Improving PID Recovery from Limit Conditions

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Abstract: This paper addresses the performance of the PID under startup or during normal operation when the PID output becomes limited. Common techniques that have been utilized to reduce the time required to get to setpoint during process startup are reviewed. The response of the PID to conditions that limit PID operation during normal operating conditions is discussed for different implementation approaches. In particular under limiting conditions, anti-reset windup is automatically activated when a positive feedback network is used to create the reset contribution. For such implementations, the recovery from a process saturation condition may be improved by modifying the PID operation. An application example is used to show the impact of this modification on response speed and overshoot.

Keywords: Process Saturation, Control Limits, PID, Control, Implementation, Positive Feedback, Compressor

1. INTRODUCTION

The PID remains the dominant technique used in the process industry for the implementation of feedback control. Within the process industry two basic forms of the PID have been adopted by the major control system suppliers: standard and series. In addition, the option is often provided for proportional action and derivative action based on the process controlled variable (PV) used in feedback or on the error between the PV and the control setpoint (SP). Many studies have been done on the PID operation where there are no limits on control adjustment of the manipulated process input. However, limits are quite common during process start-up conditions and normal process operation and a requirement exists for the PID to recover quickly from a limit condition. The performance of the PID under limit conditions is important to plant operation. The response that is observed is directly associated with the PID implementation.

During plant start-up conditions, it is often desirable to smoothly raise process temperatures, pressures, and flows to normal operating conditions in minimum time without process overshoot. Often during start-up, these adjustments must be made by the plant operator because of the limited range of process measurement. However, when process measurements are within their designed operating range, it is possible to use the PID to establish normal plant operating conditions.

At some point in plant operation, it is fairly common for one or more conditions to limit plant throughput. The advantage of the positive feedback network is well known as an implementation technique that may be used to best address these conditions that limit plant operation. The structure of the PID that has been standardized by the Fieldbus Foundation and as defined in IEC61804 is designed to enable implementations based on the use of a positive feedback network. However, the control performance that may be achieved in recovery from a long term limit condition (i.e. a process saturation condition) may not meet the plant processing requirement. Common techniques such as the use of pre-load in the positive feedback network determine the point at which the PID takes action during recovery from process saturation and provides varying degrees of improvement for variations in plant operation. To allow best performance under varying operating conditions, the PID may be modified to provide better recovery from process saturation. This modification allows the PID to take action at the time needed to avoid overshoot. The rate at which the control parameter approaches setpoint on recovery from a saturation condition determines when and by how much the PID begins to take control action.

The paper details the basis for the PID modification needed to improve recovery from process saturation and shows the implementation of this feature in an industrial control system. It also shows the response of the modified PID for compressor surge control.

2. PID Implementation

Most modern distributed control systems (DCS) are designed to support the distribution of control to fieldbus as specified in the Fieldbus Foundation specification. In a fieldbus environment, measurement, control, and calculations are represented as function blocks. Some major control systems have adopted these function blocks for use within the control system. The block definitions specify the parameters of the block, but do not define the block algorithm. However, in the case of the PID, the control implementation is most commonly structured based on the series or standard form of the PID algorithm. The Laplace transform for each form of the PID is shown below (Fig. 1).

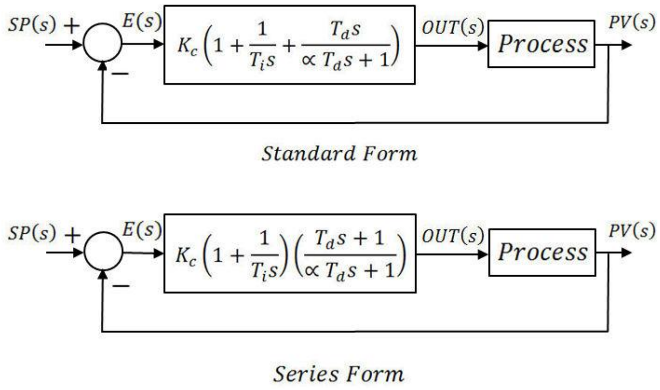

Fig. 1. Common Forms of the PID in the Process Industry

Where

K_c = Controller Gain

T_i = Reset (seconds per repeat)

T_d = Rate

$\propto$ = Rate limiting factor, e.g. 0.125

$OUT(s)$ = PID output (%)

$SP(s)$ = Setpoint

$PV(s)$ = Control Parameter

When the PID's rate term is set to zero, the series and standard form of the PID are identical in structure (Fig. 2).

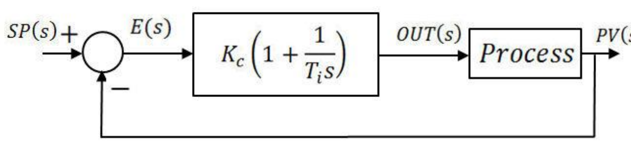

Fig. 2. PI Control

Control system manufacturers have addressed the PID implementation in a variety of ways. The PID design must provide a way to avoid reset winding up when the PID output reaches an upper or lower limit. Logic can be added to the reset calculation to stop integration of error that would drive the control output further into the limit. However, when the process is characterized by a noisy measurement or frequent disturbances such an approach may prove to be ineffective. Thus, in many commercial products the reset component is realized using a positive feedback network as detailed by Åström and Hägglund(2006), Blevins and Nixon (2010), and Rhinehart et al.(2006). An implementation of PI control utilizing a positive feedback network for the reset component is shown below (Fig. 3):

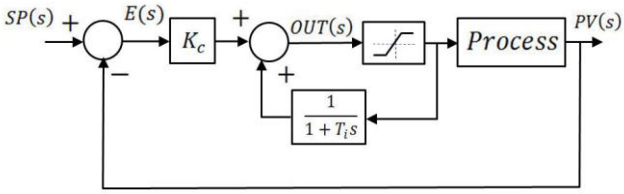

Fig. 3. PI Implementation using Positive Feedback Network

The advantages of this approach are well known in the industry. For unconstrained operation, the positive feedback network is mathematically equivalent to an integrator. However, the benefit of this approach is that the reset contribution is automatically prevented from winding up when the PID output is limited (i.e. operating at its upper or lower limit). When the process is saturated due to equipment limitations or abnormal operating condition, the control may operate at a limit condition for an extended period of time. Under this condition, the filter in the positive feedback network settles at the limit value. When operating conditions that enable operation away from a limit condition change, PID control begins to take action only when the error signal changes sign (i.e. the control parameter must transition through the setpoint before any control action is taken). As a result, when the process is recovering from a saturated process condition, the control parameter can overshoot the setpoint.

To allow control action to be taken before the control parameter transitions through setpoint, it is necessary to add rate action. However, if the control measurement is noisy it may not be possible to use rate action. Thus, as described by Shinskey (2006) some manufacturers allow a user specified "Preload value" that is automatically substituted for the positive feedback term in the PID calculation when the output becomes limited as shown below (Fig. 4).

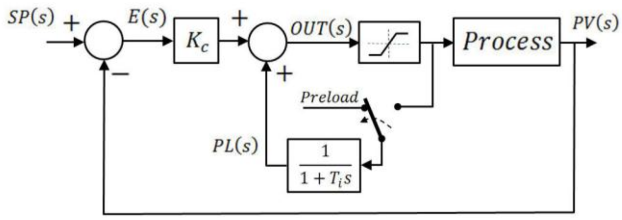

Fig. 4. Addition of Preload when PID Output is Limited

Where

$Preload$ = Constant value

$PL(s)$ = positive feedback network contribution when the PID output is limited.

For such an implementation, the point at which the controller output begins to take action when recovering from process saturation is determined by the control error as well as the pre-load value. When the control output begins to move away from the limit, the controller output is automatically used in the positive feedback network to allow normal reset action to resume. This approach may be used to avoid overshooting setpoint when recovering from a process saturation condition. However, for slow rate of change in a process disturbance that caused the limit condition, the preload value may be too large and can cause premature control action. Thus, it is not always possible to choose a pre-load value that satisfies the different conditions that may exist in an operating plant.

Ideally, the magnitude and rate of change in the control error should determine when control action is taken for recovery from process saturation. The point at which control action is taken should be automatically determined in a manner that results in the control parameter coming to setpoint without overshoot. As addressed in this paper, the PID can be modified to provide such behaviour. The point at which control action is taken as the PV approaches setpoint depends on the PV rate of change and the magnitude of the error. A better response to major upsets can be achieved when this calculated value is used in place of a user specified preload value for process saturation condition.

3. Technical Basis for Modifications

For unconstrained operation the P, D, and I components work in a coordinated fashion to provide a positional PID algorithm. If we consider the case where a positive feedback network is used to achieve the reset component, rate gain is zero and proportional action is taken on error $E(s)$, the PID transfer function is:

$$OUT(s) = E(s)K_c\left(1+\frac{1}{T_i s}\right)$$

$$\frac{OUT(s)}{E(s)} = K_c\left(1+\frac{1}{T_i s}\right) \tag{1}$$

Thus, for unconstrained conditions the standard PID operation is achieved. However, when the PID is at its output limit for an extended period of time, the proportional contribution added to the limit value determines when the output moves away from the limit. For this limited condition, the output and error are dynamically related in the following manner:

$$OUT(s) = E(s) * K_c \tag{2}$$

Thus, for the case where control is constrained the controller output will not move from its limit until the error changes sign (i.e. the process measurement goes past setpoint). However, to avoid overshooting the setpoint when recovering from process saturation it is often necessary to take control action before the measurement reaches setpoint.

When the PID output is not limited, the control measurement and controller output are related in the following manner for a first order process:

$$PV(s) = \frac{K_p OUT(s)}{1+T_p s} \tag{3}$$

Where

K_p = Process gain

T_p = Process time constant

When the PID output is limited, the output that would have been calculated if the limit were not imposed may be calculated based on the control measurement.

$$OUT(s) = PV(s)\left(\frac{1+T_p s}{K_p}\right) \tag{4}$$

If we assume that the controller gain is set for a Lambda factor of 1 and a pure lag process i.e. $K_c = \frac{1}{K_p}$ and $T_i = T_p$ then the controller output for unconstrained operation is:

$$OUT(s) = \quad E(s) * K_c * (1+T_i s) \tag{5}$$

However, when the PID output is limited the proportional contribution and the Preload value determine the PID calculated output.

$$OUT(s) = \quad E(s) * K_c + PL(s) \tag{6}$$

By comparing equation 5 and 6, it is seen that a variable term $E(s) * K_c * T_i s$ plus the limit value should be utilized rather than a fixed preload value to provide the same control response as provided when the output is not limited. This variable term may be substituted for the constant Preload value shown (Fig. 4) if the filter in the positive feedback network is not applied when the PID output has remained at its limit for an extended period of time.

From a practical standpoint, the filtering provided in the reset feedback path may be automatically reduced by a user specified factor F when the PID output reaches its output limits for an extended period of time (Fig. 5).

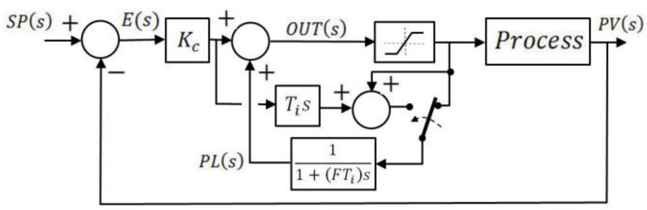

Fig. 5. PI with Variable Pre-load Capability

The PID output will begin to move from its limit at the point where the proportional contribution $E(s)*K_c$ is exactly cancelled by the added term $E(s)*K_c*T_i s$. Ideally, the filtering in the positive feedback network should be set to zero for under limit condition and to 1 for unconstrained operation. However, if the control measurement contains a significant level of noise, some filtering of the variable term $E(s)*K_c*T_i s$ may be required to avoid chatter at the limit (i.e. set to a value greater than 0 when the PID output is limited for an extended period of time).

When this variable preload value is used and the PID output has been at a limit for an extended period of time, a rapid change in the control parameter may cause the PID output to start to move from the limit even though the control parameter has not reached setpoint. For a slow change in the control measurement, little if any control action will be taken before the control parameter reaches setpoint.

4. Extension to Include Rate

When a process is characterized as having two distinct dynamics (i.e. a second order process), then the use of Rate in the PID may improve performance if the process measurement is relatively free of noise. For the case where Rate is applied with Proportional and Reset action, the PID output is:

$$OUT(s) = E(s)K_c\left(1 + \frac{1}{T_i s} + \frac{T_d s}{(\alpha T_d s + 1)}\right) \qquad (7)$$

However, when the PID output is limited then, assuming α is small, the dynamic relationship of the PID output and control error may be approximated as follows when a variable Preload value is used in the positive feedback network:

$$OUT(s) = E(s)K_c(1 + T_d s) + PL(s) \qquad (8)$$

When the PID output is not limited, the control parameter, $PV(s)$, and the PID output are related in the following manner assuming a second order process:

$$PV(s) = \frac{K_p OUT(s)}{(1+T_{p1})(1+T_{p2})} \qquad (9)$$

Where

K_p = Process gain

T_{p1} = Dominant process time constant

T_{p2} = Secondary (faster) process time constant

Thus, when the PID output is limited, the output that would have been calculated if the limit were not imposed may be calculated based on the control measurement.

$$OUT(s) = PV(s)\frac{(1+T_{p1})(1+T_{p2})}{K_p} \qquad (10)$$

If we assume that the controller gain is set for a Lambda factor of 1 (i.e. $K_c = \frac{1}{K_p}$) and the controller has been tuned to set the reset equal to the dominant time constant (i.e. $T_i = T_{p1}$) and rate has been set equal to the secondary time constant (i.e. $T_d = T_{p2}$) as suggested by Corripio and Smith (1970) the controller output and the control measurement are related in the following manner:

$$\begin{aligned} OUT(s) &= E(s)*K_c*(1+T_i s)(1+T_d s) \\ &= E(s)*K_c*\left(1+(T_i+T_d)s+T_iT_d s^2\right) \\ &= E(s)*K_c*(1+T_d s)+E(s)K*\left(T_i s+T_iT_d s^2\right) \end{aligned} \qquad (11)$$

By comparing (8) and (11), it is seen that a variable term $E(s)K_c*\left(T_i s+T_iT_d s^2\right)$ plus the constant limit value should be utilized rather than a fixed preload value. This approach should provide the same control response as that provided when the output is not limited. The control output will begin to move from its limit at the point where the proportional and rate terms are exactly cancelled by the variable preload plus the limit value. Ideally, the filtering in the positive feedback network should be removed when preload action is taken. However, if the control measurement contains a significant level of noise, some filtering of the variable term may F be required to avoid chatter at the limit (i.e. set to a value greater than 0 when the PID output is limited for an extended period of time). This option can be especially useful for PID control if the measurement contains a significant level of noise.

5. Example – Compressor Surge Control

The effectiveness of providing a variable preload to determine when control action is taken under saturated conditions has been tested and demonstrated in a surge control application. Such a capability is a standard feature of the DeltaV control system used in these tests. This capability was tested using a simulation of a “typical” compressor utilized in many plants in the chemical and refining industries.

To test the PID modifications to improve recovery from a limit condition, a dynamic high fidelity simulation was developed for a compressor and associated downstream header. A series of tests were then conducted to evaluate the effectiveness of this new capabilty in preventing violation of surge limits for a 60% drop in process demand.

5.1 Compressor Simulation

A dynamic simulation of the "typical" compressor and downstream header was implemented in one module within the control system. The process and control addressed in these test are shown below.

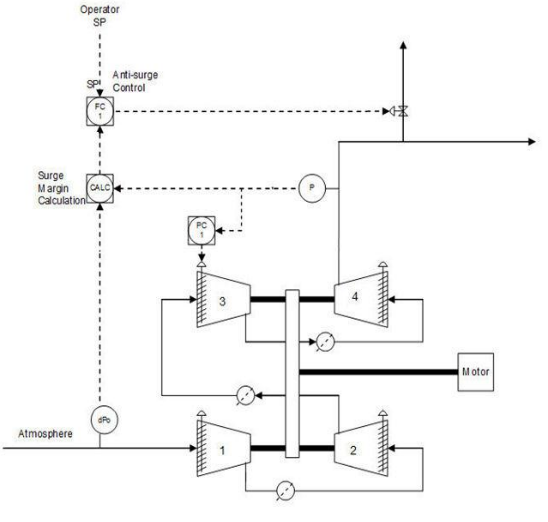

Fig. 6. Compressor Anti-surge Control

A process simulation module was created to allow the header demand to be adjusted and thus introduce a disturbance in the header. Also, parameters were provided in the simulation that may be used to adjust the header volume and vent valve characteristics. The turbine simulation is based on an extrapolation of the compressor performance curves for 20, 30, 40, 50, 60, 70, 80, and 90% Inlet Guide Vane (IGV) values as shown below (Fig. 7).

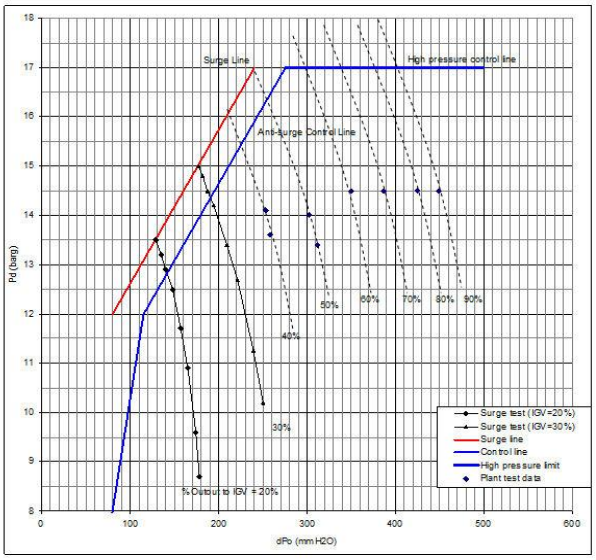

Fig. 7. Typical Compressor Performance Data

In the compressor simulation, IGV values that fall between these curves were determined by interpolation to provide values for all operating conditions.

Data on vent valve performance was used to determine the vent valve characteristics and CV. A best fit with the experimental data was achieved by quick opening valve characteristics. Since flow data was provided as measured dP(mm H2O) across the orifice (rather than actual flow value) the flow value used in the simulation is calculated in % of scale based on 100% flow at dP of 600 mm H2O.

Table 1 – Vent valve performance – load test data vs. flow calculated by process simulation

Compress Data for Constant IGV% and Vent Valve%					Calculated Vent Valve Flow (%)
IGV%	Vent %	Pd (barg)	Compressor Flow		
			dPmmH2O	Flow(%)	
20	20	12.5	148	49.66	46.67
20	30	10.9	165	52.44	53.38
30	20	14.2	194	56.86	49.75
30	30	12.7	221	60.69	57.6
30	40	11.3	239	63.11	62.76

A copy of the compressor simulation module used in these tests is shown below (Fig. 8).

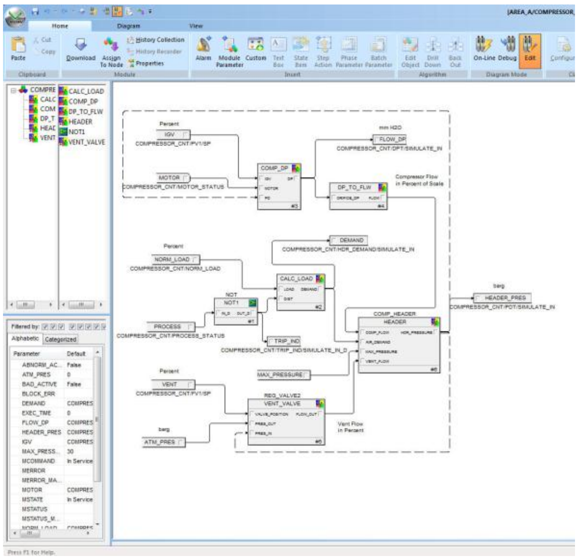

Fig. 8. Compressor Simulation Module Used in Test

The compressor control used with the simulation is "typical" of that is used for compressor anti-surge control. The compressor controls were implemented in one control module that executed at a rate of 100msec. The control outputs are accessed in the compressor simulation modules using external references. Also, the process outputs calculated in the simulation modules are written to the SIMULATE_IN parameters of the associated AI and DI blocks in the control module using external references.

Three parameters were added to the control module to support testing of the control using the process simulation:

- MOTOR_STATUS – On/Off status of the compressor motor (1 = On Condition, 0= Off)
- PROCESS_STATUS – Normal operation (1), Shutdown of downstream process (0).
- NORM_LOAD – the normal demand of the downstream process in % e.g. 80%

The Compressor control module is shown below:

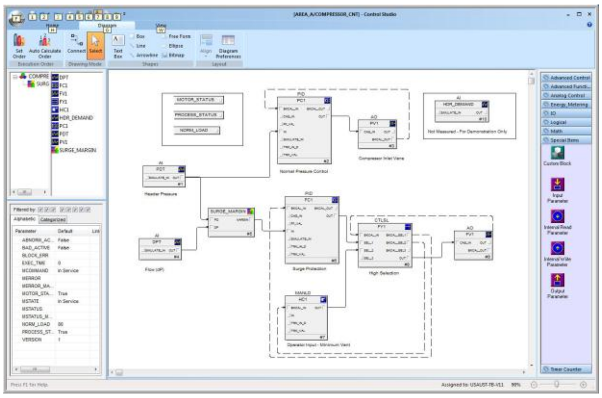

Fig. 9. Compressor Control Module Used in Test

5.2 Shutdown Response

The process simulation and control for a 60% reduction in demand on the header is shown in this section. The surge control response with no Preload added to the PID during process saturation (Fig. 10). As shown in this trend, the compressor goes below the surge line when preload is not utilized. Control action is only taken when the surge margin drops below the target value specified by the surge control setpoint.

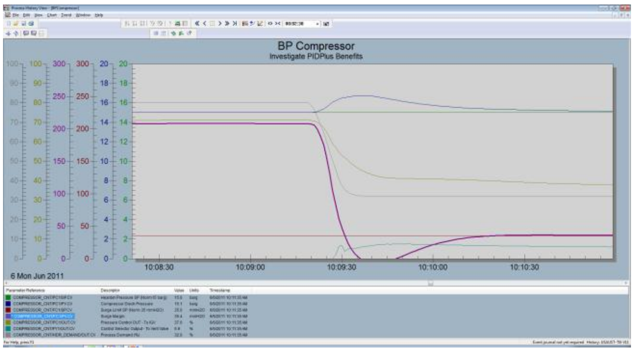

Fig. 10. Control Response for 60% reduction in Load with no Pre-load Applied in the PID

When the automatic addition of a variable pre-load under saturated conditions was enabled in the PID and the test repeated, an improved response was observed. As shown in the following trend (Fig. 11), the compressor surge margin setpoint of 35 mmH2O was not violated.

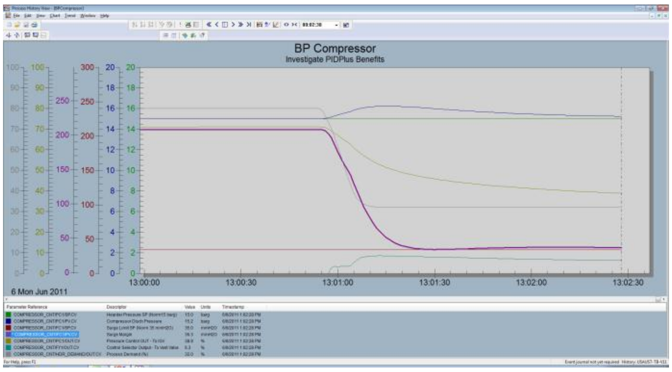

Fig. 11. Control response for 60% reduction in load with variable pre-load automatically applied in the PID

6. CONCLUSIONS

The recovery of the PID from process saturation is critical in many continuous and batch applications. By utilizing a variable preload when the PID output is limited for an extended period of time, it is possible to minimize setpoint overshoot on recovery from saturation. The benefit of this approach has been demonstrated in compressor surge control using a dynamic process simulation of a "typical"compressor used in industry. Such a capability has been incorporated as a standard feature in a commercial DCS.

Acknowledgments

Dr. Paul Oram, BP, provided input on the control requirements for a pressure blowdown application that helped spark further investigation and research into PID recovery from process saturation. The integration of this capability into the DeltaV PID is due largely to the efforts of Dr. Peter Wojsznis, Mike Ott, and Randy Balentine, Emerson. We appreciate the support that Emerson and BP provided in this research and development efforts to improve PID performance.

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