
Measurement Products

# PID control theory made easy
Optimising plant performance with modern process controllers

Power and productivity
for a better world™

# 1. What are the main types of control applications?

## Introduction

Accurate control is critical to every process. As a means of ensuring that tasks such as production, distribution and treatment processes are carried out under the right conditions for the right amount of time and in the right quantities, control devices form a crucial part of virtually every industrial process. In the past, many traditional control processes relied on either mechanical or solid state electronic technology, with pneumatics being used to produce changes in the process, such as in valve control installations for example.
With advances in computerised control technology, there are now a host of new possibilities for the way that processes can be monitored and controlled. These include the use of complex algorithms capable not only of reacting to changes in process conditions but also increasingly predicting them as well, enabling corrective action to be taken automatically.

## 1. What are the main types of control applications?

The wide variety of industrial processes in use today means there are many different types of control systems, each of which are geared towards their own particular application.

It is, however, possible to roughly segment these processes into three main categories, these being:

- Discrete processes. These types of processes are most commonly operated in manufacturing and packaging applications, where discrete items are being produced and handled. This category would also include robotic assembly processes, for example in the car-making industry.

- Batch processes. Batch processes are widely used throughout many industries, obvious examples being food and beverage, pharmaceutical and rubber processing applications such as tyre manufacture. In such processes, the main goal is to ensure that specific quantities of products are produced in a specific way, under specific conditions and for a specific period of time. With a single error potentially rendering an entire batch of products unusable, tight control of process conditions is critical.

- Continuous processes. As their name suggests, these processes are those which produce a continuous stream of products over a continuous period of time. Examples include large scale production processes in the chemicals, refining and plastics industries. In such applications, the processes tend to be largely constant, being geared towards the production of a specific product.

Of course, many applications may actually combine all of these types of processes, which will have an impact on the control system or systems used.

# 2. Types of control systems:

## 2. Types of control systems:

There are two types of traditional control systems:

– Open-loop control systems
– Closed-loop control systems

### 2.1 Open loop control systems:

Open loop controllers are also known as 'non-feedback controllers'. These controllers compute their input into a system based on a specific model / known set of conditions. They do not use data from the process to change their output or vary the process and are unable to compensate for any disturbances in process conditions. Instead, any variations in process conditions would need to be achieved by an operator manually adjusting the final control element.

As such, open loop control systems are best suited to processes where there is a relatively stable set of operating conditions or where these conditions can be governed by a known relationship. Their inherent simplicity and low cost makes open loop control systems ideally suited to simple processes where conditions are unlikely to change and where feedback is not critical.

To obtain a more accurate or more adaptive control, however, it is necessary to use a closed-loop system, where the output of the system is fed back to the inputs of the controller.

### 2.2 Closed loop control systems:

Modern control theory is based on feedback – i.e. signals from a process that can be used to control it more effectively. A closed-loop controller uses feedback to control states or outputs of a system or process. The term 'closed-loop' comes from the information path in the system – process inputs to a system have an effect on the process outputs, which is measured with sensors and processed by the controller. The result (the control signal) is used as an input to the process, closing the loop.

### 2.3 Benefits of closed-loop control systems:

Closed-loop controllers offer several key advantages over open-loop controllers, including:

– Ability to adapt to changing conditions – e.g. changing loads, process variations away from the established norm
– Ability to stabilise unstable processes
– Improved ability to help track and trace faults / problems

Some systems use closed-loop and open-loop control simultaneously. In these systems, the open-loop control is termed as 'feedforward' and serves to help improve reference tracking performance.

### 2.4 How do closed-loop control systems work?

As stated above, closed loop controllers work by using the sensed value from a process to assess and, if needs be, alter the process conditions.

A closed-loop or feedback controller works in the following way: A sensor of some type measures the output of the system and feeds it back to be compared against a reference value. The controller takes the difference between the output and the reference value and uses it to change the inputs to the system to help compensate for the difference.

This is called a single-input, single output (SISO) control system. Those with multiple inputs and multiple inputs/ outputs (MIMO) are also common.

# 3. PID controllers

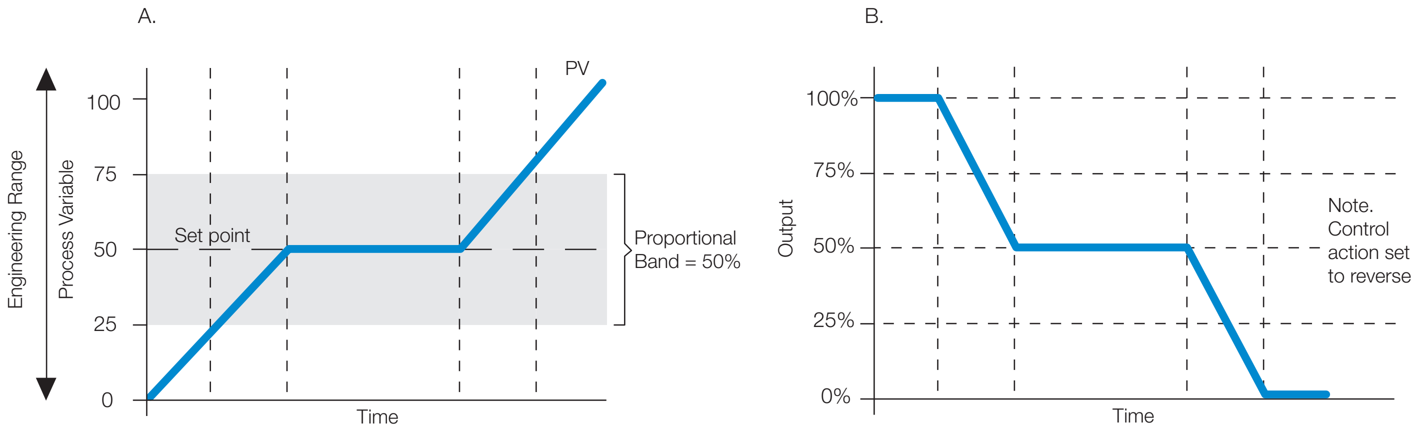



**Fig 1. Proportional action**

## 3. PID controllers

The PID controller is probably the most widely-used type of feedback controller. PID stands for Proportional-Integral-Derivative, referring to the three terms operating on the error signal to produce a control signal.

The desired parameters/conditions for a closed loop system are normally achieved by tuning the system to the inherent conditions without specific knowledge of a plant model. Stability can often be ensured using only the proportional term. Pure proportional action will result in control offset.

The integral term eliminates the offset. It does this by repeating the action of the proportional band every integral time constant. This enables the system to recover more quickly from a disturbance in conditions.

The derivative term is used to provide damping or shaping of the response. The action of derivative is to cater for disturbances and sudden changes. In effect, it is used to predict what is going to happen within the process and takes quicker action than the integral term to correct it.

PID controllers are the most well-established class of control system.

**Definitions:**

**Proportional –** Proportional control gives a change in output that is proportional to the deviation of the process variable from the set point. The range over which the output is adjusted from 0 to 100% is called the proportional band. The proportional band is expressed as a percentage of the engineering range.

When proportional-only control is used, manual reset is required. In the diagram above the manual reset is set to 50%. This means that when the process variable is 'at set point' the control output will be 50%. Adjusting the manual reset value has the effect of shifting the proportional band up and down. This has the effect of changing the control output when the process variable is 'at set point'. The manual reset would normally be adjusted by an operator every time the set point is changed, or when an offset is present for any reason.

# 4. Common control terms

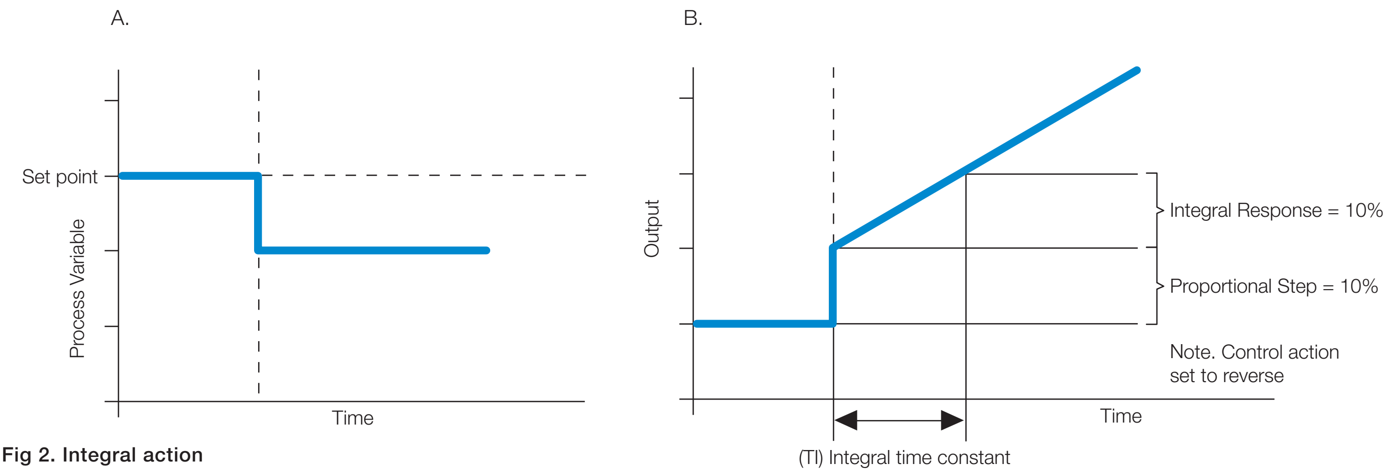



**Fig 2. Integral action**

**Integral –** Due to limitations with proportional-only control, which appear as an offset between the process variable and the set point, it is often necessary to introduce an integral action. If an offset is present, the integral action will continue to change the control output in the same direction as the proportional action, until the offset or error is removed.

The integral action is expressed as the time taken for the output to change (due to the integral action) by the same amount that it has changed due to proportional action, when a constant deviation is present. Fig 2B shows the effect that a 20 second integral action would have on the control output.

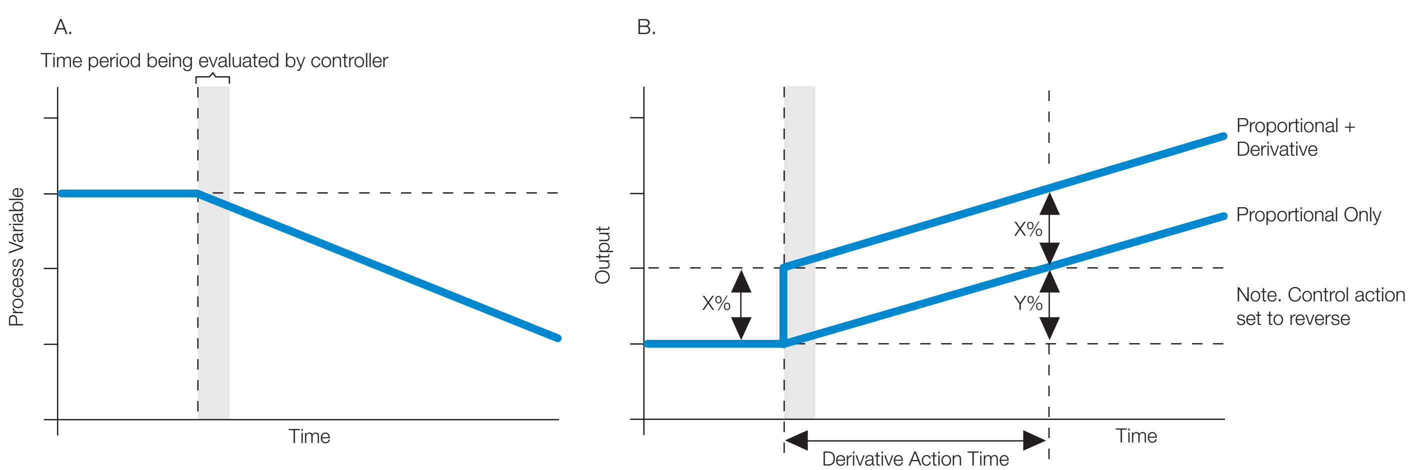
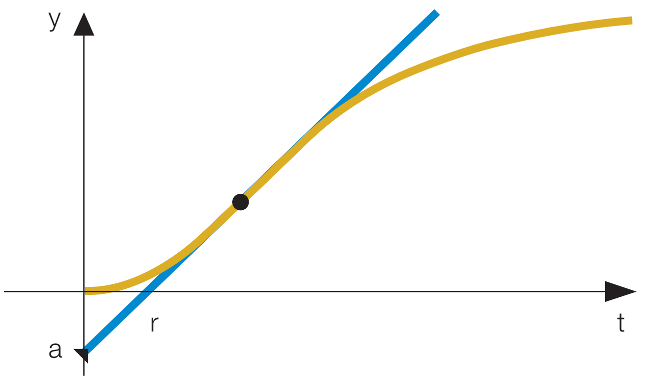



**Fig 3. Derivative action**

**Derivative –** Derivative action can be used with proportional control, with or without integral. It has the effect of making changes to the control output, dependant on the rate of change of the process variable. The amount of effect that derivative action has on the output is dependant on its setting. Derivative action is set as a time constant and has the following effect on the control output. Taking only the proportional part of the output as shown by the lower line on Fig 3B, the controller calculates forward to find out what the output will be due to the proportional action after the derivative time period. This change in output shown on the diagram as Y% is then added to the current control output value as derivative action X%.

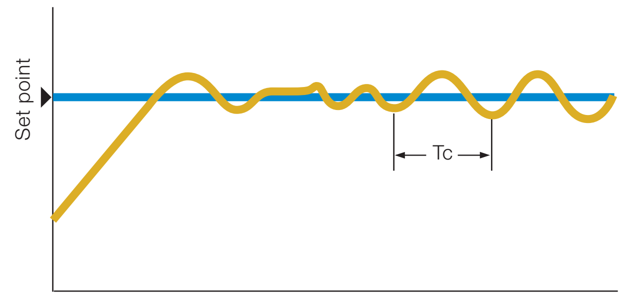
# 4. Common control terms

ZN - Open Loop Method




1. Apply a step change to the controller output and monitor the PV
2. Draw tangent at point of highest rate of change
3. Calculate intercepts with x and y axes

ZN - Closed Loop Method




1. Proportional only control
2. Make small setpoint change and observe response
3. Increase/decrease gain and repeat step until constant sustained oscillation is obtained
4. Gain = critical (ultimate) gain, period of oscillation = critical period

## 4. Common control terms

Getting the right control for a process isn't just a case of finding the right controller. Even when the choice of controller has been made, operators need to have a full understanding of all of the issues that can affect both short-term and long-term performance to enable them to achieve the optimum control for their process. The following is an explanation of some of the key terms that are likely to be encountered during both the selection and operation of a control device.

### 4.1 Loop tuning

Loop tuning is a complicated issue and much attention has been paid to trying to define and address it over the years.

In tuning a PID loop, the key challenge is to strike a balance between the response of the controller and the characteristics of the process. In a process that is relatively slow to respond to a system change, for example, the PID algorithm would need to be set up to aggressively and immediately respond in the event of any potential changes in the process or where the setpoint may have been adjusted by the operator.

On the other hand, for more sensitive processes where a system change could have a major impact on process conditions, a more gentle PID algorithm would be required, acting more slowly over a longer period.

To date, the most useful approach is that set down by JG Ziegler and NB Nichols, who worked for the Taylor Instrument company in Rochester, New York, which was later to become part of ABB.

In 1942 they published a paper entitled 'Optimum Settings for Automatic Controllers', which set out an approach for the tuning of PID parameters which was later to be adopted industry-wide. This approach involved both a test to define the speed and manner in which a process responds to a change in control, and formulas to enable the results to be used to correctly tune a controller.

The paper proposed two techniques for loop tuning, namely a closed-loop and open-loop method. The principles of these methods still provide the foundation of many of the autotune algorithms used in many modern industrial applications.

Despite its simplicity, the Ziegler Nichols control loop method can take a long time to perform and also has the potential to create uncontrolled oscillations, which affects control stability. Traditionally, a manual tuning process involved an engineer first running a Ziegler Nichols test and noting the results on a strip chart. Using this data, they would then try to interpret the characteristics of the process which would then be used to help tune the control loop. Not surprisingly, this was a time-consuming process that was open to error.

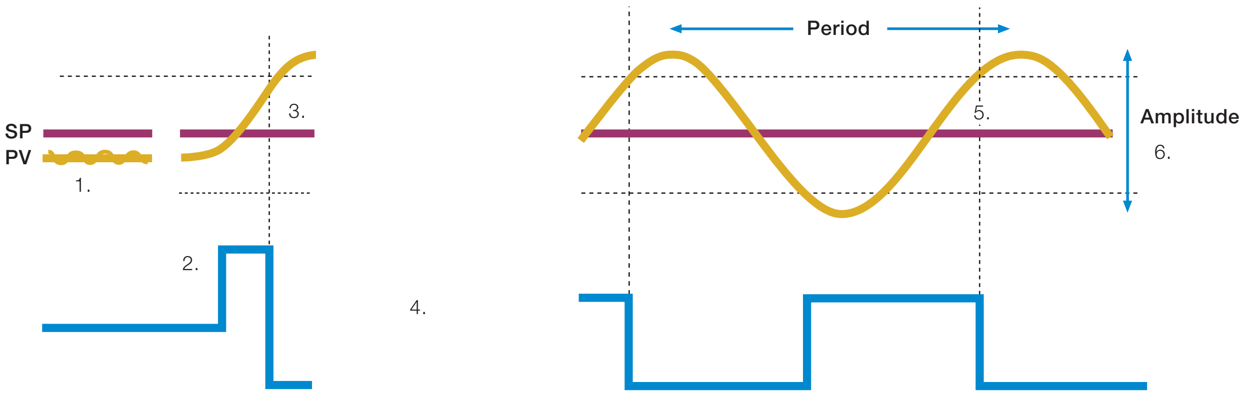
As technology has evolved, this manual process can now be carried out automatically using the autotune feature that can be found on most modern controllers.

# 4.2 Autotuning

1. Monitors noise and calculates a hysteresis value

3. When the process exceeds the hysteresis value the output is stepped down

5. When consistent oscillation is established the experiment is stopped




2. User defined initial step in the output process starts to move away from the setpoint

4. Automatically adjusts output amplitude so PV does not exceed level needed to isolate from process noise

6. The critical period and amplitude are recorded and used to calculate the optimum settings

**4.2 Autotuning**
Almost every modern controller will include an autotuning function. This function effectively enables an operator to automatically tune a controller to a process even where they have little or no knowledge of that process.

ABB's ControlMaster autotuner uses a technique developed by Astron and Hagglund from Lund University, which further refined the Ziegler Nichols closed loop tuning model. This technique basically enables a stable oscillation to be ascertained by stepping the process variable up and down within an established hysteresis band.

When the autotuner is first started, the controller switches out the normal PID algorithm and replaces it with a non-linear function whereby the controller will step up and down a prescribed parameter range until it establishes a consistent control range for the process.

This is achieved in the following way:

1. The controller begins by monitoring the inherent background noise in the process and creating an hysteresis value, whereby low and high value are established either side of the setpoint based on the minimum and maximum values that are required to achieve a reliable response.

2. A user-defined step in the controller output is then made, causing the process to start to move away from the setpoint. The response of the system is measured.

3. When the process exceeds the hysteresis value, the output is then stepped down to find the lower value.

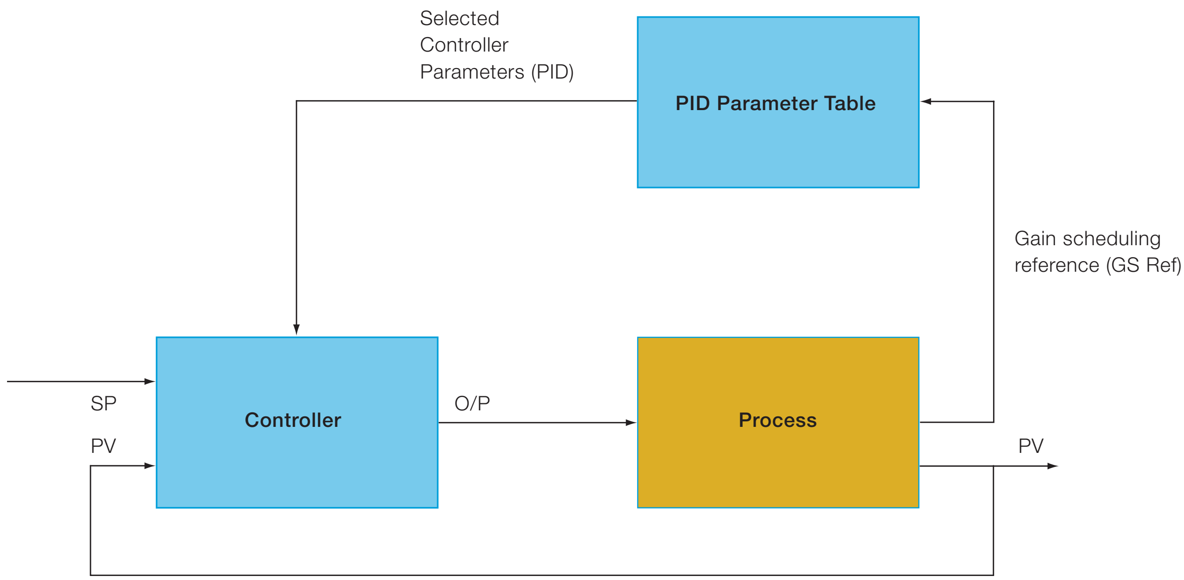
The autotuner is designed to minimise the amount of process disturbance. After the initial output step, all subsequent output steps both up and down are automatically adjusted until the minimum amount of disturbance is achieved while still being able to distinguish the process value oscillation from the process noise.

This process of stepping the output up and down is continued with the process variable passing the hysteresis thresholds until a consistent oscillation is established. At this point, the autotuner records the duration of the oscillation and its amplitude, from which the critical period and critical gain are determined.

The information created by the autotune about the process is then used to calculate the PID settings for the application.

Key advantages of autotuning:
- No detailed knowledge of the process is required
- Tuning process is executed under tight feedback control
- The tuning time is short compared with the closed loop response time
- Automatically detects processes where the use of Derivative is not appropriate

# 4.3 Gain scheduling




**4.3 Gain scheduling**
For linear processes, where the process characteristics do not change significantly with time or load conditions, then using the autotuner to set fixed PID or PI parameters will probably be sufficient to ensure effective control.

In the case of non-linear processes, however, being limited to a single set of fixed parameters can become problematic, as they have to be set for the worst case in order to find the best overall response. This means that the controller has to be given a very low gain so that it will not cause instability problems when the process is at its highest gain. The consequence of this is that very sluggish control results when the controller is operating where the process gain is at its lowest.

Gain scheduling overcomes these problems by enabling users to opt for more than one set of control parameters.

The above diagram shows how gain scheduling acts as a system with two feedback loops. The inner loop is comprised of the process and the controller while the 'outer loop' adjusts the controller parameters based on the operating conditions.

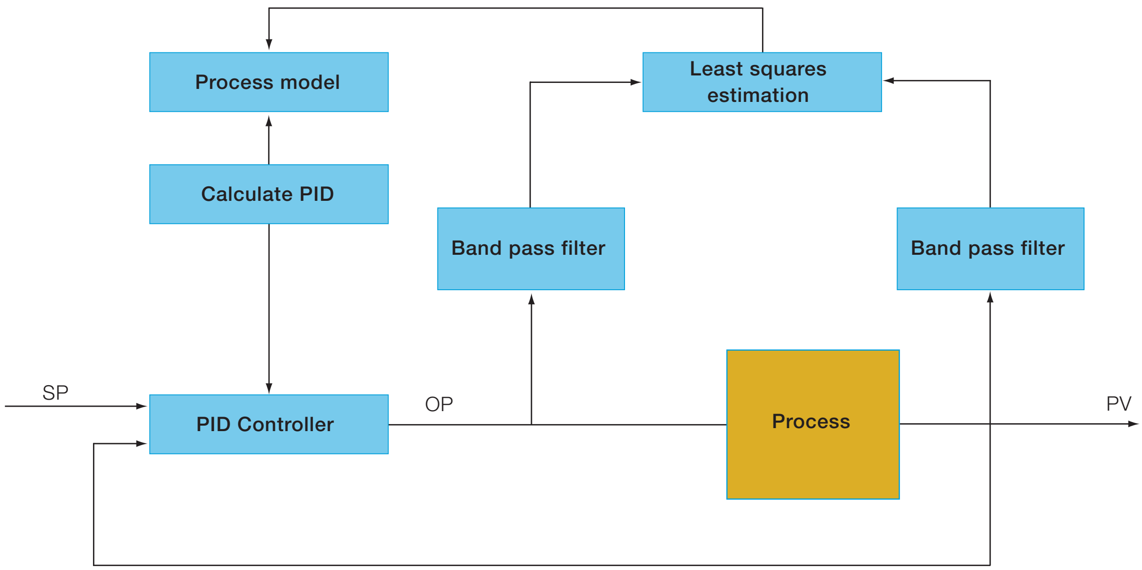
The ControlMaster provides up to three independent sets of PID parameters. The choice of a specific set is controlled by the gain scheduling reference signal (GSRef) or gain scheduling source, which can be assigned to any analog signal, both external or internal, available in the controller. Two limits are provided which set the points at which the controller will alternate between the three different PID sets. To help simplify set-up and operation, these limits are expressed in engineering units.

Compared to other adaption techniques, gain scheduling may seem relatively simple. However, its ability to respond to rapid changes in operating conditions means it has been proven to produce significant improvements in the control of a process.

Key advantages of gain scheduling:

- Improves control of non-linear processes
- Eliminates the need to have PID settings detuned to the worst case to avoid instability
- Is based on a measurable variable that correlates well with the process dynamics
- Three independent sets of PID parameters can be defined
- The reference signal can be any analog signal
- Two dedicated limits can be programmed in engineering units for ease of use
- Capable of responding to rapid changes in operating conditions

# 4.4 Adaptive control




**4.4 Adaptive control**

As described above, gain scheduling is well-suited to the control of non-linear processes which behave in a predictable way and where the characteristics can be correlated to a variable that can be easily measured.

However, this is not the case for processes which are subject either to rapid and/or unpredictable changes. In such processes, the solution is to have an adaptive control function, such as that incorporated within the ControlMaster.

The adaptive controller works by creating a mathematical model of the process which is then used to estimate the optimum controller settings for the process. This model is continually updated by using data gained from comparing the performance of the model against real-life operating conditions.

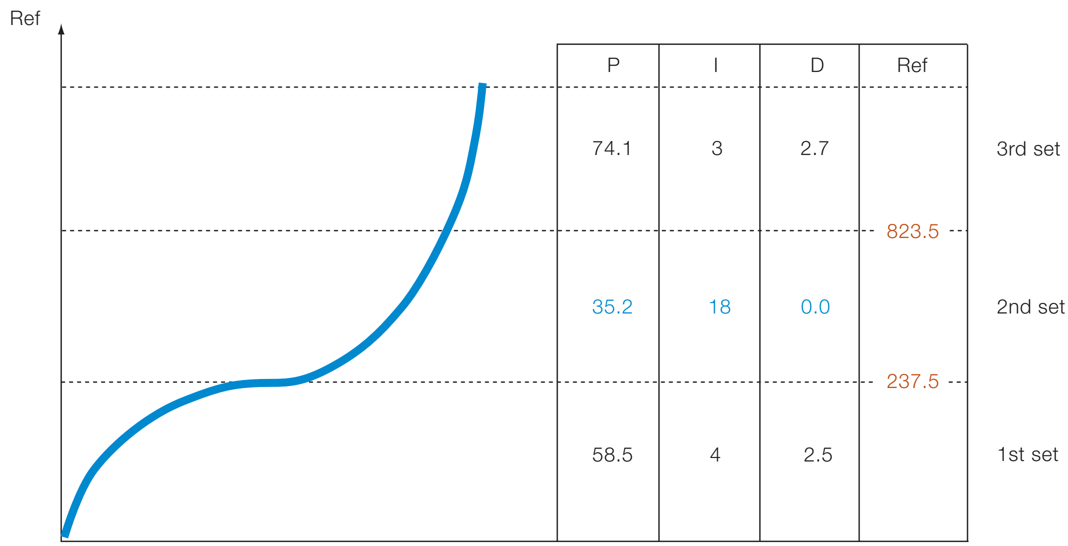
With the ControlMaster, the need to have extensive prior knowledge of the process to help with set-up of the adaptive control function can be eliminated by using the autotuner. Running the autotuner will help provide both good initial PID values and also a number of other parameters required for the proper operation of the adaptive algorithm.

The above diagram illustrates the model monitoring process. At the first stage, the control output and the process variable signals are put through a narrow band pass filter. This allows only signal data at a specific frequency to pass through, with any parts of the signal that have a higher or lower frequency being blocked. This prevents unwanted high frequency process noise and low frequency load disturbances that could otherwise distort the process model. The centre frequency of the filter is linked to the process dynamics and is one of the areas identified and set by the auto tuner.

After the signals have been filtered, a mathematical process known as 'least squares estimation' is applied to update the coefficients of the mathematical model. Using this information, the adaptive algorithm then calculates the appropriate PID settings that will provide the optimum control of the model, with the controller settings then being modified accordingly.
To ensure the model is only adjusted when necessary, the ControlMaster includes a built-in supervisory logic function. This ensures the estimates are only updated when there is information available and prevents the model from being modified when the process is under good control.

Similarly, when the supervisory logic detects that a load a disturbance has occurred, it restricts the adaption

# 4.4 Adaptive control




process until the initial effect of the disturbance has passed, enabling the data from the disturbance to be incorporated into adjusting the model.

The supervisor also checks the parameters generated by the least square algorithm to ensure that they are reasonable.

The supervisory logic function can also be useful for detecting potential fault conditions such as sticking valves. In the event of a sudden significant change in the control parameters, it will also stop the adaption process and warn the user.

As the adaptive controller uses the same process dynamics as the auto tuner, the user has the option of using PI control only or to calculate controller settings suitable for processes where the deadtime is relatively long.

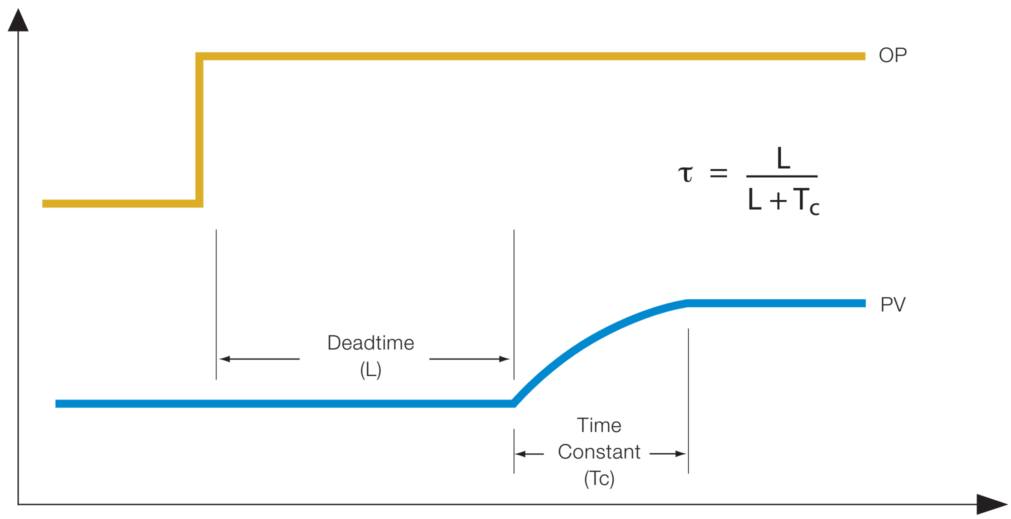
Adaptive control can also be combined with gain scheduling to deliver benefits for processes which are non-linear but which vary with time or other conditions. Here, the adaptive algorithm automatically builds individual internal models for each segment of the gain scheduler. Using these, the controller automatically updates the appropriate set of PID parameters depending on where in the process curve it is operating, as shown in the above diagram:

In this example, with the GS reference at around 500, a detected increase in the gain of the process will result in it automatically calculating new PID values for the second set of parameters only, leaving the others unmodified.

**Key advantages of adaptive control:**

- Helps control of processes with changing dynamics
- Fully integrated with auto tuner to automatically provide initial process knowledge
- Creates and updates an internal model of the process it is trying to control
- Filters the control output and the process variable signals so that unwanted information from noise and local disturbances are removed
- Signals are analysed in a least-squares estimator, with the resulting information used to update the process model
- Works out the PID settings that would work best with the internal model

# 4.5 Deadtime compensation




**4.5 Deadtime compensation**

'Deadtime' occurs where the variable being measured does not respond to a step change in the controller output for a certain period of time. It commonly occurs in applications where material is being transported via a pipeline or on a conveyor. An example is a pH dosing process. The dosing pump is often located some distance upstream from the sensor, resulting in a delay between the controller increasing the dose and the resulting effect being seen at the sensor. The time it takes for the dose to travel down the pipeline creates an effective deadtime.

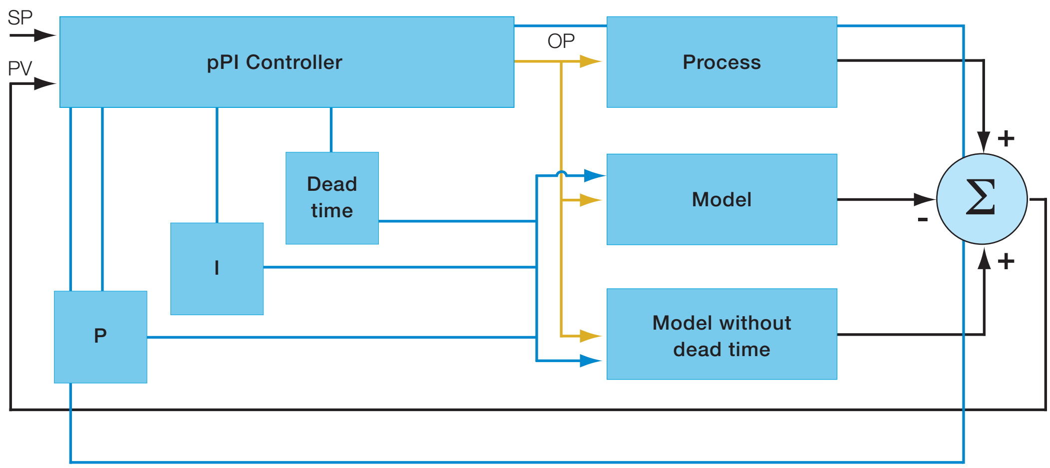
To address this, a formula has been devised called the controllability ratio. The controllability ratio is defined as the ratio of the process deadtime divided by the deadtime plus the dominant time constant. Its purpose is to ascertain how easily a particular process can be controlled.

Small values of the ratio are easy to control. As the deadtime becomes more significant compared to the time constant though - that is, as the periods of deadtime get longer - the ratio gets larger, making the process increasingly difficult to control with just a simple PID algorithm.

To overcome this, some form of predictive control is needed. The classic solution is known as a 'Smith Predictor'. This is a deadtime compensating controller which makes a prediction based on the controller output and an internal simulation of the process.

However, this approach has a number of disadvantages, the biggest of which is its complexity. To obtain the process model needed for the algorithm, a systematic identification process is needed which needs at least the process gain, time constant and the deadtime all to be specified. Combined with the PI algorithm, operators may find themselves having to tune a total of five parameters. Furthermore, unlike standard PID control, the Smith Predictor cannot be easily manually tuned by trial and error.

# 4.6 Predictive PI (pPI) control - overcoming the Smith Predictor complexity




**4.6 Predictive PI (pPI) control – overcoming the Smith Predictor complexity**
The new ControlMaster range employs a deadtime compensation controller which is much simpler to use.

Called Predictive PI (pPI) control, it is based on the work of Tore Hagglund of Lund University in Sweden. Although it shares the same structure as the Smith Predictor, the controller differs by having two process model parameters that are determined automatically based simply on the Proportional and Integral values.

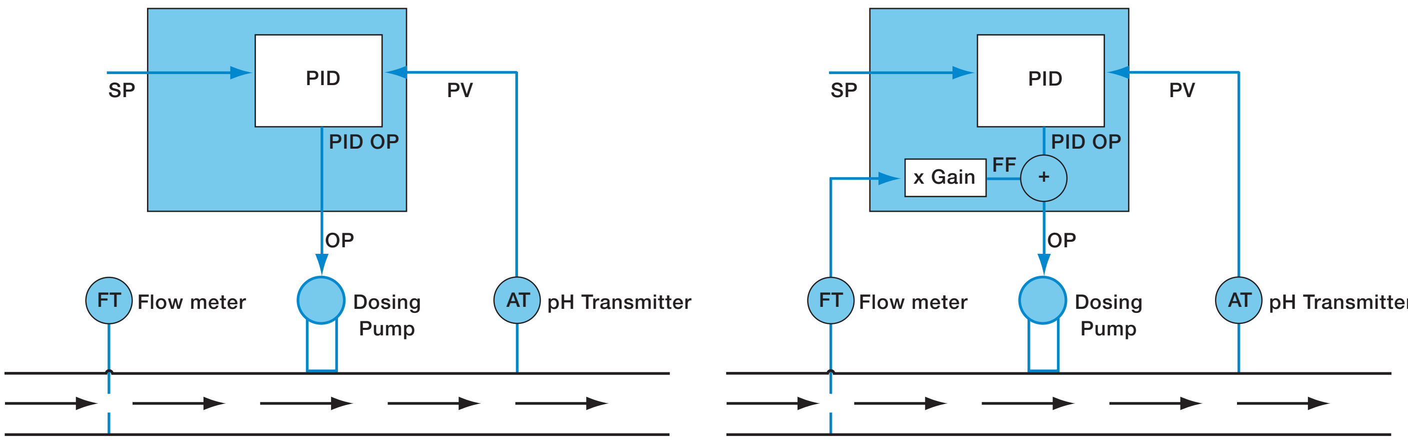
The consequence of this is that, as for a standard PID controller, there are just three parameters that need to be tuned, namely the proportional term, the integral term and an estimate of the process deadtime.

**4.6.1 PI response vs pPI**
A key benefit of predictive PI control is its ability to greatly reduce the impact of deadtime compared to standard PI control. With PI control, where a step change is made to the control setpoint, the control output will slowly increase. As the deadtime is exceeded, the process variable will also start to slowly respond. Although the control is reasonable, the response will tend to be very sluggish.

Because the pPI controller can predict what will happen, it is able to raise the control output much more quickly without the problems of overshoot or instability. Once the deadtime has elapsed, the process variable then approaches the setpoint much more quickly.

**Key advantages of predictive PI (pPI) control:**
- Much simpler to use than a Smith Predictor
- Uses same structure as a Smith Predictor, but needs no process model to be specified
- It creates its own process model from gain, integral time and deadtime
- Ideal where the deadtime is more than double the dominant time constant
- Can be manually tuned using a simple step response test

# 4.7 Feedforward Control




**4.7 Feedforward Control**
Feedforward control offers a highly effective way of compensating for measurable disturbances before they can affect the process variable. As such, it can often help deliver significant improvements in control quality.

The benefits of feedback control were outlined earlier in this paper. Although it helps to inform the process, one of its inherent drawbacks is that corrective action cannot be taken until the output deviates from the setpoint.

The following diagram shows a practical example of a dosing control installation. If the flow rate of the solution being treated changes, then the dose amount also needs to be changed accordingly.

If only feedback control is used, the controller will only realise that something has changed once the solution reaches the pH sensor. Any action by the controller to adjust the dosing output will therefore be too late to have any immediate effect on the solution currently being measured.

This situation can be resolved by measuring the flow rate upstream from the dosing pump and using this information as a feedforward signal to help achieve an output proportional to the fluid flow rate. By enabling the dosing rate to immediately track any changes in flow rate, the possibility of potentially expensive or even dangerous over or under dosing is eliminated.

The below diagram highlights the simple principle of feedforward control. Here, the feedforward signal, in this case the flow rate, is scaled by a gain factor and then added to the normal PID output. The gain itself can either be set at a fixed value by the user or adjusted dynamically using the ControlMaster's adaptive feedforward function.

Using adaptive gain confers a number of benefits. Firstly, it eliminates the need to manually calculate the required gain, reducing both the time and complexity of set up and removing the the chance of human error. Secondly, it ensures that good control is maintained irrespective of any disturbances to the system, either due to time; any changes in the properties of the solution being treated; or any other potential reasons.

**Key advantages of feedforward control:**

– Helps prevent large disturbances in output. Disturbances are detected before they can affect the process
– Helps speed up response times and eliminate delays associated with feedback control

# 5.0 Introducing the ABB ControlMaster


**5.0 Introducing the ABB ControlMaster**
The new ABB ControlMaster builds on the highly successful Commander family to offer an even wider range of control and indicator functions in just four easy to specify versions. A key feature of the CM15 indicator and the CM10, CM30 and CM50 controllers is their full color TFT display, providing operators with a clear and comprehensive display of process status and key information. Adjustment of the display via the customisation feature enables the operator to tailor their view to their requirements, while a chart display provides short term trending information.

The use of a TFT display also makes the ControlMaster range extremely easy to configure. Configuration menus are displayed in clear text, with no complex codes and abbreviations found on controllers with lesser displays. Further time savings during configuration are made possible by the use of built-in application templates, enabling operators to simply select the template best matched to their requirements, with the ControlMaster automatically configuring its I/O, display and control strategy to suit. Configuration can also be performed via DTM-based PC configuration software. Configuration files can be transferred to the ControlMaster via its front-mounted infrared port or stored locally on a PC.

The ControlMaster range offers a choice of communications options – Ethernet, Modbus, and Profibus. Ethernet communications provide the ability for users to be automatically notified of critical process events via email or remotely monitor the controller and process via the ControlMaster's integrated webserver by simply using a standard web browser. For integration with larger control systems, the Modbus (RTU and TCP) and Profibus options enable access to real time data on process values and device status.

Other new features include additional control options alongside the standard cascade, ratio and feedforward control functions to help bring even the trickiest processes under control. Predictive control algorithms including dead time compensation, makes the ControlMaster ideal for applications with long dead-times such as pH dosing applications. Added control efficiency is enabled by the inclusion of adaptive control, which allows the ControlMaster to automatically adjust its control response to suit variations in process response. Dual loop control makes it possible to use one ControlMaster to control two processes. The inclusion of additional auto tuner, math, logic, gain scheduling, totalizer, custom lineariser and delay timer functions provide powerful problem-solving functionality.

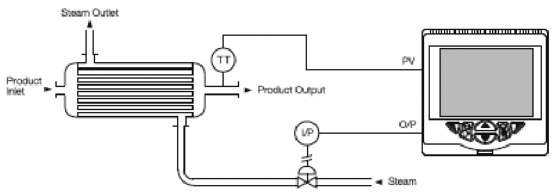
With just four models in the range, product selection for basic through to advanced applications has never been easier. Initial model selection is made based on panel cut-out and then I/O and control functionality selected to suit application requirements. When required field upgrades can be easily performed using plug and play function keys and I/O cards. The common design of all of the four models provides standard operation and configuration across the range.

All products in the ControlMaster range feature full IP66 and NEMA4X protection as standard. These high levels of protection makes the range suitable for a wide range of industrial control applications, from arduous oil and gas facilities through to the washdown environments in the food and beverage industry.

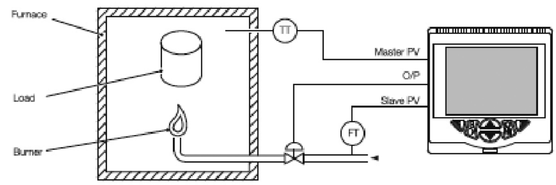
# 6.0 Examples of applications for the ABB ControlMaster

**ABB's ControlMaster process controllers are suitable for use across a wide range of applications. Typical configutrations can include:**

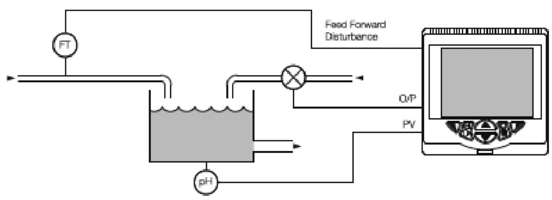
### Temperature control of a steam heated product



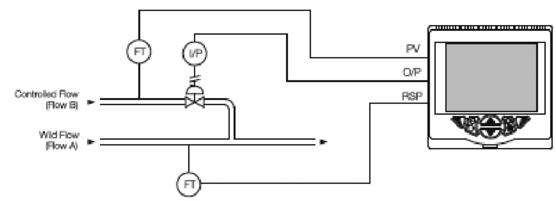

### Temperature control of electrically or gas heated furnaces



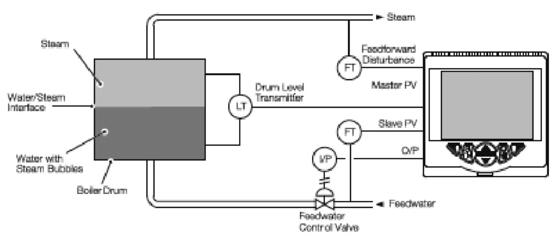

### pH control of effluent flow via acid or alkaline dosing



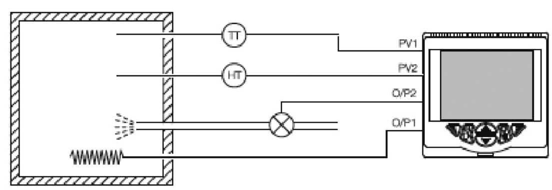

### Ratio control of product blending




### Boiler drum level control




### Independent dual loop control of temperature and humidity in a climatic chamber




### Further information

For more information about ABB's controllers, visit **www.abb.com/intrumentation** or email: **moreinstrumentation@gb.abb.com** ref. 'controllers'.

# Notes

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