SIMATIC

S7-300/400 Tips

Group	Topic
1	**Simple PID Controllers for the S7-300/400**

Overview

This programming example shows a method for programming a Proportional Integral Derivative (PID) controller on a S7 PLC. The example is already a fully functioning program, needing only for the user to tie the actual inputs and outputs to appropriate variables to be a working controller. This program is suitable for simple PID applications.

For complex PID applications, Siemens offers the SIMATIC S7 Standard Control software package, which offers numerous features that this applications tip lacks. These features include alarming, scaling, deadband control, feed-forward control, range limiting, ramp/soak steps, and an integrated scheduler. The Standard Control package includes a Windows-based configuration tool that greatly simplifies configuring and tuning a PID loop.

To prepare a user to make these programming changes, the text will explain the basics of the PID controller implemented in the sample code. Below is a brief outline for the rest of this document:

1. **What does the example program do?**
2. **Where do you use a PID controller?**
3. **Auto Mode vs. Manual Mode**
4. **What does a PID controller do, and how?**
5. **What are the Sample, Gain, Rate, and Reset?**
6. **How is the Error figured?**
7. **How is the Proportional term figured?**
8. **How is the Integral term figured?**
9. **How is the Derivative term figured?**
10. **What if the final Output is too high?**
11. **What should the user add to make the program work for his system?**
12. **Adjusting the Reset, Rate, Gain, Sample time and Mode during run-time**

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PID Explored

What does the example program do?

This programming example is a skeleton program for a true PID controller and, as such, requires that the user make a few additions (i.e. read/write input/output variables) before it is fully functional. Before discussing these, however, let's get a better feel for what a PID program actually does through a brief example.

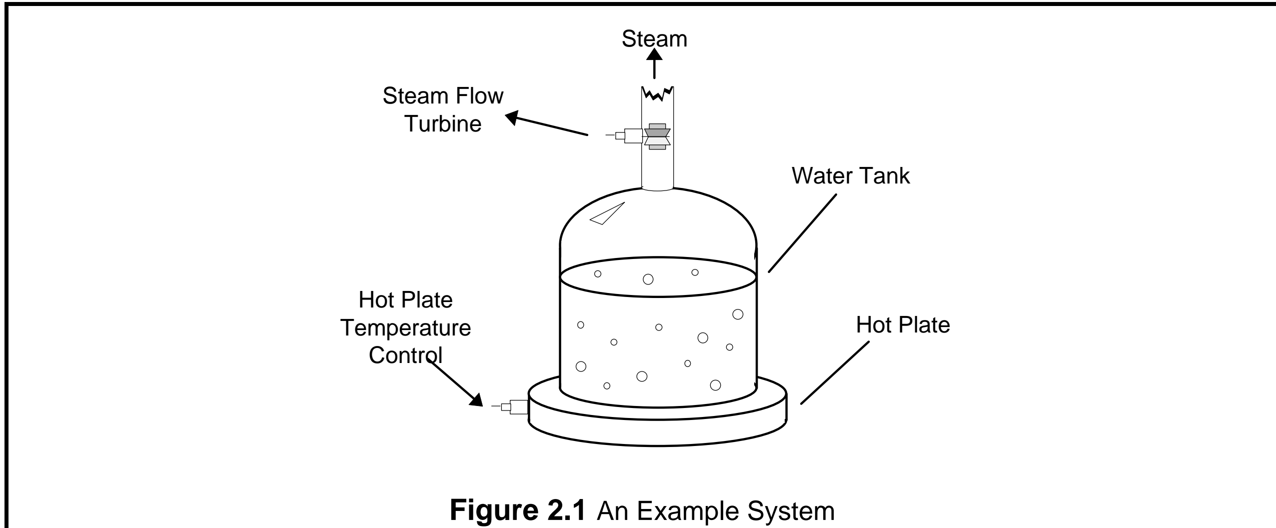

Figure 2.1 An Example System

When do you use a PID controller?

Figure 2.1 shows a picture of an example system to which a user might connect a PID controller. The figure shows a water tank sitting atop a hot plate, with a temperature control device for the hot plate and a small, monitored turbine for measuring the rate of the steam flow. This is a system that will work with a PID controller because of the relationship between the two variables: You can directly control the steam flow rate by adjusting the temperature of the hot plate. Figure 2.2 shows how both variables relate to the PID controller.

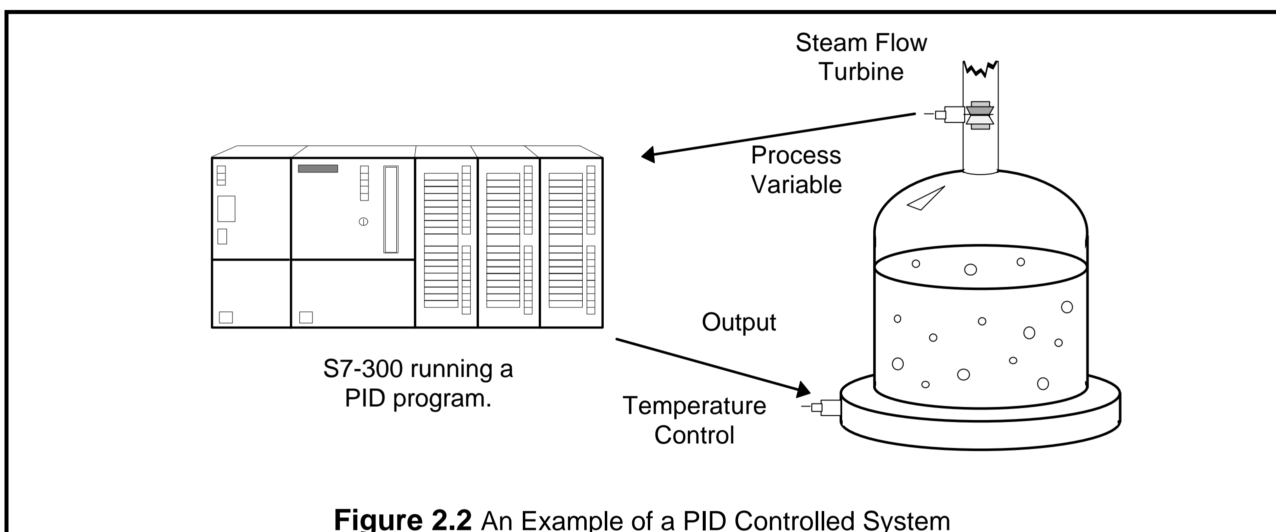

Figure 2.2 An Example of a PID Controlled System

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The variable which represents the state of the system being controlled is called the 'Process Variable.' In our example above, you can see that the rate at which the steam spins the turbine is a good indicator of the event that we are trying to control: the speed at which the water is being boiled off. The output is the variable which, being altered by the controller, can affect the process variable by different degrees based on its intensity -- By turning the hot plate up, the water boils more quickly, more steam is produced, and the turbine's speed increases.

Therefore, when a variable that accurately reflects the state of the process and an adjustable control which proportionally affects the process variable, then it is possible to use a PID controller. Common systems using PID controllers are air conditioning systems, solution mixing, heaters, etc.

Auto Mode vs. Manual Mode

There are two settings available on our PID controller. Putting a controller in *Manual* mode causes the PID loop do nothing, so that the user can directly control the output. The second, *Auto*, is the mode in which the PID loop is actually controlling the system. For the rest of this text, it will be assumed that the controller is in *Auto* mode.

What does the PID controller do, and how does it do it?

Quite simply, a PID controller adjusts the value of its output to try and balance the value of the process variable to a given 'setpoint.' To calculate the output value for a given instance, the controller finds the value of three different terms (using its user defined **Sample** time, **Gain**, **Rate**, and **Reset** values along with the calculated **Error** value): a Proportional term, an Integral term, and a Derivative term.

$$\mathbf{Output} = \mathbf{M_P} + \mathbf{M_I} + \mathbf{M_D}$$

Formula 2.1

What are the Sample, Gain, Rate, and Reset, and where do they come from?

The *sample rate* is the cycle time (in milliseconds) at which the PID loop recalculates the output. The *gain* controls the sensitivity of the output calculation by affecting the influence of all the terms. The *reset* is a time given in milliseconds which is used to increase or decrease the influence of the Integral term in the equation. Finally, the *rate* value is used to control the influence of the Derivative term in the equation. Each of these values needs to be preset by the user before the PID controller starts.

If the user does not want integral action (no I in the PID calculation), then a value of infinity or a value of 0 should be specified for the integral time. If the user does not want derivative action (no D in the PID calculation), then a value of 0 should be specified for the derivative time. If the user does not want proportional action (no P in the PID), then a value of 0 should be specified for the gain (gain is normally a multiplier in the integral and derivative coefficient calculation, but is removed from the coefficient calculation, if gain = 0, to allow I, ID, or D loop control).

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How is the Error figured?
Error is figured as the difference between the normalized values of the setpoint and the process variable. The controller calculates this value in three steps. The first two steps are to change both the setpoint and the process variable into values that are based on a 0 to 1 (normalized) scale. This is done using the formulae:

$$\mathbf{SP} = \mathbf{raw_SP} \;/\; \boldsymbol{max_val}$$
$$\mathbf{PV} = \mathbf{raw_PV} \;/\; \boldsymbol{max_val}$$
Formulae 2.2 & 2.3

In the above formulae, the **raw_SP** and **raw_PV** values are the actual values that come into the controller, and the ***max_val*** term is the maximum value that either can take on. For example, if the values of **raw_SP** and **raw_PV** were being read in as values from 0 to 27,648, then the ***max_val*** term would have the value 27,648.

After these two values have been calculated, the error term is figured as follows:

$$\mathbf{Error} = \mathbf{SP} - \mathbf{PV}$$
Formula 2.4

How is the Proportional term calculated?
The proportional term, M_P, is calculated using the following equation:

$$M_P = \boldsymbol{Gain} * \boldsymbol{Error}$$
Formula 2.2

Going back to our earlier example with the water tank, the proportional term says that as the speed of the turbine increases further above the setpoint, the heat is decreased proportionally to bring the speed down. As the turbine slows below the setpoint, the heat is increased to proportionally to bring the speed up.

How is the Integral Term calculated?
The integral term, M_I, is calculated using the following equation:

$$M_I = \mathbf{Bias} + (C_I * \boldsymbol{Error})$$
Formula 2.3

In this equation, two new terms are introduced. The first, C_I, is the coefficient of the Integral term, and is calculated from the **Reset**:

$$C_I = \mathbf{Gain} * (\mathbf{Sample} \;/\; \mathbf{Reset})$$
Formula 2.4

Both the **Sample** and **Reset** terms were introduced earlier, but in this equation their uses become apparent. The larger the **Reset** value is, the less impact the integral term will have on the output, while larger **Sample** times give it a bigger influence (**Sample** time also affects the Derivative term, which will be explained later).

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The **Bias** term in Formula 2.3 represents (technically speaking) the area under the curve of a graph plotting the Error vs. time.

Abstractly, however, the **Bias** value (ideally) grows to an output level that keeps the system stable, letting the Proportional and Derivative terms handle any small fluctuations. In relation to our water tank example from earlier, this means that eventually the **Bias** portion of M_I would be the only significant contribution to the final output value, and the M_P and M_D terms would only be active (non-zero) when a fluctuation occurred.
At a time **n** the equations for M_I and the **Bias** term are:

$$M_{I,n} = Bias_{n-1} + (C_I * Error)$$
$$Bias_n = M_{I,n}$$

Formula 2.5

How is the Derivative term calculated?
The derivative formula for a given time **n** is calculated with the following equation:

$$M_D = C_D * (PV_{n-1} - PV_n)$$

Formula 2.6

This formula only introduces 1 new term, C_D, which is calculated using Formula 2.7.

$$C_D = Gain * (Rate / Sample)$$

Formula 2.7

The **Sample** term (which is also used in figuring C_I) is the sample time from earlier. In the Derivative term, the **Sample** time is indirectly proportional to the derivative component, while the **Rate** is directly proportional.

What if the final output value is too high?
During many processes (such as the water tank example earlier), the Process variable doesn't respond immediately to a change in the value of the output -- if the water in the tank were ice cold, then even an output of 100% is not going to cause an instantaneous increase in steam flow. Likewise, setting the output to 0% when the water is boiling doesn't provide an immediate reduction in steam production.

Because of this 'system inertia,' the output value for a give time could take on a value greater than 100% or less than 0%. In response to this, the PID program implements Output Clamping. If the output is greater than 100%, then it is clamped to 100%. If the output falls lower than 0%, then it is held to 0%.

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The only problem left to solve lies with the **Bias** portion of the Integral term. When the output for a system remains at 100% for a long period of time (such as when heating up cold water in our tank from earlier), the integral sum (which the **Bias** term represents) can grow to extremely large values. This means that when the variable starts responding, the **Bias** term will be keeping the calculated output well over 100% until it can be wound down. This generally results in the output swinging wildly from one limit to the other, but can be avoided using Bias Clamping.

There are a few different types of Bias Clamping, but the only pertinent one here is the one used in the program. There are two different conditions which cause Bias clamping to occur and two formulae as well:

$$\textbf{If Output} > 1$$
$$\textbf{Bias} = 1 - (M_P + M_D)$$

Formula 2.8

$$\textbf{If Output} < 0$$
$$\textbf{Bias} = -(M_P + M_D)$$

Formula 2.9

As the formulae show, when the **Output** grows to be greater than 1, the value of the **Bias** is adjusted so that the sum of M_P, M_D, and the **Bias** will be 1. Likewise, when the **Output** slips below 0, the value of the **Bias** is adjusted so that the above sum will be 0. The adjusted **Bias** value is then clamped such that its maximum value is 1 and its minimum value is 0.

What should be added to make the program work for the system?

1. Read in the Process Variable
2. Write the Output
3. Set the Setpoint
4. Adjust the scale for the Input and Setpoint
5. Adjust the scale for the Output
6. Adjust the **Reset**, **Rate**, **Gain**, and **Sample** time values.

Read in the Process Variable

The Process variable (the variable which accurately reflects the state of the system to be controlled) should be passed to the PV parameter of the function block.

Write the Output

The OUT parameter of the PID loop should be set to the analog output being controlled in the PID function block call.

Set the Setpoint

The user’s code must pass the Setpoint value to the PID function block via the SP parameter.

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Adjust the scale for the Process Variable and Setpoint
In networks 6 through 11 of the PID function block, the program converts the (raw) PV value into a normalized (0-1) value based on a scale of 0 to 27,648. If the value that the user is reading in is on a different scale, the user has to change the 27,648s in these networks to the new value. For example, if the scale were 0 to 100, you would change the 27,648s to 100s.

Another approach would be to change the scale of the PV and SP to the 0 to 27,648 scale before passing them to the PID function block. This could be done with code in the calling block, or by a scaling function block.

Adjust the scale for the Output
In the last network in the program, the Output value is changed from a normalized value (0-1) into a scaled number (0-27,648). As in the above section, to change the scale of the output, simply change the 27,648 into the new maximum value (or rescale the output after the function block returns).

Adjust the ***Reset****,* ***Rate****,* ***Gain****, and* ***Sample*** *time values*
The final thing that the user's code needs to implement is the setting of the **Reset**, **Rate**, **Gain**, and **Sample** time values. If the PID loop's instance DB is configured as retentive, this need only be done once, by hand, after the instance DB is created in the PLC. If the PID loop's instance DB is not retentive, the loop tuning parameters must be set after each PLC restart. This could be done in OB100 (Complete Restart OB). For a PID loop instance data block *n*, the values should be placed as follows:

Reset	⇒ DB*n*.DBD18 (real), time in milliseconds
Rate	⇒ DB*n*.DBD14 (real), time in milliseconds
Gain	⇒ DB*n*.DBD10 (real), unitless factor
Sample	⇒ DB*n*.DBD22 (real), time in milliseconds

The sample time should be set to the same period at which the PID loop function block called.

Adjusting the Reset, Rate, Gain, and Sample time, and Mode during run-time
Changes in the **Reset**, **Rate**, **Gain**, and **Sample** time values take effect the next time the PID loop function block is called.

The PID loop mode is controlled via the mode_req function block parameter. When mode_req is FALSE (0), the loop will transition to or remain in Manual mode when the function block is next called. When mode_req is TRUE (1), the loop will transition to or remain in Auto module when the function block is next called.

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PID Example Program

This is not part of the PID program per se, but shows how the PID function block is called.

Symbol Table

The symbol table attaches functional names to PLC memory addresses. The functional names will be used in the example program.

	Symbol	Address	Data Type	Comment
1	basicPID	FB 101	FB 101	
2	loop_mode	M 101.0	BOOL	
3	pidDB	DB 101	DB 101	
4	raw_OUTPUT	MW 2	INT	
5	raw_PV	PIW 256	INT	
6	raw_SP	MW 0	INT	
7	loop_scheduler	T 0	TIMER	
8	loop_time	M 6.1	BOOL	
9	mode_req	I 4.2	BOOL	
10	loop_OUT	PQW 256	INT	
11				

OB 100

OB 100 is executed once when the PLC program starts after being in program mode, or turned off. If the PID instance data block is not retentive, OB100 is an appropriate place to load the data block with gain, rate, reset, and sample time values.

OB100 : Complete Restart OB

Network 1 : On restart, initialize PID loop

Set PID loop tuning parameters to initial values.
A good, safe starting point for gain is 1.0

Network 2 : Rate tends to make fast loops unstable, so it is often set to 0

Network 3 : Set reset time constant to 5000 milliseconds, or 5 second.

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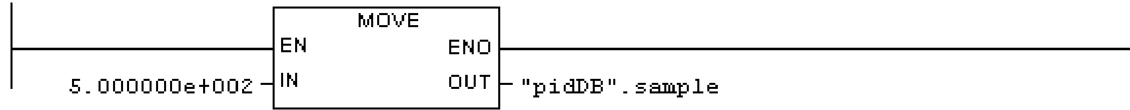
Network 4 : Loop sample time = 500 milliseconds, or 1/2 second.

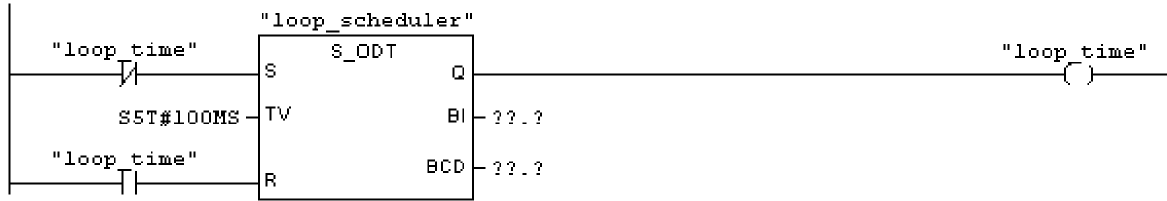


OB 1

OB 1 is the main "scanned" portion of the PLC program. It is executed as often as possible while the PLC is in Run mode. The example program periodically calls the PID function block from OB 1.

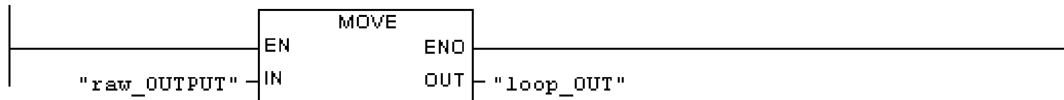
OB1 : Example program showing PID loop operation.

Network 1 : PID loop scheduling timer.



Network 2 : Periodically call PID function block

Network 3 : Copy output to Analog Output point



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FB 101

FB 101 is the PID calculation function block.

Address	Decl.	Symbol	Data Type	Initial Value	Comment
0.0	in	mode_req	BOOL	FALSE	requested mode, false=manual, true=auto
2.0	in	PV	INT	0	process variable in 0..27648 range
4.0	out	mode	BOOL	FALSE	current mode, false=manual, true=auto
6.0	in_out	SP	INT	0	setpoint in 0..27648 range
8.0	in_out	OUT	INT	0	output in 0..27648 range
10.0	stat	gain	REAL	1.000000e+000	proportional gain factor
14.0	stat	rate	REAL	0.000000e+000	derivative time, in msec
18.0	stat	reset	REAL	1.000000e+004	integration time, in msec
22.0	stat	sample	REAL	1.000000e+002	sample time, in msec
26.0	stat	PVscl	REAL	5.000000e-001	PV, scaled to 0..1
30.0	stat	SPscl	REAL	5.000000e-001	SP, scaled to 0..1
34.0	stat	OUTscl	REAL	5.000000e-001	OUT, scaled to 0..1
38.0	stat	error	REAL	0.000000e+000	error term
42.0	stat	bias	REAL	0.000000e+000	integration accumulator
46.0	stat	PVold	REAL	5.000000e-001	last sample's PV term
50.0	stat	I_Coeff	REAL	0.000000e+000	precalculated integration coefficient
54.0	stat	D_Coeff	REAL	0.000000e+000	precalculated derivative coefficient
58.0	stat	curMode	BOOL	FALSE	current mode, false=manual, true=auto
58.1	stat	firstCycle	BOOL	FALSE	first calc after mode change
0.0	temp	Mp	REAL		proportial term of PID
4.0	temp	Mi	REAL		integration term of PID
8.0	temp	Md	REAL		derivative term of PID
12.0	temp	Ma	REAL		P and D contribution to output

FB101 : Basic PID, without alarms, options, etc.

```
This function block performs a simple, position algorithm PID calculation.  The
block should be called with a separate instance data block for each PID loop.
For each PID loop, the block should be called regularly at the interval
specified in the #sample parameter.

The engineer is responsible for setting appropriate values in the #gain, #rate,
#reset, and #sample fields in the instance data block.  The other fields in the
be changed by the programmer: these fields are used by the loop for internal
calculations.

While in Manual mode, the loop does not perform the PID calculation.  The user
may write values to the OUT parameter to manually control the output while in
Manual mode. While in Auto mode, the loop does the PID calculation and writes to
the output.  On a Manual -> Auto transition, the loop does a "Bumpless Transfer"
The loop sets the setpoint (SP parameter) to the current PV, and sets the
loop's integration term (#bias) to the current output (OUT parameter).  This
has the effect of keeping the calculated loop output at the same value as the
last Manual mode loop output.   After putting a loop in Auto mode, you should
change the SP (setpoint) to the required value, as the "Bumpless Transfer" will
have changed it to equal the PV.
```


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```
Network 1 : precalculate PID coefficients

      L     0.000000e+000
      T     #I_Coeff                    //default to no I term
      L     #reset                      //if reset = 0, then
      ==R                               // no integration done
      JC    noi
      L     #sample                     //if reset <> 0 then
      TAK                               //I_Coeff := sample/reset
      /R
      T     #I_Coeff
noi:  L     #rate                       //D_Coeff := rate/sample
      L     #sample
      /R
      T     #D_Coeff

Network 2 : multiply I, D coefficients by gain, if gain used

      L     0.000000e+000               //if (gain <> 0.0)
      L     #gain
      ==R
      JC    mdch
      L     #I_Coeff                    // then I_Coeff := I_Coeff * gain
      *R
      T     #I_Coeff
      L     #D_Coeff                    // then D_Coeff := D_Coeff * gain
      L     #gain
      *R
      T     #D_Coeff

Network 3 : Auto -> Manual transition

mdch: AN    #mode_req                   //Manual requested
      A     #curMode                    //..and currently Auto
      JCN   ckma                        //if not Auto->Manual, check Manual->Auto
      R     #firstCycle                 //set flags for Manual mode
      R     #curMode
      R     #mode
      BEC                               //and done with PID calculation, so exit

Network 4 : Manual->Auto Transition

ckma: A     #mode_req                   //Auto requested
      AN    #curMode                    //..currenly in Manual
      JCN   ckmn                        //if no mode change, then next rung
      L     #OUT                        //Bumpless transfer:
      ITD                               //  bias = output, in 0..1 range
      DTR
      L     2.764800e+004
      /R
      T     #bias                       //  output -> bias
      L     #PV                         //  PV -> setpoint
      T     #SP
      S     #firstCycle                 //set flags for Auto
      S     #curMode
      S     #mode

Network 5 : If manual mode, then done

ckmn: AN    #curMode
      BEC
```


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```
Network 6 : scale PV: if > 100% then clamp at 100%

      L     #PV                         //if PV <= 27648
      L     27648
      >I
      JCN   pltl                        //then next rung
      L     1.000000e+000               //else set scaled
      T     #PVscl                      //  PV to 100%
      JU    psdn

Network 7 : if PV < 0%, then clamp to 0%

pltl: L     #PV                         //if PV > 0
      L     0
      <=I
      JCN   pgt0                        //then next rung
      L     0.000000e+000               //else set scaled
      T     #PVscl                      //   PV to 0%
      JU    psdn

Network 8 : 0 < PV <= 100%, so PVscl = PV/27648

pgt0: L     #PV                         //PV known to be positive, so sign ok
      DTR                               //convert PV to real
      L     2.764800e+004
      /R                                //convert to 0..1 scale
      T     #PVscl

Network 9 : Scale setpoint: if SP > 100%, clamp to 100%

psdn: L     #SP                         //if SP < 100%
      L     27648
      <I
      JC    sltl                        //then next rung
      L     1.000000e+000               //else set scaled SP
      T     #SPscl                      //  to 100%
      JU    ssdn

Network 10 : if SP < 0%, clamp to 0%

sltl: L     #SP                         //if sp >= 0%
      L     0
      >=I
      JC    sgt0                        //then next rung
      L     0.000000e+000               //else set scaled SP
      T     #SPscl                      //  to 0%
      JU    ssdn

Network 11 : 0% < SP < 100%, so SPscl = SP / 27648

sgt0: L     #SP                         //SP known to be positive, so sign ok
      DTR                               //convert SP to real
      L     2.764800e+004
      /R                                //convert to 0..1 scale
      T     #SPscl

Network 12 : calculate error

ssdn: L     #SPscl                      //error = SP - PV
      L     #PVscl
      -R
      T     #error
```


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Network 13 : Calculate PID terms

```
      L     #gain                        //error still in AC2
      *R
      T     #Mp                          //Mp = gain * error
      L     #error
      L     #I_Coeff
      *R
      L     #bias
      +R
      T     #Mi                          //Mi = bias + (I_Coeff * error)
      L     0.000000e+000
      T     #Md                          //Md defaults to 0
```

Network 14 : If derivative used then calculate Md

Md is only used if the rate > 0 ms, and we have a "last sample's PV" to calculate the change from.

```
      L     #D_Coeff                     //if rate = 0
      L     0.000000e+000
      <>R
      AN    #firstCycle                  //or first cycle in Auto
      JCN   noMd                         //then next rung
      L     #PVold
      L     #PVscl
      -R
      L     #D_Coeff
      *R
      T     #Md                          //else Md = D_Coeff * (PVold - PV)
noMd: NOP   0
```

Network 15 : Calculate provisional output (before bias clamping)

```
      L     #PVscl                       //store current PV for next Md calc
      T     #PVold
      L     #Mp
      L     #Md
      +R
      T     #Ma                          //Ma = Mp + Md
      L     #Mi
      +R
      T     #OUTscl                      //provisional output = Ma + Mi
```

Network 16 : Bias Clamping: if Output > 100%, clamp and backcalculate bias

```
      L     #OUTscl
      L     1.000000e+000
      <=R
      JC    bc0                          //if output <= 1 then next rung
      T     #OUTscl                      //else clamp output to 100%
      L     #Ma                          //and back-calcuate Mi so that
      -R                                 // Ma + Mi = 100%
      T     #Mi
      JU    bias
bc0:  NOP   0
```


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```
Network 17 : Bias Clamping: if Output < 0%, clamp and backcalculate bias

      L     #OUTscl
      L     0.000000e+000
      >=R
      JC    bias                        //if output >= 0 then next rung
      T     #OUTscl                     //else clamp output to 0%
      L     #Ma                         //and back-calculate Mi so that
      NEGR                              // Ma + Mi = 0%
      T     #Mi

Network 18 : Clamp bias to 0..1 range

bias: L     #I_Coeff                    //if bias not used, then skip
      L     0.000000e+000
      ==R
      JC    dout
      L     #Mi                         //if Mi > 1.0
      L     1.000000e+000
      <=R
      JC    blt1
      T     #Mi                         // Mi := 1.0
blt1: L     #Mi                         //if Mi < 0.0
      L     0.000000e+000
      >=R
      JC    bgt0
      T     #Mi                         // Mi := 0.0
bgt0: L     #Mi
      T     #bias                       //bias = clamped Mi

Network 19 : Reset first cycle flag and unscale output

dout: SET                               //reset first cycle flag
      R     #firstCycle
      L     #OUTscl                     //convert output to 0..27648
      L     2.764800e+004
      *R
      TRUNC                             //and convert to integer
      T     #OUT
```

General Notes

The SIMATIC S7-300/400 Application Tips are provided to give users of the S7-300/400 some indication as to how, from the view of programming technique, certain tasks can be solved with this controller. These instructions do not purport to cover all details or variations in equipment, nor do they provide for every possible contingency. Use of the S7-300/400 Application Tips is free.

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