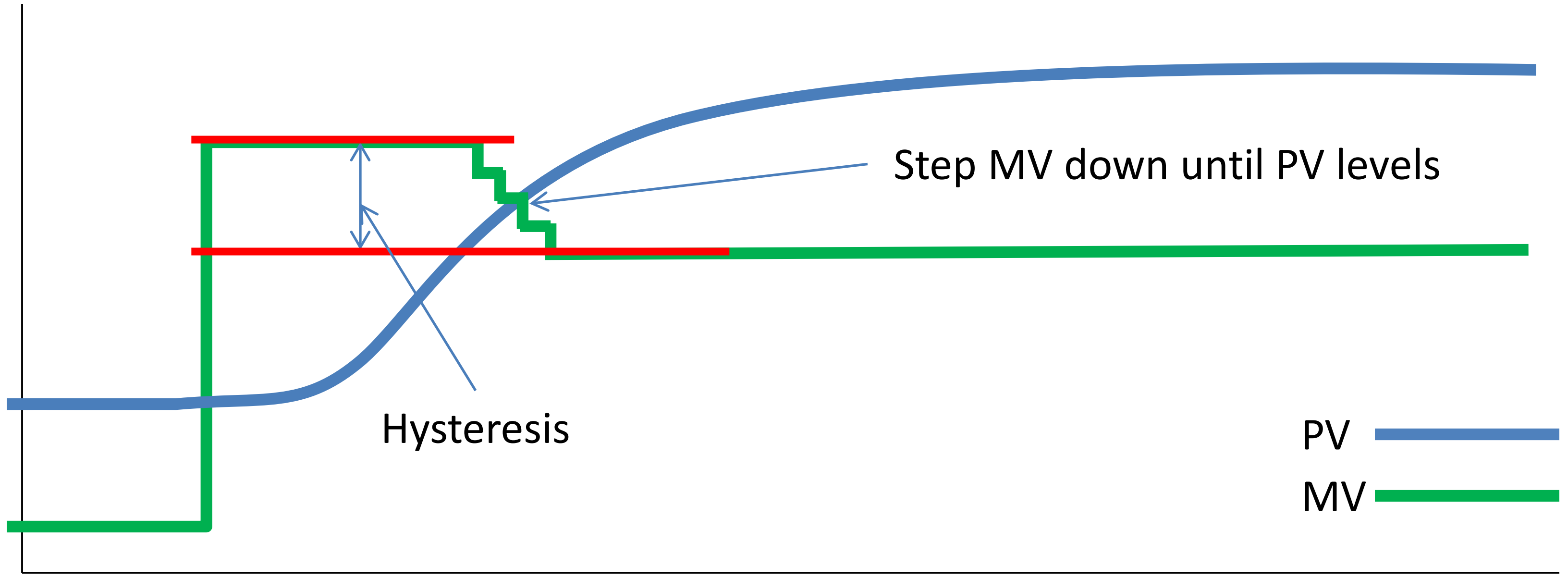
You must step the MV to create a change in the PV **then** step the MV back down until the PV levels off.

This will produce a response in an Integrating Process that looks much like the response seen in a Self Regulating Process.

PID Tuning – Integrating Process

Integrating Tuning Procedure

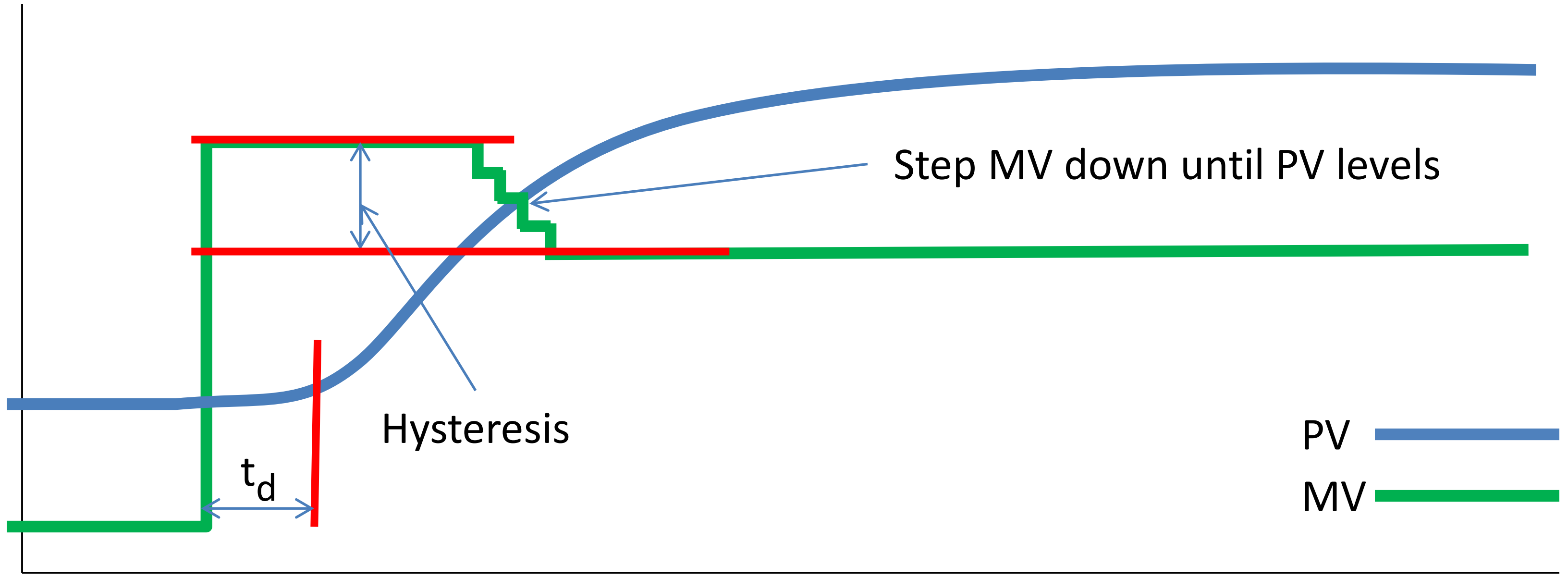
Measure the hysteresis, H (units=%). The Hysteresis is a measure of how much extra you had to move the actuator in the reverse direction to get the PV back to where you started.



PID Tuning – Integrating Process

Integrating Tuning Procedure

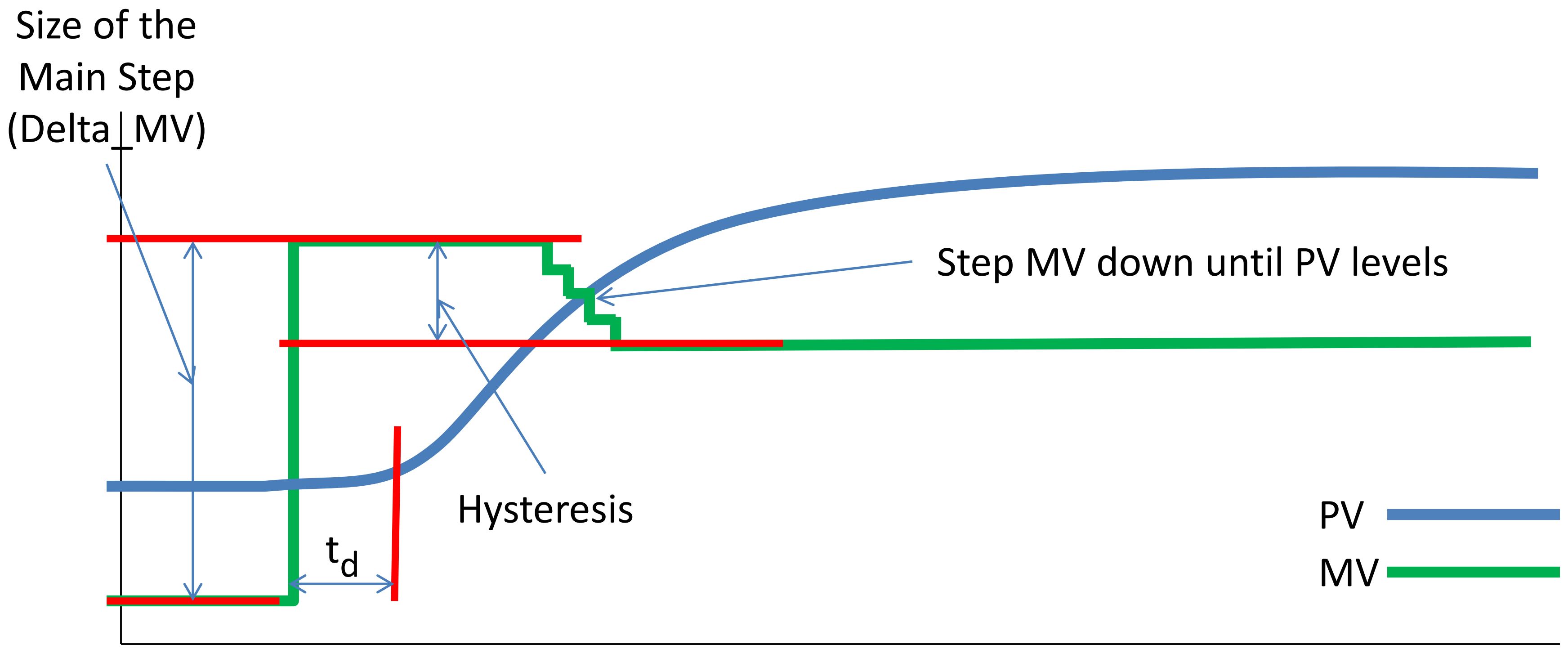
Measure the deadtime, t_d (units=seconds). The dead time is the time difference between where the MV stepped up and the PV started to respond.



PID Tuning – Integrating Process

Integrating Tuning Procedure

Measure the size of the main step to obtain Delta_MV



PID Tuning – Integrating Process

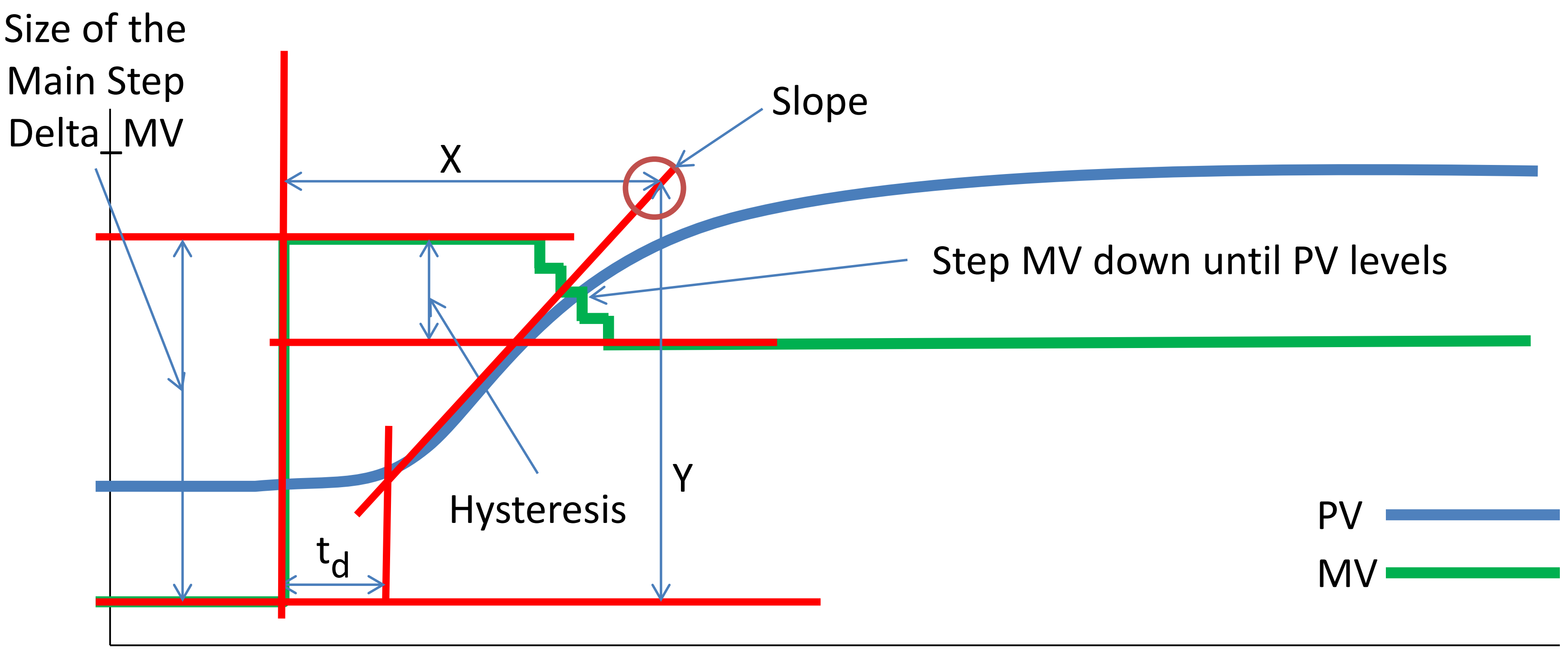
Integrating Tuning Procedure

Measure the initial slope of the PV immediately after the main step and draw a line that follows the line of the initial slope

Pick a point on the line and measure the distances X and Y

Slope = Y/X

gp (Process Gain) = Slope / Delta_MV



PID Tuning – Self Regulating

Integrated Tuning Procedure

Calculate settings for Controller Gain (Kc), Integral Time (Ti), and Derivative Time (Td), using the tuning rules below.

- For P Term: Kc = 1 / (2 * t_d * gp)
- For I Term: I = 4 / gp * Kc
- For D Term: Integrating processes almost always use just PI control so switch D off or set to 0

PID Tuning – Dynamic Tuning Parameters

Dynamic Tuning Parameters

You may want to implement the use of Dynamic Tuning Parameters in your PID loop. In any process where the slope of the PV in response to a change in the MV varies due to external forces interacting with the process it may be advantageous to provide two (Or more) sets of tuning parameters that can be dynamically switched in as the process environment varies.

- In Kettle Boil control the tuning parameters that get the boil process started can be very different from the parameters required to keep the boil stable at temperature and pressure.
- In Wort Cooling for a Knockout the tuning parameters that work well to allow aggressive cooling at the beginning of the KO may be different once the cooling valve(s) are opened and stabilized.

In Review

Loop Parameters

SP – Setpoint (Where you want to be)

PV – Process Variable (Where you are)

Error – Difference between the SP and the PV

MV - Manipulated Variable

P – Proportional Gain [Kc] (How much if the instantaneous error to apply to the correction)

I - Integral [*T*i] (How much of the error to integrate over time)

D - Derivative [*T*d] (Correction based on Predicted Rate of Change of the Error)

In Review

The Effects of Proper Tuning on Process Reactions

In general a properly tuned PID loop will require less energy and will provide a higher throughput for your process.

Process Types

For most PID loops in a modern brewery the process types fall into two areas:

- Self Regulating
- Integrating

Dynamic Tuning Parameters

You may want to implement the use of Dynamic Tuning Parameters in your PID loop.

In Review

Interview the Operators

- While the operators may not be familiar with the control strategy used in your facility, they will already have worked out how to overcome issues using manual control.
- Operators are more familiar with the systems than anyone else in the plant.
- The basic idea is to identify problems outside of the loop tuning that may be affecting the performance.
- There is no point tuning a loop on a broken process.

So address any process fundamentals before going to work on the tuning.

Questions