

TOSHIBA

AG-TS03***-E043

PROGRAMMABLE CONTROLLER
PROSEC T-series

APPLICATION GUIDE
– PID Function –

TOSHIBA CORPORATION

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Safety Precautions


This application guide is prepared for users of Toshiba programmable controller PROSEC T-series (hereafter called PLC).

Read this guide and your PLC's manual thoroughly to use the PLC system safely.

Hazard Classifications

In this guide, the following two hazard classifications are used to explain the safety precautions.

 **WARNING** Indicates a potentially hazardous situation which, if not avoided, could result in death or serious injury.

 **CAUTION** Indicates a potentially hazardous situation which, if not avoided, may result in minor or moderate injury. It may also be used to alert against unsafe practices.

Even a precaution is classified as CAUTION, it may cause serious results depending on the situation. Observe all the safety precautions described on this guide.

Safety Precautions

CAUTION

- Read the Safety Precautions described in your PLC's User's Manual before using the PLC.
- Carefully design the fail-safe system in order to avoid unsafe situation caused by PLC failure.
When PLC detects an error in its self-diagnosis, the PLC goes into error down mode. In the error down mode, all the PLC outputs become OFF and the analog outputs becomes 0 (zero).
- When you change the PID parameters, carefully check for safety.

About This Guide

This application guide explains the PID (Proportional Integral Derivative) instruction available in the Toshiba T-series PLCs, and shows examples of how to configure build a PID control loops. For detailed information on individual PLCs, please refer to the User's Manual for that PLC.

The PID function is used to control process variables such as temperature, pressure, liquid level, or flow rate. Because the controlled process characteristics vary widely, this guide explains basic/general methods to use the PID function. For precise PID tuning, knowledge of process being controlled is required.

This application guide contains the following 5 sections.

Section 1. Overview

Introduces a typical PID control system configuration in which the PLC control is used.

Section 2. PID Basics

Provides basic information on the PID control and PID parameters.

Section 3. PID3 Instruction

PID3 is the name of programming instruction in the T-series PLC, which executes the PID equation. This section contains a detailed description of the PID3 instruction.

Section 4. Application Notes

Provides examples of how the PID3 instruction is used.

Section 5. Tuning Technique

Introduces general methods for PID loop tuning.

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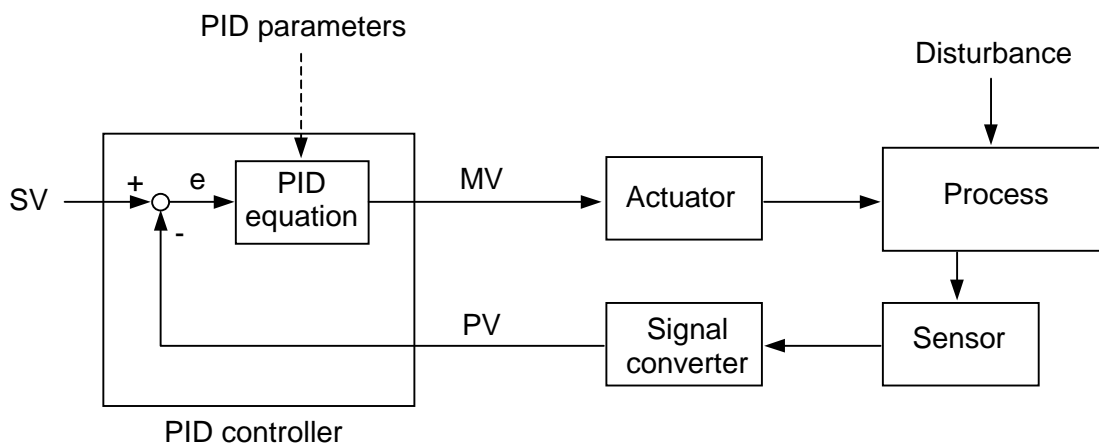
1. Overview

1.1 PID control system

Normally the PID function is used to control process variables such as temperature, pressure, liquid level, or flow rate.

The PID controller receives the process variable (PV) and controls the manipulation variable (MV) in order to adjust the PV to match the set value (SV).

The figure below shows a typical configuration for a PID control system.



In the above figure:

Process: A reaction which is controlled by physical values such as temperature, pressure, flow rate, etc.

Sensor: A detector that detects the controlled physical values. It can be a thermocouple, RTD, pressure gage, flow meter, etc.

Signal Converter: A device that transmits a weak sensor signal to the PID controller by converting it into the signal suited for the environment such as 4 - 20 mA, 1 - 5 Vdc, pulse train, etc.

Actuator: A device that regulates fluid or electric power to the process according to the signal generated by the PID controller. It can be a control valve, thyristor, variable speed drive, etc.

PV: Process variable ... normally 4 - 20 mA or 1 - 5 Vdc analog signals

MV: Manipulation variable ... normally 4 - 20 mA, 1 - 5 Vdc or a time-proportional pulse.

SV: Set value.

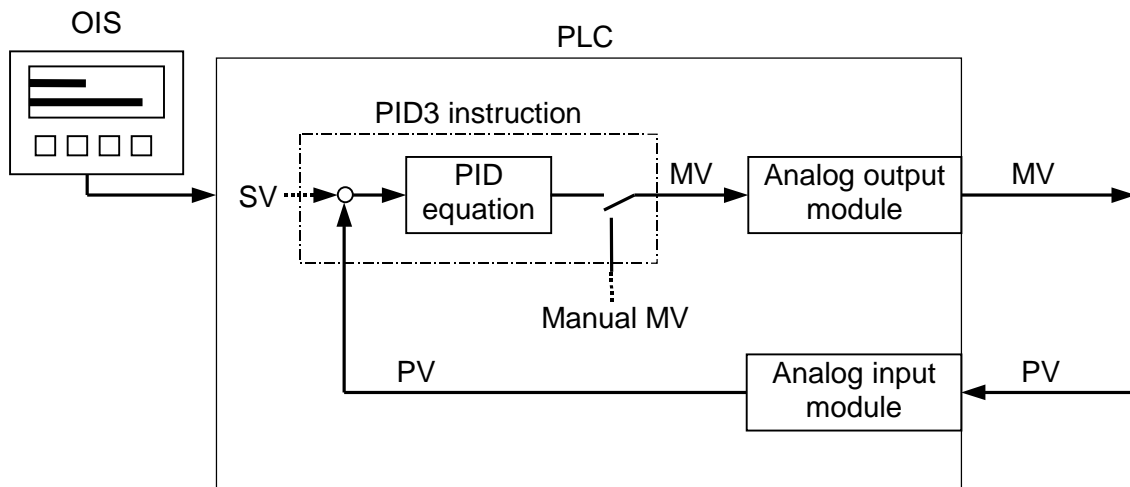
PID Equation: Controls the MV based on the magnitude of e and Δe and the PID tuning parameters. These parameters may be more or less aggressive based on system time responses and operator preferences.

1. Overview

1.2 PLC Configuration for PID Control

The T-series PLC use the PID3 instruction to execute the PID equation. In this guide, PID control is discussed using the PID3 instruction.

The figure below shows a typical PLC configuration where analog signals are used for the PV and the MV. An operator interface station (OIS) is used to set the SV, and to display the PV and the MV.



In the PLC, a PID3 function block, analog input module and an output modules are used for PID control (one PID loop). To configure two or more PID loops, two or more PID3 function blocks are used. The number of the PID3 function blocks programmed in a PLC is only limited by the total program memory capacity of the PLC. However, the number of the PID loops configurable by one PLC is normally limited by the available number of analog inputs/outputs, and the PLC execution speed vs. the required control interval.

NOTE The PID3 instruction is supported by the following PLC models and versions. The standard T3 does not have this instruction.

T3H Version 1.1 or later
T2N Version 1.0 or later
T2E Version 1.0 or later
T2 Version 1.4 or later
T1S Version 1.0 or later
T1 Version 1.1 or later

The T3H (version 1.1 or later) also supports the floating-point type PID3 (FPID3). The operation of the FPID3 is the same as the PID3 except for the type of data use. In this guide, the FPID3 instruction is not discussed.

2. PID Basics

2.1 Direct action and reverse action

There are two basic actions of PID with respect to the control direction of MV. These are direct action and reverse action.

- Direct action will lead the MV to increase when the PV is larger than the SV.
(For example, cooling application)
- Reverse action will lead the MV to decrease when the PV is larger than the SV.
(For example, heating application)

2.2 PID Parameters

2.2.1 Proportional (P) control action

Proportional (P) control generates the MV in proportion to the error (E). Here, the error (E) is the difference between the SV and the PV, and defined as follows:

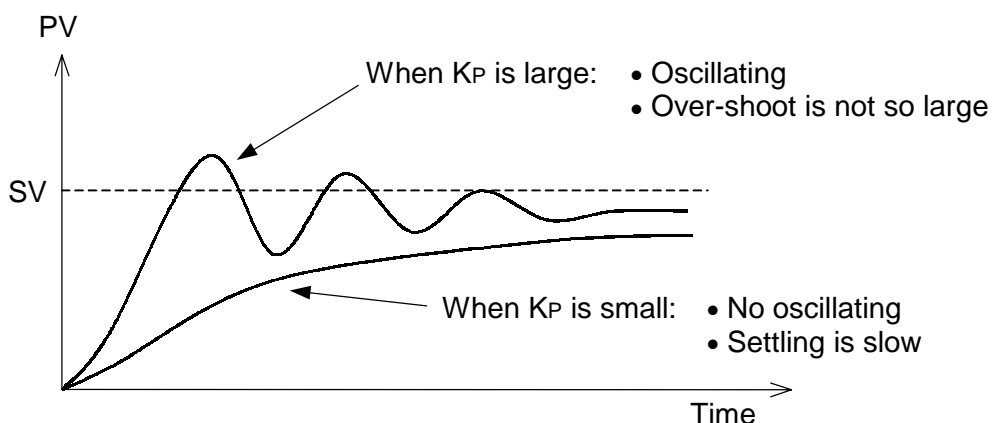
$$E = SV - PV$$

In the P control action, the MV is calculated as follows.

$$MV = K_P \cdot E$$

K_P is called proportional gain.

Generally, P control action works as follows:



With just P control, an offset (residual error) will remain. Therefore, P control is used with I control (PI control) to eliminate the offset.

2. PID Basics

2.2.2 Integral (I) control action

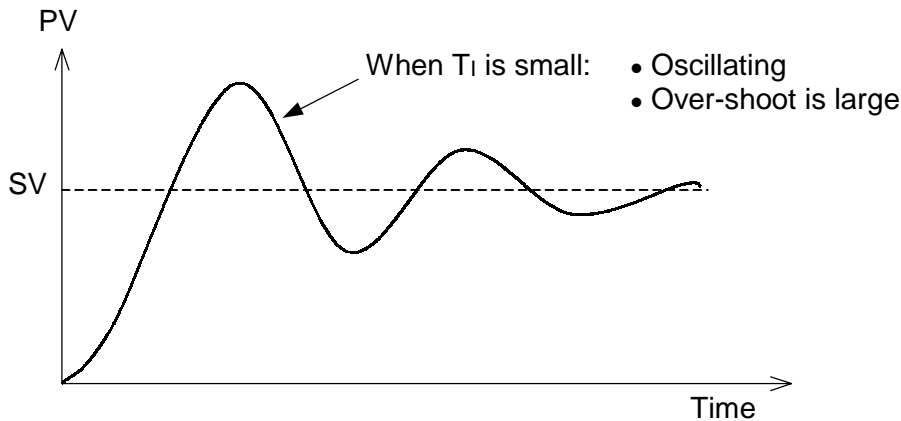
Integral (I) control will generate the MV in proportion to the time-integral of the error (E). While the error (E) exists, the I control will modulate the MV to eliminate the error (E). Generally the MV with I control is calculated as follows:

$$MV = K_P \cdot \frac{1}{T_I} \int E dt$$

T_I is called integral time, the unit of measure is 'seconds per repeat'

When T_I is large, the MV will change slowly. When T_I is small, the MV will change rapidly. That is, the smaller the T_I , the larger the integral gain.

When T_I is too small, oscillation of PV will appear as figure below.



The I control is not used by itself. It is used with P (PI control) or P and D (PID control).

NOTE When the SV is changed, E may remain for a relatively long time, and the MV may reach either its minimum or maximum value. If I continues to integrate beyond this point there will be a significant lag time in response to an overshoot (a change in the direction of E). This problem is called 'reset windup', the name originating with pneumatic controls and their 'gain, reset and rate' tuning parameters. To prevent this, the PID3 instruction has a feature called anti-reset windup, which stops the I control action when the MV reaches its limit.

2.2.3 Derivative (D) control action

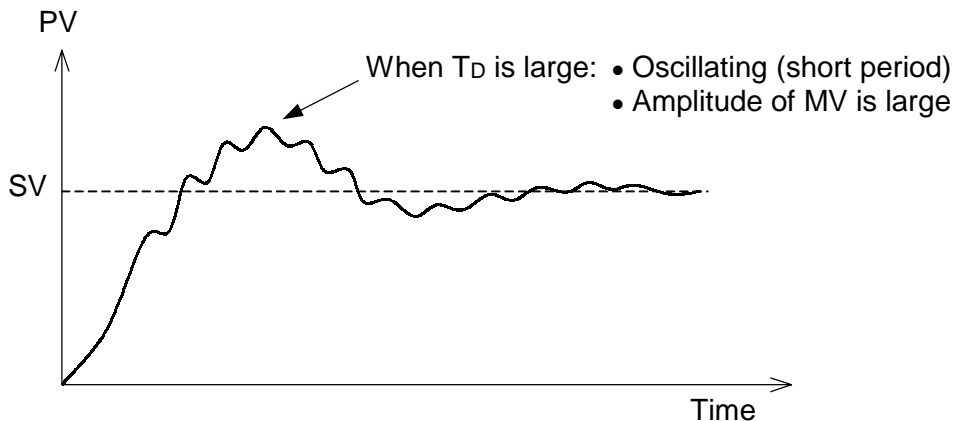
Derivative (D) control will generate the MV in proportion to the rate of change in the error (E). By adding the D control, quick corrective action can be obtained at the beginning of an upset condition. Generally the MV by the D control is written as follows.

$$MV = K_P \cdot T_D \frac{d}{dt} E$$

T_D is called derivative time, the unit of measure is 'repeats per second'.

When T_D is large, MV is relatively large for any E. That is, the larger the T_D , the larger the derivative gain. If T_D is 0 (zero), the D control does not function.

When T_D is too large, short periodic oscillations of PV will appear:



The D control is not used by itself. It is used with P and I (PID control).

D control is poorly suited for processes which oscillate rapidly and is seldom used in processes which have a fast response time (most pressure or flow loops). For processes with long lag times (many temperature and some level loops), D control can reduce both the magnitude of e and the potential for large overshoots caused by a given upset condition. Note that these same processes often act as mechanical integrators and the I tuning parameter can actually stimulate a worsening of the overshoot or oscillation problem.

NOTE The above equation for the D control is the complete derivative. However, for the actual process, such complete derivative action is harmful. Therefore, in the PID3, an incomplete derivative action is used. Also, in the PID3, derivative is applied only for a change in PV, not for the error. This is called pre-derivative PID. This method is used to prevent the unnecessary large changing of the MV for the SV is being changed.

2. PID Basics

2.3 Operation Mode

Generally a PID controller has two operation modes, Auto mode and Manual mode. Auto mode is the mode in which the MV is controlled by the PID equation. Manual mode is the mode in which the MV is changed by operator.

When the operation mode is changed from Manual to Auto, and vice versa, the MV should not be changed rapidly (bumped). Normally a PID controller has a function that enables it to hold the current MV during mode changes. This function is called bumpless transfer.

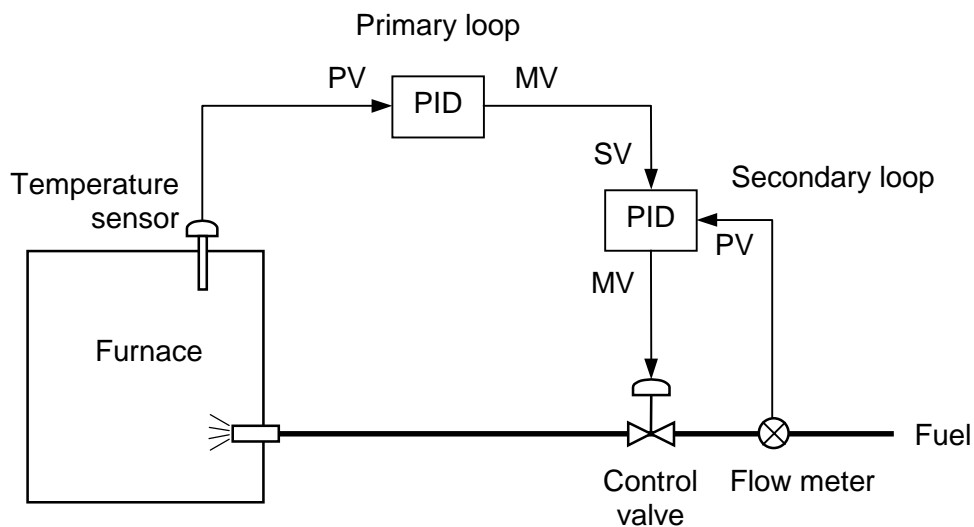
Some PID algorithms have a function called SV tracking. When the SV tracking function is enabled, the SV is automatically over-written by the current PV during Manual mode. As the result, when the mode is changed from Manual to Auto, the control operation continues smoothly, since the SV and the PV are identical. A frequent operator complaint about SV tracking is that the SV must always be re-entered after each change from manual to auto mode. Therefore when SV tracking is implemented in a PID algorithm a manual switch is normally provided to allow operators the option of disabling it.

NOTE In the PID3 instruction, a bumpless transfer function is available. The PID3 does not have the SV tracking function. However, this function can be easily programmed into preceding circuits in the PLC. See section 4.4, "Adding SV Tracking"

2.4 Cascade Control

In some applications, two PID controllers are used in combination. In this configuration, the MV of the primary PID controller is connected to the SV of the secondary PID controller. This is called cascade control. The benefit of cascade control is quicker suppression of disturbances or upsets. That is, the secondary PID loop is expected to suppress errors before their influence appears on the PV of the primary PID loop.

The figure below shows an example of cascade control.



Cascade control is effective only when the response of the secondary process is much faster than the primary process. In the above example, the primary loop is for temperature and the secondary loop is for flow rate. Normally, response of temperature control loop is far slower than the flow loop. In this example configuration, cascade control can be effective.

In cascade control, the MV tracking function in the primary PID is required. This function provides bumpless transfer when the secondary PID changes from the local auto mode to the cascade mode. Then, the MV of the primary PID tracks the local SV of the secondary PID when the secondary PID is in local mode.

NOTE The PID3 instruction supports the cascade mode and MV tracking.

3. PID3 Instruction

3. PID3 Instruction

IMPORTANT The PID3 instruction must be programmed in a main program block, and the PLC scan mode must be set for constant (fixed interval) scan mode.

FUN 156	PID3	Pre-derivative real PID
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Expression

Input •[A PID3 B → C]• Output

Function

Performs PID (Proportional, Integral, Derivative) control which is a fundamental method of feedback control. The PID3 instruction has the following features.

- For derivative action, an incomplete derivative method is used to suppress interference of high-frequency noise and to expand the stable application range. D control acts on PV rather than the error, E
- Controllability and stability are enhanced by using an advanced digital PID algorithm incorporating such features as incomplete derivative and bumpless transfer.
- Auto, cascade and manual modes are supported in this instruction.
- A digital filter is available for the PV.
- An MV tracking function is available.
- PID control with dead-band is available.
- Direct / reverse action is selectable.
- Rate limit of the SV change (in auto mode) is available, Also the rate limit of MV change and upper/lower limit of MV are available.

Execution condition

Input	Operation	Output
OFF	Initialization	OFF
ON	Executes PID equation every setting interval	ON when executed

Operand

	Name	Device (Bit)										Register										Constant	Index					
		X	Y	S	L	R	Z	T	C	I	O	X	Y	S	L	R	W	T	C	D	F			I	O	I	J	K
A	Top of input data											√	√	√	√	√	√	√	√	√	√							√
B	Top of parameter											√	√	√	√	√	√	√	√	√	√							√
C	Top of output data												√	√	√	√	√	√	√	√	√							√

Note: For the T1/T1S, registers LW, W and F, and index modifications are not available.

3. PID3 Instruction

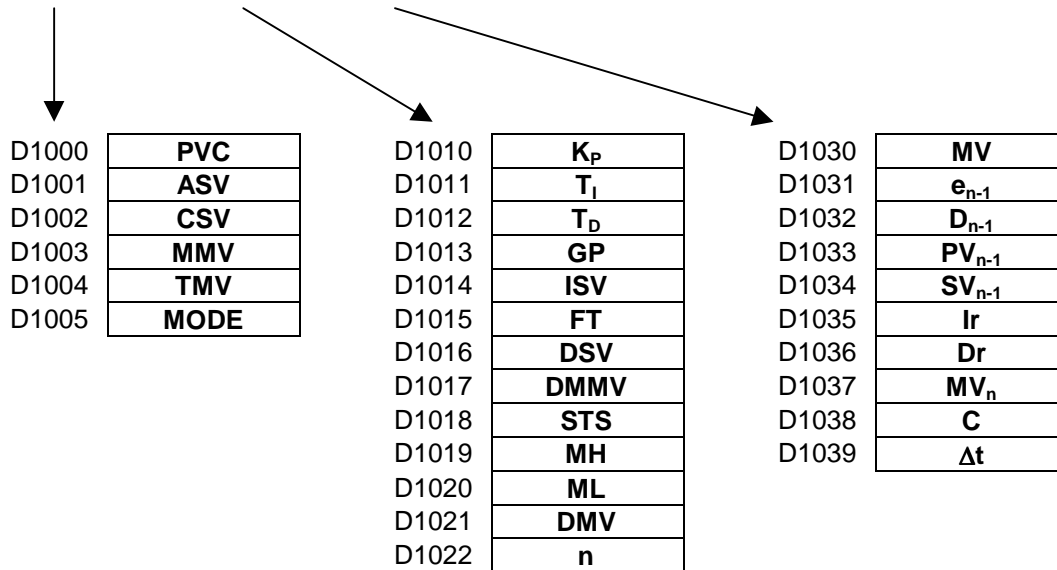
Data configuration

Input data			Control parameter			Output data		
A	Process variable	PVC	B	Proportional gain	K_P	C	Manipulation variable	MV
A+1	A-mode set value	ASV	B+1	Integral time	T_I	C+1	Last error	e_{n-1}
A+2	C-mode set value	CSV	B+2	Derivative time	T_D	C+2	Last derivative value	D_{n-1}
A+3	M-mode MV input	MMV	B+3	Dead-band	GP	C+3	Last PV	PV_{n-1}
A+4	MV tracking input	TMV	B+4	A-mode initial SV	ISV	C+4	Last SV	SV_{n-1}
A+5	Mode setting	MODE	B+5	Input filter constant	FT	C+5	Integral remainder	I_r
			B+6	ASV rate limit	DSV	C+6	Derivative remainder	D_r
			B+7	MMV rate limit	DMMV	C+7	Internal MV	MV_n
			B+8	Initial status	STS	C+8	Internal counter	C
			B+9	MV upper limit	MH	C+9	Control interval	Δt
			B+10	MV lower limit	ML			
			B+11	MV rate limit	DMV			
			B+12	Control interval	n			

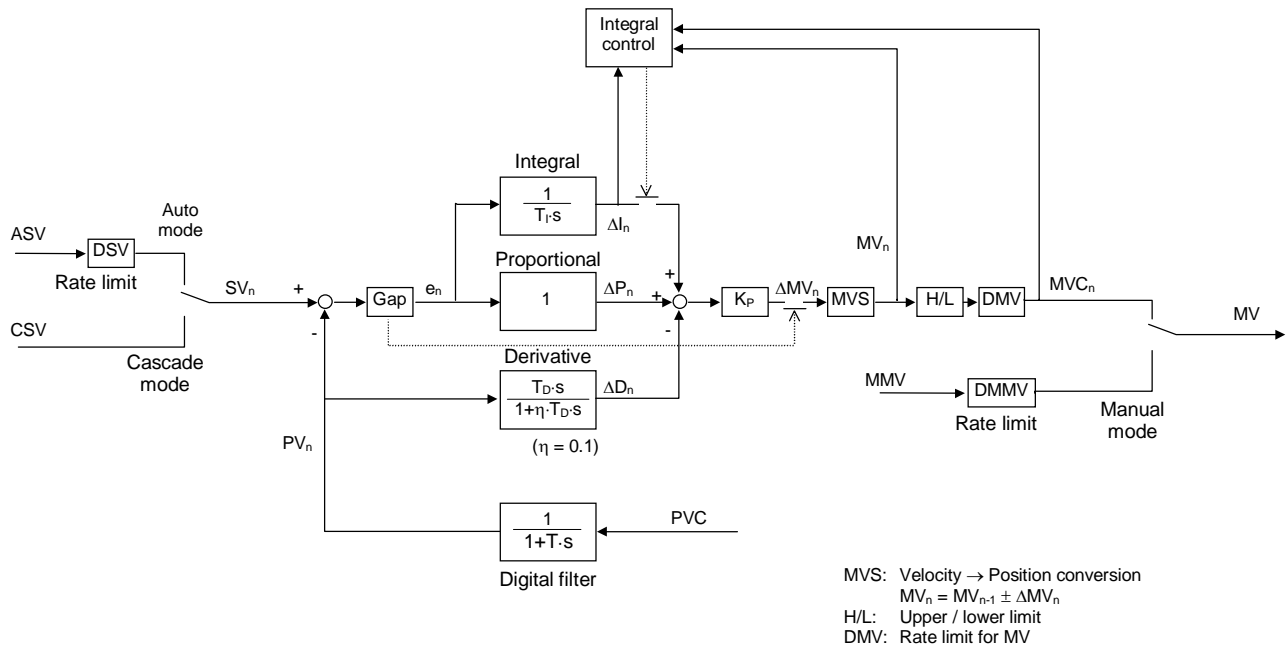
A-mode: Auto mode
C-mode: Cascade mode
M-mode: Manual mode

For example, when a PID3 instruction has the following operands, the registers are assigned as follows.

• [D1000 PID3 D1010 → D1030] •



Control block diagram



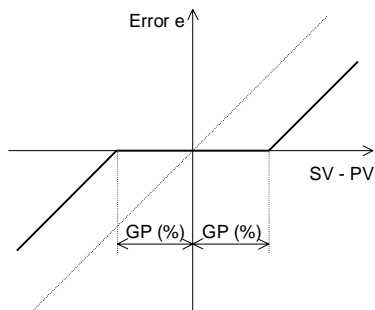
Integral action control:

When MV is limited by upper, lower or rate of change (MH, ML, DMV), and the integral value has same sign as limit over, the integral action is stopped.

Velocity → Position conversion:

In Direct action mode, MV increases when PV is increased. → $MV_n = MV_{n-1} - \Delta MV_n$
 In Reverse action mode, MV decreases when PV is increased. → $MV_n = MV_{n-1} + \Delta MV_n$

Gap (dead-band) operation: In the range of $e + GP(\%)$ and $e - GP(\%)$ no PID action will occur.



3. PID3 Instruction

Algorithm

Digital filter:

$$PV_n = (1 - FT) \cdot PVC + FT \cdot PV_{n-1}$$

Here,

$$0.000 \leq FT \leq 0.999 \quad (\text{The bigger } FT, \text{ the longer time constant})$$

PID algorithm:

$$\Delta MV_n = KP \cdot (\Delta P_n + \Delta I_n + \Delta D_n)$$

$$MV_n = MV_{n-1} \pm \Delta MV_n$$

Here,

$$\Delta P_n = e_n - e_{n-1}$$

$$e_n = SV_n - PV_n \quad (\text{If } GP \neq 0, \text{ Gap is applied})$$

$$\Delta I_n = \frac{e_n \cdot \Delta t + I_r}{T_I} \quad (\text{If } T_I = 0, \text{ then } \Delta I_n = 0)$$

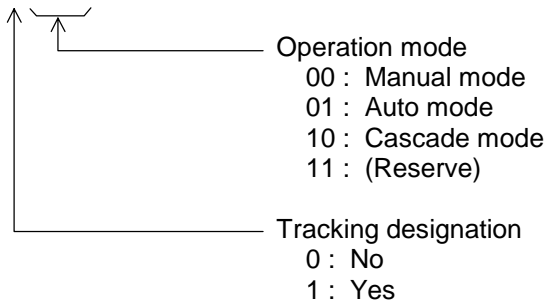
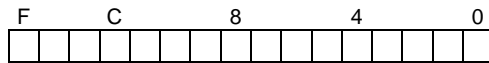
$$\Delta D_n = \frac{T_D \cdot (PV_{n-1} - PV_n) - \Delta t \cdot D_{n-1} + D_r}{\Delta t + \eta \cdot T_D}$$

$$D_n = D_{n-1} + \Delta D_n$$

$$\eta = 0.1 \text{ (Fixed)}$$

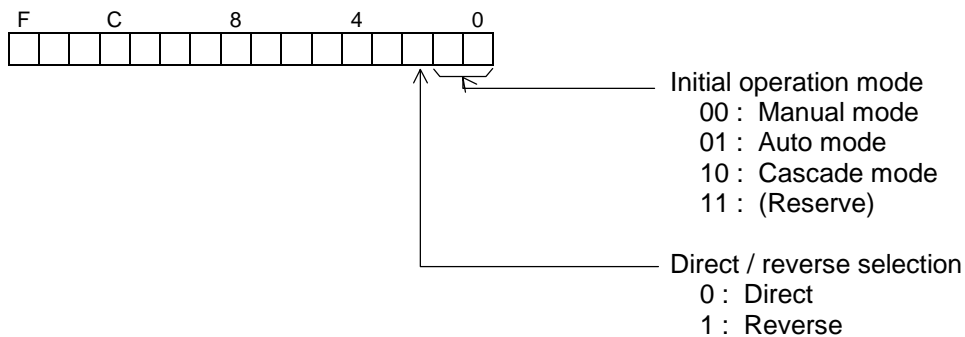
Parameter details

A	Process variable PVC (0.00 to 100.00 %)	Data range: 0 to 10000
A+1	Auto mode set value ASV (0.00 to 100.00 %)	Data range: 0 to 10000
A+2	Cascade mode set value CSV (0.00 to 100.00 %)	Data range: 0 to 10000
A+3	Manual mode MV MMV (-25.00 to 125.00 %)	Data range: -2500 to 12500
A+4	MV tracking input TMV (-25.00 to 125.00 %)	Data range: -2500 to 12500
A+5	Mode setting MODE	



3. PID3 Instruction

<i>B</i>	Proportional gain K_P (0.00 to 327.67)	Data range: 0 to 32767
<i>B+1</i>	Integral time T_I (0.000 to 32.767 min.) (If $T_I = 0$, integral action is disabled)	Data range: 0 to 32767
<i>B+2</i>	Derivative time T_D (0.000 to 32.767 min.)	Data range: 0 to 32767
<i>B+3</i>	Gap (dead-band) GP (0.00 to 10.00 %)	Data range: 0 to 1000
<i>B+4</i>	Auto mode initial set value ISV (0.00 to 100.00 %)	Data range: 0 to 10000
<i>B+5</i>	Input filter constant FT (0.000 to 0.999)	Data range: 0 to 999
<i>B+6</i>	ASV rate limit DSV (0.00 to 100.00 %/Δt)	Data range: 0 to 10000
<i>B+7</i>	MMV rate limit DMMV (0.00 to 100.00 %/Δt)	Data range: 0 to 10000
<i>B+8</i>	Initial status STS	



<i>B+9</i>	MV upper limit MH (-25.00 to 125.00 %)	Data range: -2500 to 12500
<i>B+10</i>	MV lower limit ML (-25.00 to 125.00 %)	Data range: -2500 to 12500
<i>B+11</i>	MV rate limit DMV (0.00 to 100.00 %/Δt)	Data range: 0 to 10000
<i>B+12</i>	Control interval setting n (1 to 32767 times)	Data range: 1 to 32767

The PID equation is executed every n scans. Therefore, the control interval $\Delta t = n \times$ constant scan interval. When $n \leq 0$, $n = 1$ is used)

<i>C</i>	Manipulation variable MV (-25.00 to 125.00 %)	Data range: -2500 to 12500
<i>C+1</i> : <i>C+9</i>	Internal work area, do not use elsewhere in the program.	

3. PID3 Instruction

Operation

1. When the instruction input is OFF:

The PID3 instruction is initialized.

- Operation mode is set as specified by $B+8$. $A+5$ bit 0, 1 \leftarrow $B+8$ bit 0, 1
(The status of bits 0 & 1 in register $B+8$ are transferred to bits 0 & 1 of register $A+5$)
- Auto mode SV (ASV) is set as specified by $B+4$. $ASV \leftarrow ISV$
(The value in register $B+4$ is transferred to register $A+1$)
- Manual mode MV (MMV) is set as current MV. $MMV \leftarrow MV$
- Internal calculation data is initialized.
- MV remains unchanged.

2. When the instruction input is ON:

The PID calculation is executed every n scans which is specified by $B+12$. The following operation modes are available based on the setting in $A+5$.

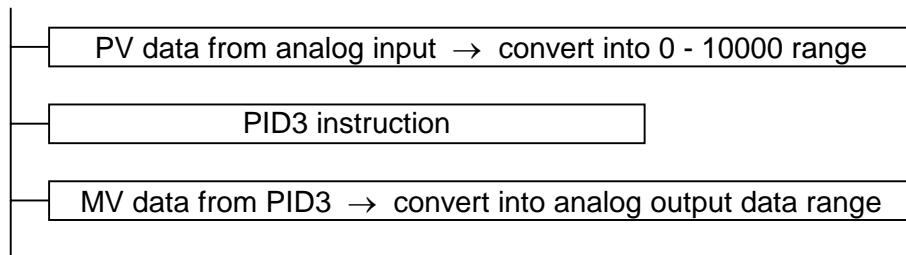
- Manual mode
In this mode, the MV can be directly controlled by the input value of MMV. MV rate of change limit for manual mode (DMMV) is effective. Upper/lower limit (MH/ML) and rate of change limit (DMV) are not effective. When the mode is changed from manual to auto or cascade, the operation is started from the current MV.
- Auto mode
This is the normal PID control mode with ASV as set value. The Set value rate limit (DSV), manipulation variable upper/lower limit (MH/ML) and rate limit (DMV) are effective. Bumpless transfer from auto mode to manual mode is available. (Manual mode manipulation variable MMV tracks the current MV automatically. $MMV \leftarrow MV$)
- Cascade mode
This mode is for PID cascade control. PID control is executed with CSV as the set value. Different from the auto mode, the set value rate limit (DSV) is not effective. The Manipulation variable upper/lower limit (MH/ML) and rate limit (DMV) are effective. Bumpless transfer from cascade mode to manual mode is available. (the Manual mode manipulation variable (MMV) tracks the current MV automatically. $MMV \leftarrow MV$)
And, bumpless transfer from cascade mode to auto mode is available. (Auto mode set value ASV tracks the current CSV automatically. $ASV \leftarrow CSV$)
- MV tracking
This function is available in auto and cascade modes. When the MV tracking designation ($A+5$, bit 2) is ON, tracking input (TMV) is directly output as MV. Manipulation variable upper/lower limit (MH/ML) is effective, but MV rate limit (DMV) is not effective. When the MV tracking designation is changed to OFF, the operation starts from the current MV.

4. Application Examples

4.1 PID3 Instruction Application Notes

When using the PID3 instruction, note the following items.

- The PID3 can only be used in the main program.
- The PLC must be set for the constant scan (fixed interval) mode.
The setting range of the constant scan is 10 to 200 ms, in 10 ms increments.
The PID3 execution cycle (Δt : loop update cycle) is determined as follows:
$$\Delta t = n \times \text{constant scan setting (n: control interval setting, } B+12)$$
Normally, the shorter the Δt , the better for PID control. However, minimum constant scan is limited by the actual program execution time.
- In the PID3 instruction, the SV, PV and MV are handled as %. (0.01% units). The data range 0 - 10000 corresponds to 0% - 100%.
On the other hand, analog input/output data normally has the range 0 - 4000 counts for 12 bit A/D and D/A modules and 0 - 250 for 8 bit modules.
Therefore, data conversion is necessary before and after the PID3 instruction.



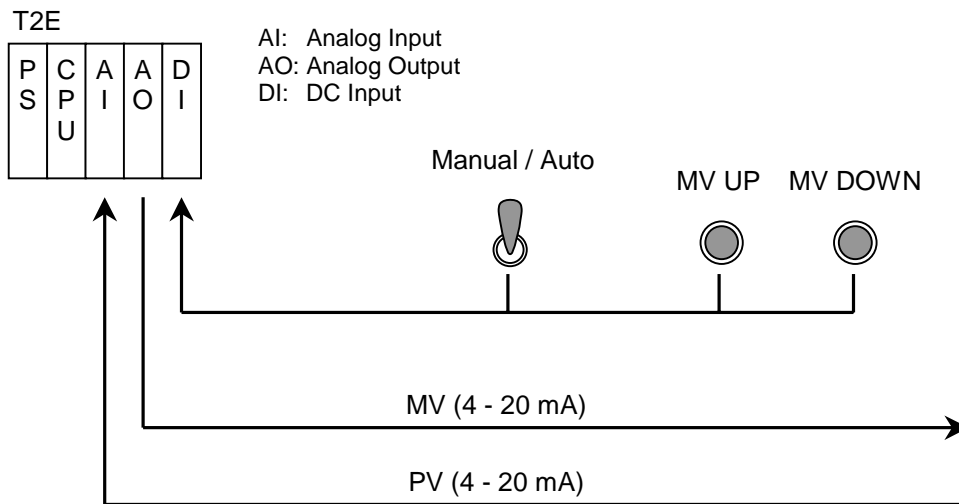
- The number of PID3 function blocks used (number of PID loops) in a program is not limited functionally. However, there is a practical limit based on the available number of analog input/output channels, PLC execution speed, and the total program capacity.
- If the sensor used has non-linear characteristics, the function generator instruction (FG = FUN165) or square root instruction (RT = FUN167) can be used to convert the PV into linear data.
- If a serious error is detected in the PLC, the PLC turns OFF all discrete outputs and forces analog outputs to 0 (zero). Configure fail-safe systems external to the PLC so that unsafe situations will not occur in the event of the PLC going into the error mode.

4. Application Examples

4.2 Basic PID Control Program

The following program is an example of simple PID control. In this program, PID3 works to control the PV at 40% without setting the SV externally.

Sample system configuration



Sample operation

The Manual/Auto mode switch controls the PID operation mode between manual and auto modes. In the manual mode, the MV is controlled manually by pressing the UP or DOWN button. Every time the button is pressed, the MV is increased/decreased by 0.01 %. And when the button is pressed for more than 2 seconds, the MV will increase or decrease continuously. In the auto mode, PID control is executed. In this example, the SV is preset to 40 %.

Device/register assignment

XW000 ... Analog input for PV (0 - 4000)
YW004 ... Analog output for MV (0 - 4000)
X0060 ... Manual/Auto mode switch (OFF = manual, ON = auto)
X0061 ... MV increase in manual mode (continuous increase in 2 seconds increments)
X0062 ... MV decrease in manual mode (continuous decrease in 2 seconds decrements)
D1000 - D1039 ... Used for PID3
D0600 - D0607 ... Used for input/output data conversion
T000 - T003 Used to create timing

The PLC (T2E) is used with 100 ms constant scan mode.

4. Application Examples

Sample program

```

1  -|^|-[ 00600 MOV D1010][ 00450 MOV D1011][ 00090 MOV D1012]-----
      |
      +[ 00000 MOV D1013][ 04000 MOV D1014][ 00000 MOV D1015]-----
      |
      +[ 10000 MOV D1016][ 00100 MOV D1017][ 00004 MOV D1018]-----
      |
      +[ 10000 MOV D1019][ 00000 MOV D1020][ 00100 MOV D1021]-----
      |
      +[ 00001 MOV D1022]-----

2  [00100 TON T000]-----[MCS ]
3  [XW000 * 10000 -> D0601.D0600][D0601.D0600 DIV 04000 -> D0602]
4  [D0602 MOV D1000]-----
5  [D1000 PID3 D1010 -> D1030]-----
6  [D1030 * 04000 -> D0605.D0604][D0605.D0604 DIV 10000 -> D0606]
7  [D0606 MOV YW004]-----
8  -----[MCR ]
9  X0060
   -|/|-[ 00000 MOV D1005]-----
      |
      X0061 X0062
      +--| |---|/|---|^|---[ +1 D1003]-----
          |
          +[00200 TON T001][D1003 + 00005 -> D1003]-----
          |
          +[D1003 > D1019][D1019 MOV D1003]-----
      X0062 X0061
      +--| |---|/|---|^|---[ -1 D1003]-----
          |
          +[00200 TON T002][D1003 - 00005 -> D1003]-----
          |
          +[D1003 < D1020][D1020 MOV D1003]-----
10 X0060
   -| |---[ 00001 MOV D1005]-----

```

4. Application Examples

Rung 1 is for setting PID3 parameters. The following parameters are used in this example.

D1010 = 600 K_P (Proportional gain) = 6
D1011 = 450 T_I (Integral time) = 0.45 min. = 27 s
D1012 = 90 T_D (Derivative time) = 0.09 min. = 5.4 s
D1013 = 0 GP (Dead-band) = 0 %
D1014 = 4000 ISV (Initial set value) = 40 %
D1015 = 0 FT (Input filter constant) = 0
D1016 = 10000 ... DSV (ASV rate limit) = 100 %
D1017 = 100 DMMV (MMV rate limit) = 1 %/100 ms
D1018 = 4 STS (Initial status) = Reverse action (sets bit 2 ON)
D1019 = 10000 ... MH (MV upper limit) = 100 %
D1020 = 0 ML (MV lower limit) = 0 %
D1021 = 100 DMV (MV rate limit) = 1 %/100 ms
D1022 = 1 Control interval is 100 ms (PLC is 100 ms constant scan mode)

Rung 2 is for the delay at start-up. (1 second)

Rungs 3 and 4 are for the PV analog input data conversion. They convert 0 - 4000 into 0 - 10000 data range.

$$D1000 = XW000 \times 10000 / 4000$$

Rung 5 is the PID3 function.

Rungs 6 and 7 are for the MV data conversion to analog output. They convert 0 - 10000 into 0 - 4000 data range.

$$YW004 = D1030 \times 4000 / 10000$$

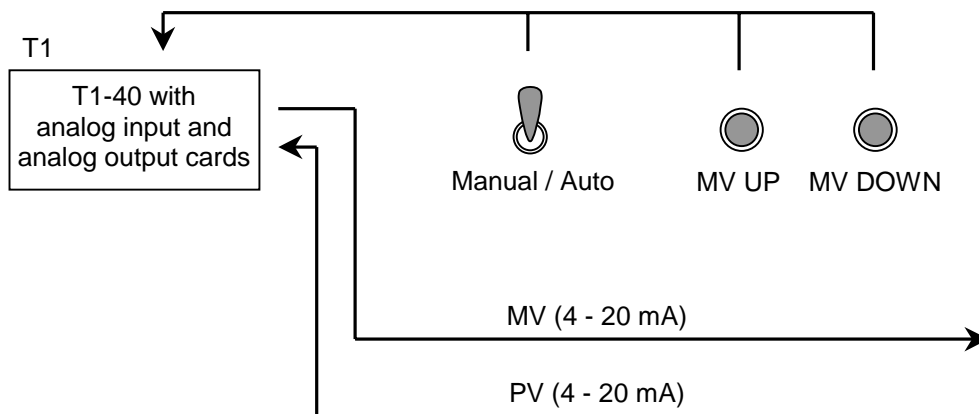
Rung 9 is for manual operation. When X0060 is OFF (Manual), the value 0 is written into D1005 (PID3 mode) to change the PID3 to manual mode. During manual mode, if X0061 (Up) turns ON, the MV is increased. And if X0062 (Down) turns ON, the MV is decreased.

Rung 10 is for auto mode. When X0060 is ON (Auto), the value 1 is written into D1005 (PID3 mode) to change the PID3 to auto mode. In this example, the SV is preset to 4000 (40 %).

4.3 Adding a Dead-Band

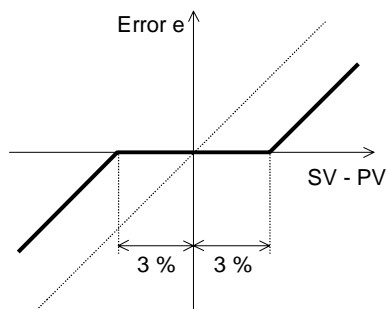
In some applications for stable operation it is better to reduce the corrective action (MV change) for small deviations. For this purpose a dead-band can be added to the PID3 instruction. The following program is an example of adding the dead-band. This program is similar to the one shown in section 4.2. The I/O allocation is different.

Sample system configuration



Sample operation

The operation is same as the example in section 4.2, except the dead-band is added as follows.



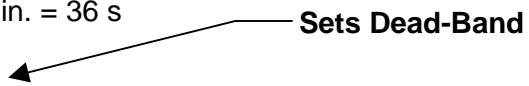
Device/register assignment

- XW004 ... Analog input for PV (800 - 4000)
- YW005 ... Analog output for MV (800 - 4000)
- X0000 ... Manual/Auto mode switch (OFF = manual, ON = auto)
- X0001 ... MV increase in manual mode (continuous increase in 2 seconds)
- X0002 ... MV decrease in manual mode (continuous decrease in 2 seconds)

The PLC (T1-40) is used with 50 ms constant scan mode.

4. Application Examples

Rung 1 is for setting PID3 parameters. The following parameters are used in this example.

D0810 = 400 K_P (Proportional gain) = 4
D0811 = 600 T_I (Integral time) = 0.6 min. = 36 s
D0812 = 0 T_D (Derivative time) = 0
D0813 = 300 GP (Dead-band) = 3 % 
D0814 = 4000 ISV (Initial set value) = 40 %
D0815 = 0 FT (Input filter constant) = 0
D0816 = 10000 ... DSV (ASV rate limit) = 100 %
D0817 = 100 DMMV (MMV rate limit) = 1 %/50 ms
D0818 = 4 STS (Initial status) = Reverse action
D0819 = 10000 ... MH (MV upper limit) = 100 %
D0820 = 0 ML (MV lower limit) = 0 %
D0821 = 100 DMV (MV rate limit) = 1 %/50 ms
D0822 = 1 Control interval is 50 ms (PLC is 50 ms constant scan mode)

Rung 2 is for delay at start-up. (1 second)

Rungs 3 and 4 are for the PV analog input data conversion. They convert 800 - 4000 into 0 - 10000 data range. The FG instruction is used in this example.

Rung 5 is the PID3 instruction.

Rungs 6 and 7 are for the MV data conversion for analog output. They convert 0 - 10000 into 800 - 4000 data range. The FG instruction is used in this example.

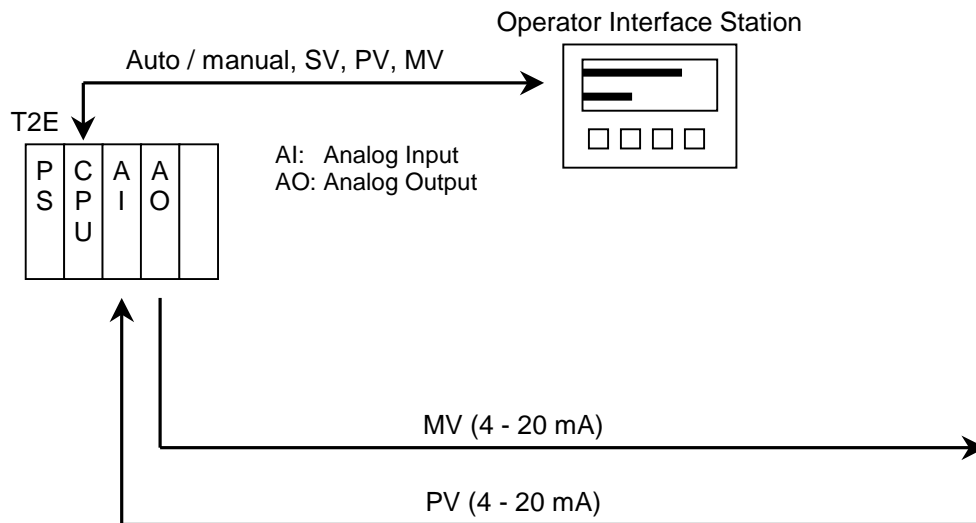
Rung 9 is for manual operation, and the rung 10 is for auto mode. Refer to section 4.2 for the description.

4. Application Examples

4.4 Adding SV Tracking

When the PID operation mode is changed from manual to auto, the MV is immediately modulated to bring the PV to the SV. However, it is sometimes essential to maintain stability during this mode change. For this purpose, SV tracking is used. SV tracking means that the SV is over-written by the value of the current PV while in manual mode. As the result, there is no deviation between SV and PV when the mode is changed from manual to auto. Then operator can change the SV gradually to avoid a process bump.

Sample system configuration



Sample operation

In this example, an operator interface station (or OIS) is used to monitor/control the PID3 operation. The OIS can control the PID3 mode (auto/manual), the MV in manual mode, and the SV in auto mode, by accessing the T2E's respective registers.

Device/register assignment

- XW000 ... Analog input for PV (0 - 4000)
- YW004 ... Analog output for MV (0 - 4000)
- D1000 ... PV (0 - 10000) (monitored by OIS)
- D1001 ... Auto mode SV (0 - 10000)
(controlled by OIS in auto mode, tracks SV in manual mode)
- D1003 ... Manual mode MV (0 - 10000) (controlled by OIS in manual mode)
- D1005 ... PID3 operation mode (0 = manual, 1 = auto) (controlled by OIS)

The PLC (T2E) is used with 100 ms constant scan mode.

Sample program

```

1  -|^|-[ 00600 MOV D1010][ 00450 MOV D1011][ 00090 MOV D1012]-----
      +[ 00000 MOV D1013][ 00000 MOV D1014][ 00000 MOV D1015]-----
      +[ 00010 MOV D1016][ 00010 MOV D1017][ 00004 MOV D1018]-----
      +[ 10000 MOV D1019][ 00000 MOV D1020][ 00100 MOV D1021]-----
      +[ 00001 MOV D1022]-----
2  [D1005 = 00000][D1000 MOV D1001][D1000 MOV D1034]-----
3  [XW000 * 10000 -> D0601.D0600][D0601.D0600 DIV 04000 -> D0602]
4  [D0602 MOV D1000]-----
5  [D1000 PID3 D1010 -> D1030]-----
6  [D1030 * 04000 -> D0605.D0604][D0605.D0604 DIV 10000 -> D0606]
7  [D0606 MOV YW004]-----

```

Rung 1 is for setting PID3 parameters. The following parameters are used in this example.

D1010 = 600 K_P (Proportional gain) = 6
 D1011 = 450 T_I (Integral time) = 0.45 min. = 27 s
 D1012 = 90 T_D (Derivative time) = 0.09 min. = 5.4 s
 D1013 = 0 GP (Dead-band) = 0 %
 D1014 = 0 ISV (Initial set value) = 0 %
 D1015 = 0 FT (Input filter constant) = 0
 D1016 = 10 DSV (ASV rate limit) = 0.1 %/100 ms
 D1017 = 10 DMMV (MMV rate limit) = 0.1 %/100 ms
 D1018 = 4 STS (Initial status) = Reverse action
 D1019 = 10000 ... MH (MV upper limit) = 100 %
 D1020 = 0 ML (MV lower limit) = 0 %
 D1021 = 100 DMV (MV rate limit) = 1 %/100 ms
 D1022 = 1 Control interval is 100 ms (PLC is 100 ms constant scan mode)

Rung 2 is for SV tracking. When D1005 is 0 (manual mode), the value of D1000 (PV) is copied to D1001 (auto mode SV) and D1034 (last SV).

Rungs 3 to 7 are the same as in section 4.2. Refer to section 4.2.

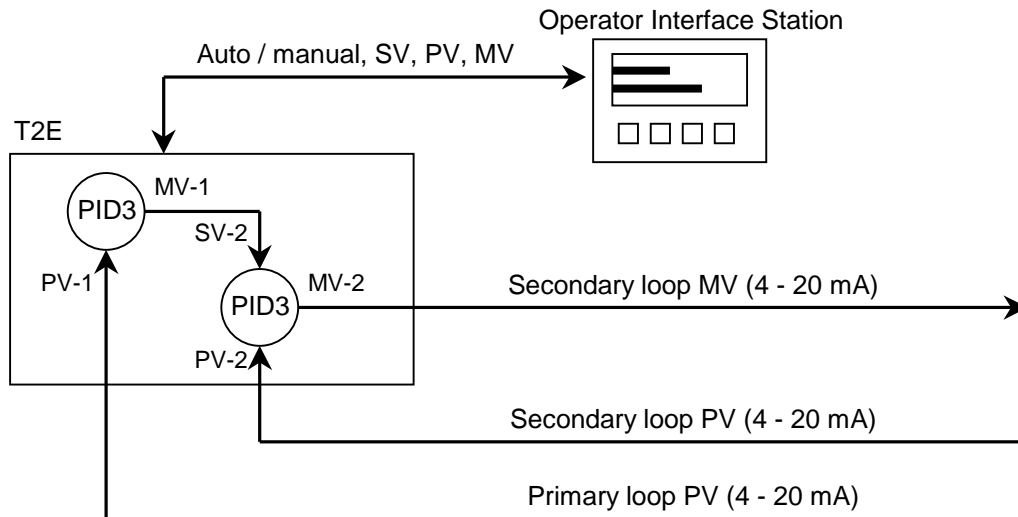
4. Application Examples

4.5 Cascade Control with MV Tracking

This is an example of cascade control. The primary and the secondary loops are configured by two PID3 instructions in the PLC. For the primary loop, MV tracking function is added.

MV tracking function: When the secondary loop is in other than cascade mode, the primary loop MV tracks the secondary loop SV. It is used to prevent sudden change of the secondary loop MV when the secondary loop is changed to the cascade mode.

Sample system configuration



Sample operation

In this example, an operator interface station (or OIS) is used to monitor/control the PID3 operation. The OIS can control the PID3 mode (auto/manual/cascade), the MV in manual mode, and the SV in auto mode, by accessing the designated registers in the T2E.

Device/register assignment

- XW000 ... Analog input for primary loop PV (0 - 4000)
- XW001 ... Analog input for secondary loop PV (0 - 4000)
- YW004 ... Analog output for secondary loop MV (0 - 4000)
- D1000 ... Primary loop PV (0 - 10000) (monitored by OIS)
- D1001 ... Primary loop SV (0 - 10000) (controlled by OIS)
- D1003 ... Primary loop manual MV (0 - 10000) (controlled by OIS in manual mode)
- D1004 ... Primary loop tracking MV
(tracks secondary loop SV when secondary loop is other than cascade mode)
- D1005 ... Primary PID3 operation mode (0 = manual, 1 = auto) (controlled by OIS)

4. Application Examples

D1050 ... Secondary loop PV (0 - 10000) (monitored by OIS)
D1051 ... Secondary loop auto SV (0 - 10000) (controlled by OIS in auto mode)
D1052 ... Secondary loop cascade SV (0 - 10000) (connected with primary loop MV)
D1053 ... Secondary loop manual MV (0 - 10000) (controlled by OIS in manual mode)
D1055 ... Secondary PID3 operation mode (0 = manual, 1 = auto, 2 = cascade)
(controlled by OIS)

The PLC (T2E) is used with 100 ms constant scan mode.

Sample program

```
1  -|^|-[ 00600 MOV D1010][ 00450 MOV D1011][ 00090 MOV D1012]-----
      |
      +[ 00000 MOV D1013][ 00000 MOV D1014][ 00000 MOV D1015]-----
      |
      +[ 00010 MOV D1016][ 00010 MOV D1017][ 00004 MOV D1018]-----
      |
      +[ 10000 MOV D1019][ 00000 MOV D1020][ 00100 MOV D1021]-----
      |
      +[ 00001 MOV D1022]-----

2  [D1055 <> 00002]-----+ [0002 TSET (01) D1005]-----
                          |
                          +[D1051 MOV D1004]-----

3  [D1055 = 00002][0002 TRST (01) D1005]-----

4  [D1005 = 00000][D1000 MOV D1001][D1000 MOV D1034]-----

5  [XW000 * 10000 -> D1041.D1040][D1041.D1040 DIV 04000 -> D1042]

6  [D1042 MOV D1000]-----

7  [D1000 PID3 D1010 -> D1030]-----
```

Rungs 1 to 7 are for the primary PID3 loop.

4. Application Examples

```
8  -|^|-[ 00300 MOV D1060][ 00130 MOV D1061][ 00000 MOV D1062]-----
      +[ 00000 MOV D1063][ 00000 MOV D1064][ 00000 MOV D1065]-----
      +[ 00010 MOV D1066][ 00010 MOV D1067][ 00004 MOV D1068]-----
      +[ 10000 MOV D1069][ 00000 MOV D1070][ 00100 MOV D1071]-----
      +[ 00001 MOV D1072]-----

9  [D1055 = 00000][D1050 MOV D1051][D1050 MOV D1084]-----

10 [XW001 * 10000 -> D1091.D1090][D1091.D1090 DIV 04000 -> D1092]

11 [D1092 MOV D1050]-----

12 [D1030 MOV D1052]-----

13 [D1050 PID3 D1060 -> D1080]-----

14 [D1080 * 04000 -> D1095.D1094][D1095.D1094 DIV 10000 -> D1096]

15 [D1096 MOV YW004]-----
```

Rungs 8 to 15 are for the secondary PID3 loop.

Rung 1 is for setting PID3 parameters. The following parameters are used in this example.

D1010 = 600 K_P (Proportional gain) = 6
D1011 = 450 T_I (Integral time) = 0.45 min. = 27 s
D1012 = 90 T_D (Derivative time) = 0.09 min. = 5.4 s
D1013 = 0 GP (Dead-band) = 0 %
D1014 = 0 ISV (Initial set value) = 0 %
D1015 = 0 FT (Input filter constant) = 0
D1016 = 10 DSV (ASV rate limit) = 0.1 %/100 ms
D1017 = 10 DMMV (MMV rate limit) = 0.1 %/100 ms
D1018 = 4 STS (Initial status) = Reverse action
D1019 = 10000 ... MH (MV upper limit) = 100 %
D1020 = 0 ML (MV lower limit) = 0 %
D1021 = 100 DMV (MV rate limit) = 1 %/100 ms
D1022 = 1 Control interval is 100 ms (PLC is 100 ms constant scan mode)

4. Application Examples

Rungs 2 and 3 are for MV tracking. When the value in D1055 is not 2 (secondary PID3 is not in cascade mode), tracking flag (bit 2 of D1005) is set to ON, and the value of D1051 (auto SV of secondary PID3) is copied to D1004 (tracking MV). When D1055 is 2 (secondary PID3 is in cascade mode), tracking flag (bit 2 of D1005) is reset to OFF.

Rung 4 is for SV tracking. When D1005 is 0 (manual mode), the value of D1000 (PV) is copied to D1001 (auto SV) and D1034 (last SV).

Rungs 5 and 6 are for the PV analog input data conversion. They convert 0 - 4000 into 0 - 10000 data range.

Rung 7 is the primary PID3 loop.

Rung 8 is for setting the secondary PID3 parameters. The following parameters are used in this example.

D1060 = 300 K_P (Proportional gain) = 3
D1061 = 130 T_I (Integral time) = 0.13 min. = 7.8 s
D1062 = 0 T_D (Derivative time) = 0
D1063 = 0 GP (Dead-band) = 0 %
D1064 = 0 ISV (Initial set value) = 0 %
D1065 = 0 FT (Input filter constant) = 0
D1066 = 10 DSV (ASV rate limit) = 0.1 %/100 ms
D1067 = 10 DMMV (MMV rate limit) = 0.1 %/100 ms
D1068 = 4 STS (Initial status) = Reverse action
D1069 = 10000 ... MH (MV upper limit) = 100 %
D1070 = 0 ML (MV lower limit) = 0 %
D1071 = 100 DMV (MV rate limit) = 1 %/100 ms
D1072 = 1 Control interval is 100 ms (PLC is 100 ms constant scan mode)

Rung 9 is for SV tracking. When D1055 is 0 (manual mode), the value of D1050 (PV) is copied to D1051 (auto SV) and D1084 (last SV).

Rungs 10 and 11 are for the PV analog input data conversion. They convert 0 - 4000 into 0 - 10000 data range.

Rung 12 transfers the primary loop MV (D1030) to the secondary loop cascade SV (D1052).

Rung 13 is secondary PID3 loop.

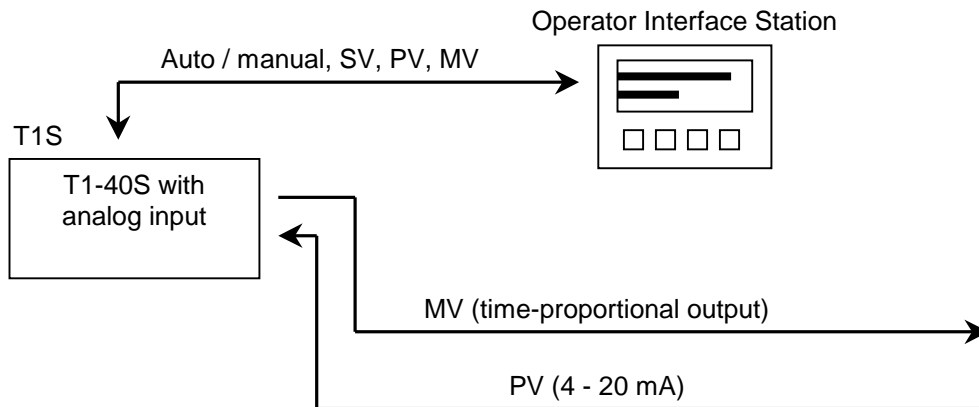
Rungs 14 and 15 are for the MV data conversion for analog output. They convert 0 - 10000 into 0 - 4000 data range.

4. Application Examples

4.6 Time-Proportional Output

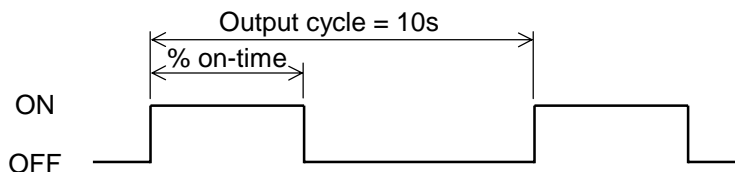
In some applications a discrete output is used for the MV instead of an analog output. In this case a time-proportional pulse is used as the MV. The following example shows how to convert the MV percentage (from the PID3 instruction) to a time-proportional output.

Sample system configuration



Sample operation

In this example an operator interface station (or OIS) is used to monitor/control the PID3 operation. The OIS can control the PID3 mode (auto/manual), the MV in manual mode, and the SV in auto mode, by accessing the dedicated registers in the T1S. The MV is a time-proportional discrete output as follows.



Device/register assignment

- XW004 ... Analog input for PV (800 - 4000)
- Y0020 ... Time-proportional output (control cycle is 10 seconds in this example)
- D1000 ... PV (0 - 10000) (monitored by OIS)
- D1001 ... Auto mode SV (0 - 10000) (monitored by OIS in auto mode)
- D1003 ... Manual mode MV (0 - 10000) (controlled by OIS in manual mode)
- D1005 ... PID3 operation mode (0 = manual, 1 = auto) (controlled by OIS)

The T1-40S PLC is used with a 50 ms constant scan mode. The timer interrupt is set at 10 ms intervals.

4. Application Examples

Main Program:

Rung 1 is for setting PID3 parameters. The following parameters are used in this example.

D1010 = 350 K_P (Proportional gain) = 3.5
D1011 = 380 T_I (Integral time) = 0.38 min. = 22.8 s
D1012 = 90 T_D (Derivative time) = 0.07 min. = 4.2 s
D1013 = 0 GP (Dead-band) = 0 %
D1014 = 0 ISV (Initial set value) = 0 %
D1015 = 0 FT (Input filter constant) = 0
D1016 = 100 DSV (ASV rate limit) = 1 %/50 ms
D1017 = 100 DMMV (MMV rate limit) = 1 %/50 ms
D1018 = 4 STS (Initial status) = Reverse action
D1019 = 10000 ... MH (MV upper limit) = 100 %
D1020 = 0 ML (MV lower limit) = 0 %
D1021 = 100 DMV (MV rate limit) = 1 %/50 ms
D1022 = 1 Control interval is 50 ms (PLC is 50 ms constant scan mode)

Rung 2 is for SV tracking. Refer to section 4.4.

Rungs 3 and 4 are for the PV analog input data conversion. They convert 800 - 4000 into 0 - 10000 data range.

Rung 5 is the PID3 instruction.

Rungs 6 and 7 are for the time-proportional output.

D1040 specifies the output cycle time in 10 ms base (10 seconds in this example).

D1041 specifies the output on time in a 10 ms base. It is converted from the MV (D1030) calculated in the PID3 instruction. A time-proportional output is created in Timer Interrupt Program based on the data in D1040 and D1041.

Timer Interrupt Program:

Rung 1 creates a ring counter (D1050) from 0 to D1040. It increases every 10 ms until it reaches 10s.

Rung 2 controls the time-proportional output (Y0020). It is ON at $D1050 \leq D1041$.

Rung 3 is for direct output to Y0020. It uses the direct I/O instruction, FUN 235.

5. Tuning Techniques

Two typical PID tuning methods are introduced in this section. These are the Transient Response Method and the Critical Gain Method.

During the PID tuning process, it is necessary to watch the PV behavior. For this purpose either of the following can be used; an operator interface station that can display the PV time trend in chart form or the PLC's sampling trace function (available with the T-PDS programming software).

Note that the following PID tuning methods give only a general guideline for selecting PID parameters. They are merely a starting point for a careful step by step approach to parameter optimization.

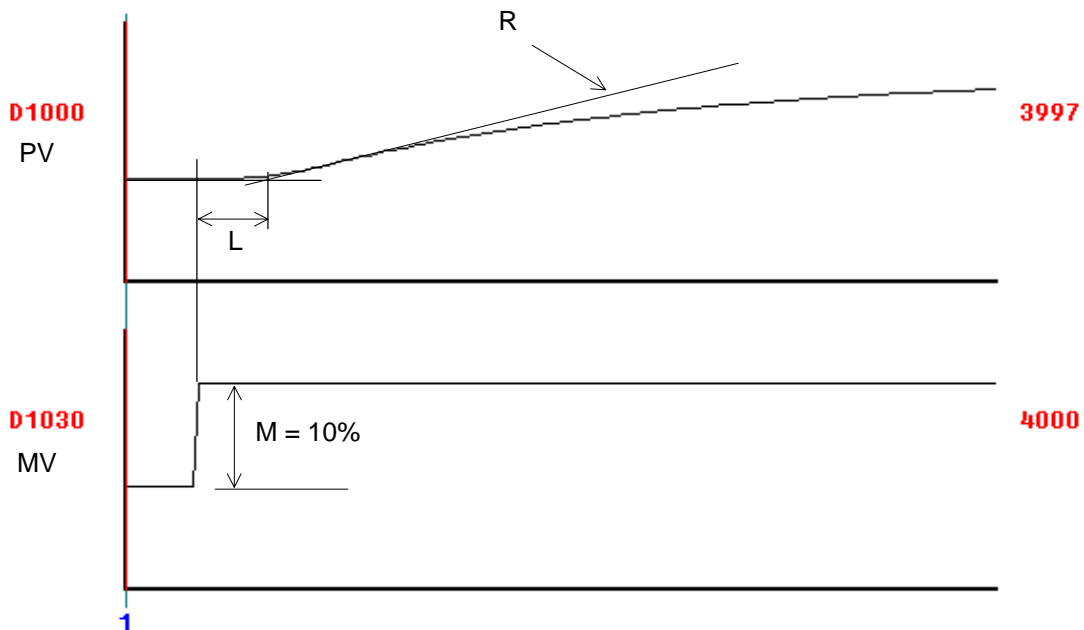
IMPORTANT During PID tuning it is important that strict attention to personal safety is observed.

5. Tuning Technique

5.1 Transient Response Method

This method can be used to obtain the initial PID parameters (K_P , T_I , and T_D) by introducing a step change in MV and watching the response of PV in manual mode.

1. Create the PID control program in the PLC. The PV and the MV data must be correctly converted from the analog input/output data range. Refer to section 4.
2. Connect the process control equipment to the PLC.
3. Place the PLC in the RUN Mode. The PID3 instruction must be set for manual mode.
4. While monitoring the PV and the MV, adjust the MV manually with the goal of stable control at some nominal setpoint.
5. Change the MV in a step function. The change value (percentage) should still keep the process in a safe operating range (10 % change is used in the following example).
6. Chart the PV and the MV. Measure the time lag L (min.) and the maximum rate of change R (%/min.) of the PV as follows.



In this example;
MV change $M = 10\%$
 $L = 15\text{ s} = 0.25\text{ min.}$
 $R = 9\text{ \%/min.}$

7. From the measured L and R, initial PID parameters can be determined as follows:
(based on Ziegler-Nichols method)

$$\begin{aligned}K_P &= 1.2 \times M / (RL) \\ &= 1.2 \times 10 / (9 \times 0.25) \\ &= 5.3\end{aligned}$$

$$\begin{aligned}T_I &= 2 \times L \\ &= 2 \times 0.25 \\ &= 0.5 \text{ min.}\end{aligned}$$

$$\begin{aligned}T_D &= 0.5 \times L \\ &= 0.5 \times 0.25 \\ &= 0.125 \text{ min.}\end{aligned}$$

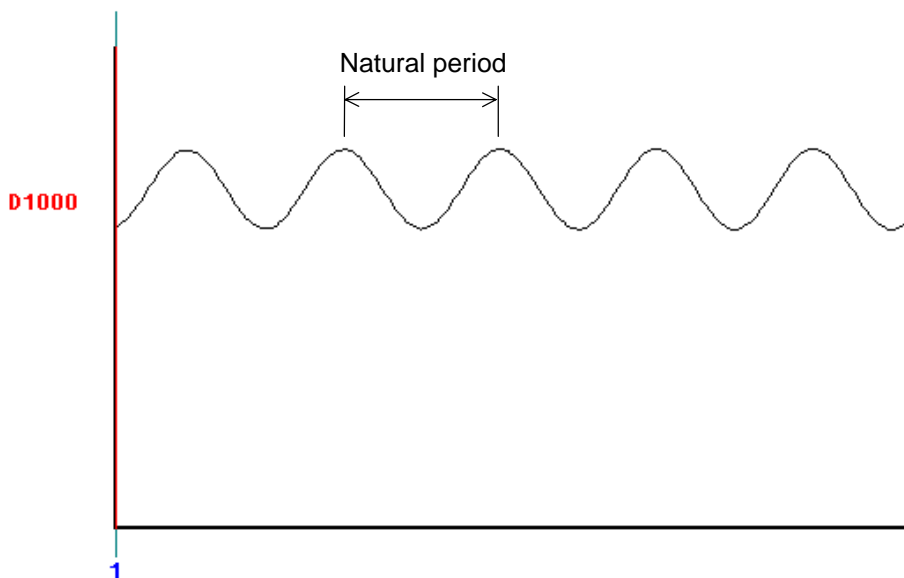
8. Set the parameters calculated above in specified registers of the PID3 instruction.
9. Place the PID3 instruction in the auto mode. If the process behavior is acceptable, the PID tuning is complete. Repeat the adjustments until the ideal process behavior is observed. When making adjustments, place the PID3 instruction in manual mode, enter the adjustments, and then place the PID3 in auto mode again.

5. Tuning Technique

5.2 Critical Gain Method

This is another method to obtain the initial PID parameters (K_P , T_I , and T_D) by knowing the natural period of the process.

1. Create the PID control program in the PLC. The PV and the MV data must be correctly converted from the analog input/output data range. Refer to section 4..
2. Connect the process control equipment to the PLC.
3. Place the PLC in the RUN Mode. The PID3 instruction must be in manual mode.
4. While monitoring the PV and the MV, adjust the MV manually with the goal of stable control at some nominal setpoint.
5. Set the initial PID parameters as follows.
 $K_P = 1$
 $T_I = 0$
 $T_D = 0$
6. Place the PID3 instruction in auto mode.
7. Increase the K_P gradually until the PV oscillates above and below the SV in an even manner. Record the time of one oscillation cycle. This is the natural period P_u of the process. Record the K_P used to achieve this oscillation. It is the critical gain K_{cu} . Then return PID3 operation to the manual mode.



In this example, the natural period $P_u = 50 \text{ s} = 0.83 \text{ min}$.
The critical gain $K_{cu} = 8.5$

5. Tuning Technique

8. From the measured P_u and K_{cu} , initial PID parameters can be determined as follows: (based on Ziegler-Nichols method)

$$\begin{aligned}K_P &= 0.6 \times K_{cu} \\ &= 0.6 \times 8.5 \\ &= 5.1\end{aligned}$$

$$\begin{aligned}T_I &= 0.5 \times P_u \\ &= 0.5 \times 0.83 \\ &= 0.415 \text{ min.}\end{aligned}$$

$$\begin{aligned}T_D &= 0.125 \times P_u \\ &= 0.125 \times 0.83 \\ &= 0.104 \text{ min.}\end{aligned}$$

9. Set the parameters calculated above in the PID program.
10. Place the PID3 instruction in the auto mode. If the process behavior is acceptable, the PID tuning is complete. Repeat the adjustments until ideal process behavior is observed. When making adjustments, place the PID3 instruction in the manual mode, enter the adjustments, and then place the PID3 in auto mode again.

Additional References on PID Control

Toshiba has gone to great lengths to implement a PID function block (PID3) in the Toshiba T-Series Programmable Controllers that is efficient, flexible and easy to use. However, PID Control and PID Loop Tuning can be very complex subjects. If more detail on these subjects is desired, the following references are available

Balchen, Jens G. and Kenneth I. Mumme. *Process Control, Structures and Applications*. New York: Van Nostrand Reinhold Company, 1988.

Anderson, Norman A. *Instrumentation for Process Measurement and Control*. 3rd ed. Rednor, PA: Chilton Company, 1980.

Intech December 1994, *Controller Tuning and Control Loop Performance* by David W. St. Clair of Straight-Line Control Company at 302-731-4699.

Corripio, Armando B. *Tuning of Industrial Control Systems*. Instrumentation Society of America, 1990.

Shinskey, F.G. *Process Control Systems*. 3rd ed. New York, NY. McGraw-Hill Book Company, 1988.

TOSHIBA

TOSHIBA INTERNATIONAL (EUROPE) LTD.

1 Roundwood Avenue
Stockley Park, Uxbridge
Middlesex, ENGLAND UB11 1AR
Tel: 0181-756-6000 Fax: 0181-848-4969

TOSHIBA INTERNATIONAL CORPORATION

Industrial Division
13131 West Little York Road
Houston, TX. 77041, U.S.A.
Tel: 713-466-0277 Fax: 713-466-8773

TOSHIBA INTERNATIONAL CORPORATION PTY. LTD.

Industrial Division
2 Morton Street, Parramatta
N.S.W. 2150, AUSTRALIA
Tel: 02-9768-6600 Fax: 02-9890-7542

TOSHIBA CORPORATION

Industrial Equipment Department
1-1, Shibaura 1-chome, Minato-ku
Tokyo 105-8001, JAPAN
Tel: 03-3457-4900 Fax: 03-5444-9268