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Abstract: Major advances that improve control in the process industry have been made over the last ten years in the basic PID technology of modern distributed control systems. This paper addresses the impact that international standards have on control implementation and the tools utilized in industry for monitoring and commissioning PID control. Examples are used to illustrate how new technologies, such as model switching for process identification, have allowed manufacturers to introduce a new level of ease-of-use in tools developed for on-demand and adaptive tuning. This paper discusses PID modifications that improve the speed of recovery from process saturation conditions that are common in industrial applications. Also, details are provided on PID modifications that enable effective control with non-periodic measurement updates by wireless transmitters. Finally, prospective future directions for industrial PID controllers are sketched.

Keywords: Process Saturation, Wireless Transmitters, Control, PID, Monitoring, IEC61804, Fieldbus, Function Block

1. INTRODUCTION

Within the process industry the PID remains the dominant technique for feedback control. Thus, there is continued interest by the academic community and control system manufacturers in PID modifications that may improve control performance and in tools that make it easier to commission control and monitor its performance. Much of the basic PID research published in the literature focuses on control performance for unconstrained operation of linear and stationary processes. In contrast, work within the process control industry focuses on increasing utilization of single loop and multi-loop control based on PID taking into account process non-linearity and operating constraints.

The IEC61804 standard for function blocks in the process industry and the Fieldbus Foundation function block specification define the structure and parameters that are used in PID control. Adoption of these standards allows process control manufacturers to provide a consistent means of implementing process control in controllers and field devices. Having a consistent representation of the PID and consistency in block parameter names and structures makes it easier for manufacturers to provide tools for PID control. A new generation of performance monitoring tools allows a process or control engineer or an instrumentation technician to easily identify any issues in control loop performance.

Technology for on-demand loop tuning is available in most control systems. The challenge is to structure the user interface in a manner that allows a control loop to be tuned with little or no knowledge of process control. To minimize the user involvement with control, adaptive tuning based on model switching is available in commercial control systems.

Within the process industry, various techniques have traditionally been used to speed the response of the PID recovery from a process saturation condition. New work in this area demonstrates how the PID may be modified to speed recovery from process saturation. Such enhancements benefit process saturation applications such as compressor anti-surge control.

The recent introduction of wireless transmitters and wireless actuators in the process industry has sparked new interest in PID modifications that allow effective control using non-periodic information updates. The underlying assumption in process control has always been that control is executed on a periodic basis and that a new measurement value is available each execution. However, to minimize power consumption a wireless transmitter may transmit a new measurement infrequently and only if the measurement has changed a significant amount. Thus, to effectively utilize a wireless measurement such as that provided by WirelessHART transmitters, it is necessary to modify the PID to work with non-periodic measurement updates. Details on how the PID has been modified in a commercial control system are intended to demonstrate how non-periodic measurement updates can be used in control.

The paper is structured as follows – section 2 outlines the state of process automation, section 3 discusses performance monitoring tools, section 4 and 5 addresses on-demand and adaptive tuning, section 6 presents PID design for process saturation, section 7 demonstrates PID modifications for wireless control and finally section 8 provides conclusions and some thoughts on future PID direction.

2. STATE OF PROCESS AUTOMATION

The control systems installed in the process industry may involve the control of multiple unit operations with hundreds of measurements and control loops as illustrated (Fig. 1). Although these systems are designed to automatically archive operational data in a historian, it is very time consuming to manually examine this data to determine if there has been a change in control performance. There is neither time nor resources to manually examine the control performance to pro-actively address issues that impact operation efficiency or limit plant production.

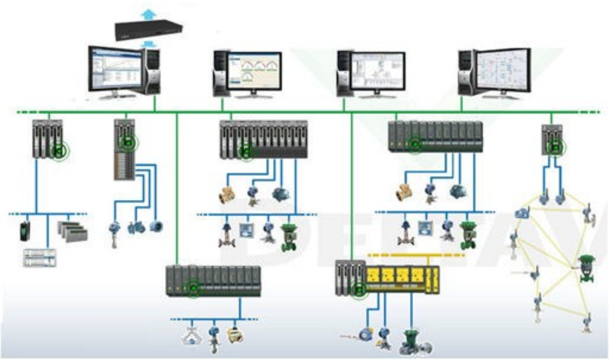


Fig. 1. Example Distributed Control Systems

It can be shocking to examine control utilization in a plant where performance tools have not been used. For example, in the mid-1980's a control survey was conducted at a major pulp and paper plant where the control system had recently been updated to the latest Distributed Control system. At that time performance tools were not available to automatically evaluate control system performance. However, it was possible to manually evaluate control utilization using a snapshot of the plant operation. The results of this survey are shown in Table 1.

Table 1 – Pulp and Paper Mill – Control Utilization

Process Area	Control Loops	Normal Mode	Utilization
Bleach Plant	78	60	76%
Power House	185	130	70%
Pulp Mill	174	116	66%
Paper Mill	236	134	56%

After seeing the results of this survey, an instrumentation team was formed to investigate loops that were not running in their normal design mode. This team was responsible for making sure measurement, control valve, and process problems were addressed in a timely fashion. The reduction in variability led to significant improvements in plant throughput and product quality. Two years later the plant set a new production record.

Recently a survey of seven areas in a petrochemical plant was conducted using performance monitoring tools to collect a snapshot of the control utilization, as shown in Table 2.

Table 2 – Petrochemical Complex – Control Utilization

System	Loops	Utilization
PX	471	67.3%
APS&VPS, CLE, Sulphur Recv	469	59.7%
Refinery	478	60.9%
IGCC/Auxiliary Boiler	946	52.7%
Ethylene	1355	77.5%
FCCU	475	48%
C4	164	68.9%

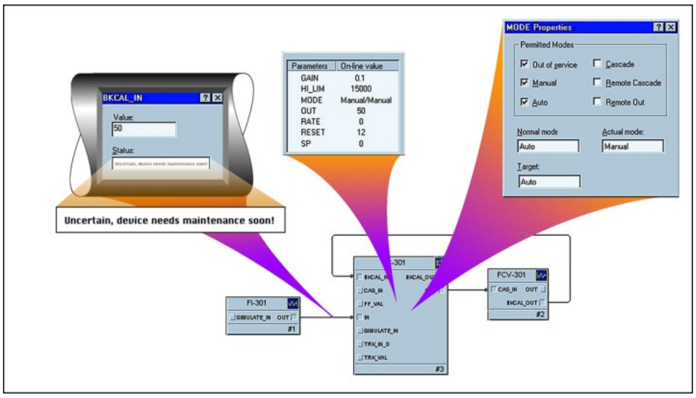
Once the plant management became aware of the low control utilization, manpower and funding were provided to investigate and correct the measurement and control issues that were preventing the operator from using the control. This led to significant operational improvements.

The path for improving control performance thus should start with an assessment of control utilization. The automatic collection of control-utilization statistics is a major benefit in identifying problems in measurement, control or process design.

3. PERFORMANCE MONITORING TOOLS

Most performance monitoring tools provide an instantaneous and historic view that summarizes control loop utilization by process area. If the utilization is lower than normal the user may select a detail view of the process area that shows the utilization for each control loop.

One of the most obvious reasons for poor control utilization is a broken or unreliable transmitter. If the control system is designed to be consistent with the international function block standard, IEC61804, then status associated with the measurement provides a direct indication of the measurement condition. The percent time the measurement had a status of Bad, Uncertain or Limited may be used to determine measurement health. The Target and Actual attributes of the Mode parameter defined by the standard may be used to determine if a PID is running in its designed mode of operation. Thus, the parameter attributes (Fig. 2) are the basis for evaluating measurement health and control utilization as detailed by Blevins et al. (1996).



BKCAL_IN

Value: 50

Status: Uncertain, device needs maintenance soon!

Uncertain, device needs maintenance soon!

Parameters	On-line value
GAIN	0.1
HI_LIM	15000
MODE	Manual/Manual
OUT	50
RATE	0
RESET	12
SP	0

MODE Properties

Permitted Modes

☑ Out of service ☐ Cascade
☑ Manual ☐ Remote Cascade
☑ Auto ☐ Remote Out

Normal mode: Auto

Actual mode: Manual

Target: Auto

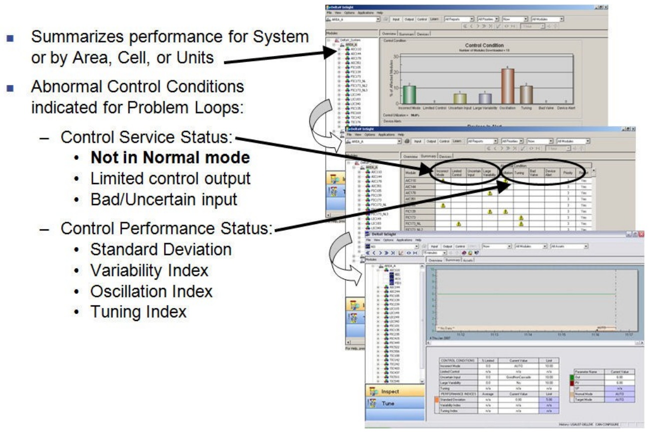
Fig. 2. Standard PID Parameters

When the control measurement health is Good further investigation is needed to determine the cause of poor control utilization. Some of the most common problems that impact control loop operation are:

- Incorrect Tuning
- Valve/Actuator malfunction
- Changing Process Gain
- Split Range Setup
- Process Dynamics
- Loop Interaction.

The control performance monitoring tool may provide information that helps the user to resolve these issues as addressed by. Wojsznis et al. (1995).

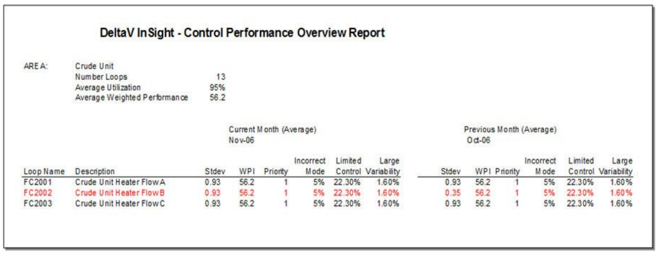
An example of a control performance monitoring tool's functionality is illustrated below (Fig. 3) and also shows some of the information that is automatically collected about the control system performance.



- Summarizes performance for System or by Area, Cell, or Units
- Abnormal Control Conditions indicated for Problem Loops:
  - Control Service Status:
    - **Not in Normal mode**
    - Limited control output
    - Bad/Uncertain input
  - Control Performance Status:
    - Standard Deviation
    - Variability Index
    - Oscillation Index
    - Tuning Index

Fig. 3. Tools to Examine Control Utilization

An important part of any performance monitoring tool is its report generation capability. Such reports may be used to gain management support required to address low control utilization or to determine the source of excessive process variation that impacts production or product quality. An example of a performance monitoring report is shown below (Fig. 4).



DeltaV InSight - Control Performance Overview Report

AREA:	Crude Unit	
	Number Loops	13
	Average Utilization	95%
	Average Weighted Performance	56.2

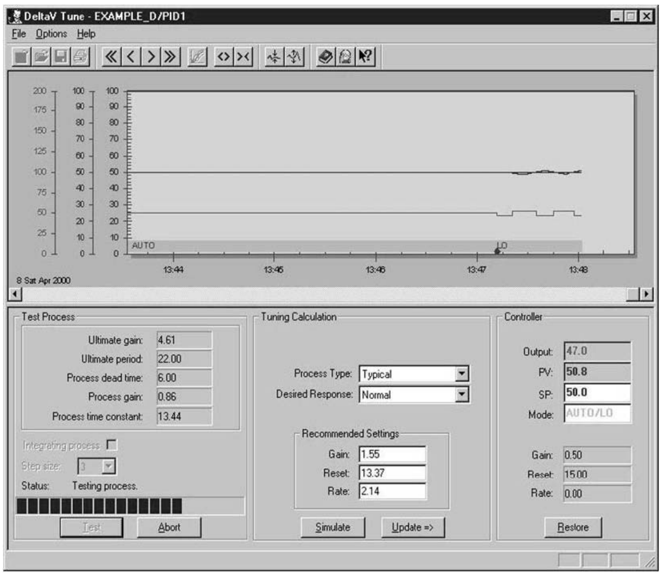
		Current Month (Average) Nov-06						Previous Month (Average) Oct-06					
Loop Name	Description	Stdev	WPI	Priority	Incorrect Mode	Limited Control	Large Variability	Stdev	WPI	Priority	Incorrect Mode	Limited Control	Large Variability
FC2001	Crude Unit Heater Flow A	0.93	56.2	1	5%	22.30%	1.60%	0.93	56.2	1	5%	22.30%	1.60%
FC2002	Crude Unit Heater Flow B	0.93	56.2	1	5%	22.30%	1.60%	0.35	56.2	1	5%	22.30%	1.60%
FC2003	Crude Unit Heater Flow C	0.93	56.2	1	5%	22.30%	1.60%	0.93	56.2	1	5%	22.30%	1.60%

Fig. 4. Example Performance Report

Through the use of performance monitoring tools, it is possible to effectively analyze and diagnose control performance with minimum manpower. Utilizing such tools can have a significant impact on plant throughput and product quality.

4. ON_DEMAND TUNING

Most control systems include on-demand auto-tuning to establish PID block tuning. Control system manufacturers have adopted different technologies to implement auto-tuning. One of the most effective on-demand tuning technologies is relay oscillation as originally developed by Åström and Hägglund as shown by Wojsznis et al. (1999). Using this method the ultimate gain and period of the loop may be established by conducting one simple test. Analysis of the initial portion of the process response in the test provides the process deadtime. Based on the ultimate gain, ultimate period and process dead time, the process time constant and gain may be calculated. Thus, tuning rules based on ultimate gain and period, such as modified Ziegler Nichols tuning or model based rules such as Lambda tuning and Internal Model Control may be used to determine the PID tuning. One implementation based on this method is shown below (Fig. 5).



Test Process:
Ultimate gain: 4.61
Ultimate period: 22.00
Process dead time: 6.00
Process gain: 0.86
Process time constant: 13.44
Integrating process ☐
Step size: 3
Status: Testing process.

Tuning Calculation:
Process Type: Typical
Desired Response: Normal
Recommended Settings: Gain: 1.55 Reset: 13.37 Rate: 2.14

Controller:
Output: 47.0
PV: 50.8
SP: 50.0
Mode: AUTO/LO
Gain: 0.50
Reset: 15.00
Rate: 0.00

Fig. 5. On-demand Tuning Interface

Selecting the Test button to initiate a test and after testing is complete selecting the update button transfers tuning to the PID.

5. ADAPTIVE TUNING

Adaptive tuning of a PID allows the process model to be automatically established based on the normal setpoint changes made by the operator when the PID is in an automatic mode of operation or on PID output changes when the PID is in a manual mode. Various techniques have been used in industry to provide adaptive tuning. In the late 1990's research was published on controller switching as a means of establishing a controller that gives best performance. This work sparked an investigation and development of model switching with re-centering and interpolation as a technique for process model identification.

For a self-regulating process (Gain, Lag, Dead Time) every parameter has 3x3x3 model variations for model switching adaptation as illustrated below (Fig. 6).

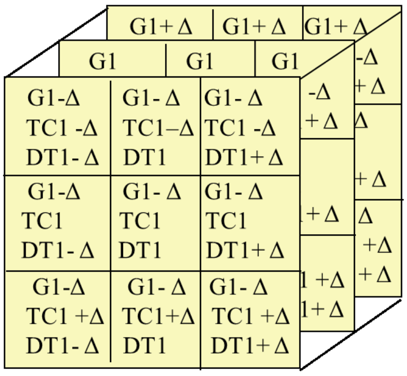


Fig. 6. Model Switching Adaptation

Every parameter value of the model is evaluated independently. The weight assigned to the parameter value is the inverse of the squared error. The adapted parameter value is the weighted average of all evaluated values. To allow the data used in adaptive control to be collected without communication skew or jitter, adaptive control is implemented directly in the PID (Fig. 7).

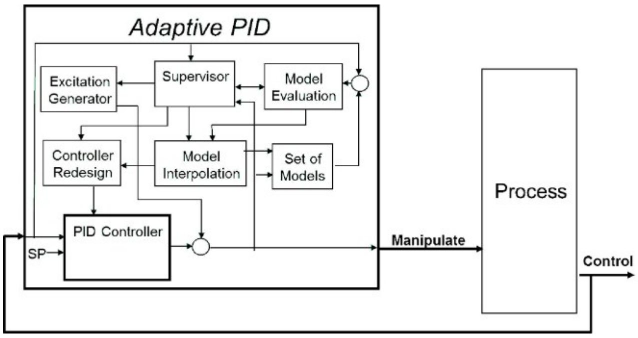
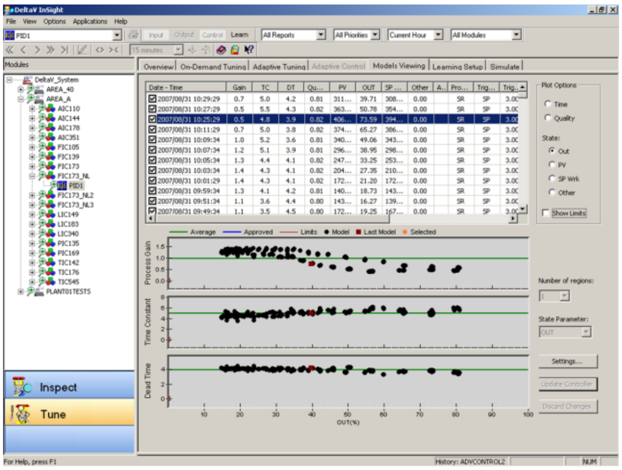


Fig. 7. Adaptive Control Implementation

As a new model is identified it is automatically reported to a workstation where for each PID up to 200 models are collected. By plotting these model parameters it is possible to identify process non-linearity (Fig. 8).



Date - Time	Gain	TC	DT	Qu...	PV	OUT	SP ...	Other	A...	Pro...	Trig...	Trig...
☑ 2007/08/31 10:29:29	0.7	5.0	4.2	0.81	311...	39.71	308...	0.00		SR	SP	3.0
☑ 2007/08/31 10:27:29	0.5	5.5	4.3	0.82	363...	50.78	354...	0.00		SR	SP	3.0
☑ 2007/08/31 10:25:29	0.5	4.8	3.9	0.82	406...	73.59	394...	0.00		SR	SP	3.0
☑ 2007/08/31 10:11:29	0.7	5.0	3.8	0.82	374...	65.27	386...	0.00		SR	SP	3.0
☑ 2007/08/31 10:09:34	1.0	5.2	3.6	0.81	340...	49.06	343...	0.00		SR	SP	3.0
☑ 2007/08/31 10:07:34	1.2	5.1	3.9	0.81	296...	38.95	298...	0.00		SR	SP	3.0
☑ 2007/08/31 10:05:34	1.3	4.4	4.1	0.82	247...	33.25	253...	0.00		SR	SP	3.0
☑ 2007/08/31 10:03:34	1.4	4.3	4.1	0.82	204...	27.35	210...	0.00		SR	SP	3.0
☑ 2007/08/31 10:01:29	1.4	4.3	4.1	0.82	172...	21.20	172...	0.00		SR	SP	3.0
☑ 2007/08/31 09:59:34	1.3	4.1	4.2	0.81	140...	18.73	143...	0.00		SR	SP	3.0
☑ 2007/08/31 09:51:34	1.1	3.6	4.4	0.80	143...	16.27	139...	0.00		SR	SP	3.0
☑ 2007/08/31 09:49:34	1.1	3.5	4.5	0.80	172...	19.25	167...	0.00		SR	SP	3.0

Fig. 8. Viewing Identified Process Models

If the process is found to be non-linear, an option is provided that allows models that have been identified at various points over the plant operating range to be automatically used to set the PID tuning. Such capability may be used to provide best control for all regions of operation.

6. RECOVERY FROM PROCESS SATURATION

At some point in plant operation, it is fairly common for one or more conditions to limit plant throughput. In many industrial controllers PID reset windup is prevented by calculating the integral contribution using a positive feedback network as addressed by Shinskey (2006), Rhinehart et al. (2006), Blevins and Nixon (2010) and Åström and Hägglund (2006). The PID structure standardized by the Fieldbus Foundation and IEC61804 enables implementations that calculate the reset contribution in this manner. However, with this design recovery from a long term limit condition (i.e. a process saturation condition) may not meet the plant processing requirement.

Techniques such as the use of a pre-load provide some improvement for variations in plant operation. However, to achieve best performance under varying operating conditions, the PID may be modified to provide better recovery from process saturation as shown in Figure 9.

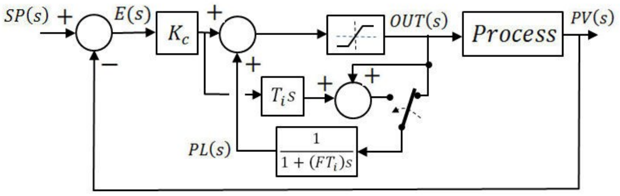


Fig. 9. PI with Variable Pre-load Capability

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.

One process application that demonstrates the benefit of variable pre-load is boiler outlet steam temperature control (Fig. 10).

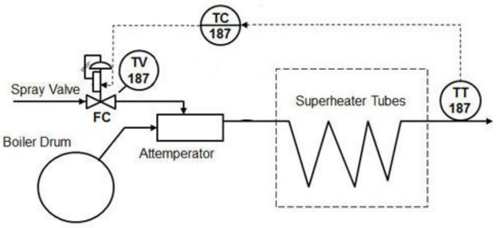


Fig. 10. Boiler Outlet Steam Temperature Control

If steam generation exceeds the attemperator capacity the boiler outlet steam temperature will exceed the outlet setpoint with the spray valve fully open. When boiler firing rate is reduced, the spray value should be cut back as the outlet temperature drops. The improved response for a 50% drop in steam generation is illustrated below (Fig. 11).

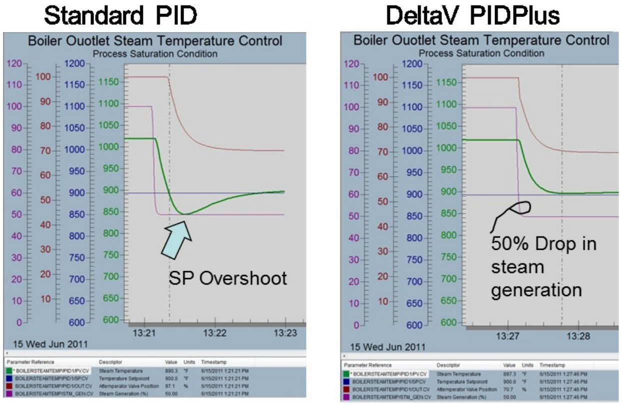


Fig. 11. Response For 50% Drop in Steam Generation

7. PID Modifications for Wireless Control

Utilizing wireless communication to provide a measurement used in closed loop control presents many technical challenges as detailed in Han et al. (2010). To reduce transmitter power consumption, it is desirable to minimize how often a measurement value is communicated. However, multi-loop controllers are commonly designed to over-sample the measurement by a factor of 2-10X. Also, to minimize control variation, the typical rule of thumb is that feedback control should be executed 4X to 10X times faster than the process response time i.e. process time constant plus process delay as illustrated (Fig. 12).

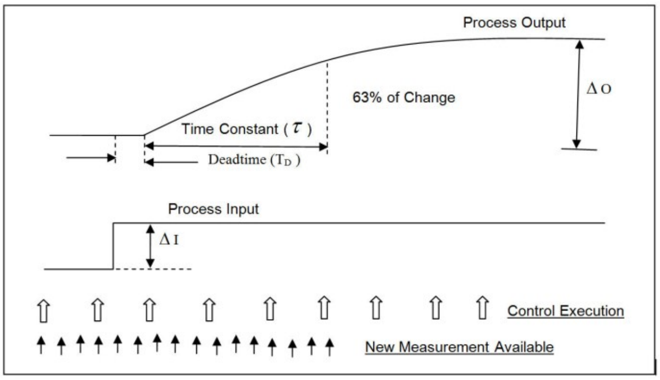


Fig. 12. Control Data Sampling rate

If the traditional approach is taken in scheduling control 4-10X faster than the process response, the power consumption associated with wireless transmission of the measurement value for each control execution would be excessive for all but the slowest types of processes. Slowing down the control execution to reduce the power consumption associated with communication may increase control variability when the process is characterized by frequent unmeasured disturbances. Ideally the power consumption could be minimized by transmitting the measurement value only as often as required to allow control action to correct for unmeasured disturbances or changes in operation point.

One approach to minimize the power consumed in communicating new measurement values is to design the transmitter and wireless communication according to the following rules:

Rules for Transmitting a New Measurement Value

1. The transmitter will periodically sample the measurement 4-10x faster than the process response time.
2. If the magnitude of the difference between the new measurement value and the last communicated measurement value is greater that a specified resolution or if the time since the last communication exceeds a refresh time the new value will be communicated.

However, the underlying assumption in the control design (using z transform, difference equations) and digital implementation of the PID is that the algorithm is executed on a periodic basis. When the measurement is not updated, the calculated reset action may not be appropriate. To provide best control when a measurement is not updated on a periodic basis, the PID may be restructured to reflect the reset contribution for the expected process response since the last measurement update. One means of doing this is illustrated (Fig. 13).

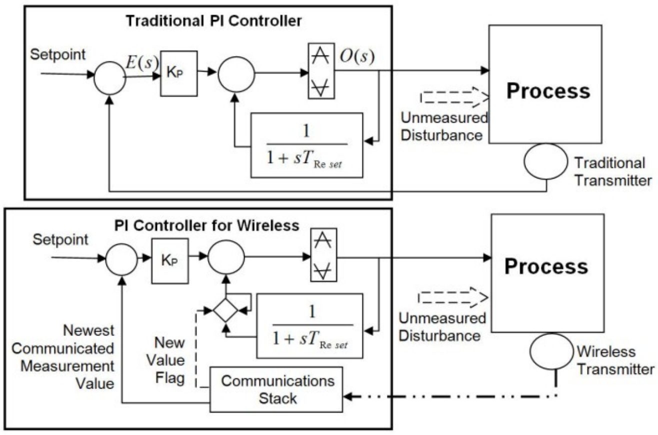


Fig. 13. PID Restructured for Wireless Measurement

The positive feedback network used to create the reset contribution is modified to have the following behavior.

1. Maintain the last calculated filter output until a new measurement is communicated.
2. When a new measurement is received, use the new filter output as the positive feedback contribution.

For those processes that require PID control, the rate contribution to the PID output should be recomputed and updated only when a new measurement is received as discuss by Siebert et al.(2011). The derivative calculation should use the elapsed time since the last new measurement.

The closed loop response of the PI controller modified for wireless communication is illustrated in Figure 13 for both setpoint and load disturbances. In this example, the wireless transmitter follows the Rules for Transmitting a New Measurement Value. Also, the response is shown for a standard PI controller where the wired measurement value is communicated as frequently as the PI control algorithm executes (Fig.14).

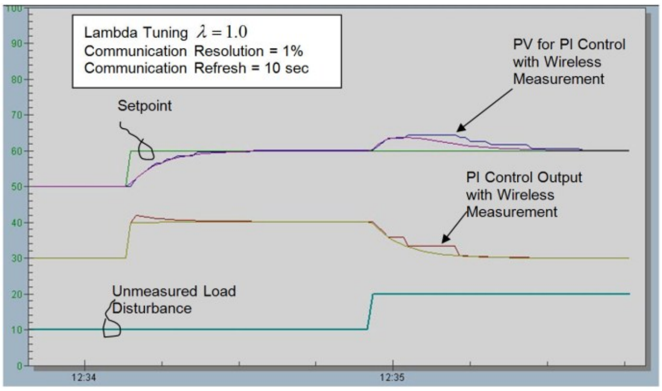


Fig. 14. Control for Wireless Measurement

In this example, the number of communications was reduced by over 96 % when the rules for wireless communication were followed. The impact of non-periodic measurement updates on control performance is minimized through the use of the modified PI algorithm for wireless communication. The difference in control performance is shown below in terms of Integral Absolute Error (IAE) for periodic measurement update vs. non-periodic.

Table 3 – Communications and Control Comparison

Communications/Control	Number of Communications	IAE
Periodic /standard PI controller	692	123
Update Using communication Rules/ PI controller for Wireless	25	159

The power for the transmitter can be significantly reduced when the communication rules and the PI controller modifications are used with wireless transmitters. This reduction in power requirement increases the potential for the number of control applications that may be addressed using wireless transmitters.

8. CONCLUSIONS

Presented in the paper are PID enhancements that significantly improve control performance and functionality. In particular, a method for improving the recovery of the PID from process saturation is of interest to the process industry. Also, the use of non-periodic measurement updates is a requirement when PID control is done utilizing wireless transmitters. Modifications to PID to address recovery from process saturation and the use of non-periodic measurement updates have been presented as implemented in a commercial process control system. Further research into the performance provided by the modifications would be of interest. Based on the achieved results it seems very probable that in the next few years PID control get smarter and will continue to be the main workhorse of process industry control.

Acknowledgments

The integration of modifications into the DeltaV PID for process saturation, non-periodic update, on-demand tuning and adaptive control is due largely to the efforts of Dr. Peter Wojsznis, Dr. Willy Wojsznis, Mike Ott, John Caldwell, and Randy Balentine, Emerson. Support for field testing of PID performance was provided by BP, Lubrizol, Texas Eastman, Canfor, Husky Oil, University of California, Santa Barbara and University of Texas. Also, the support that Karl Åström, Lund University, provided in the development of on-demand tuning is gratefully acknowledged.

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