Wireless Measurement and Control

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Key words: battery life, carbon dioxide recovery, conductivity measurement, electrode technology, electrode testing, electrode diagnostics, inferential measurement, pH control, pH measurement, pH noise, solution pH temperature compensation, wireless control, wireless measurement

ABSTRACT

Wireless measurements can reduce maintenance and noise problems in addition to installation costs by the elimination of wiring problems and electromagnetic interference. Less recognized are the opportunities afforded by wireless measurements for troubleshooting and optimizing measurement locations as well as developing and prototyping process control innovations. However, battery life and network integrity raise reliability, security, and maintenance questions. Communication interruptions and discontinuous updates can cause oscillations for traditional PID controllers. This paper addresses these concerns and discusses the potential use of wireless pH measurements for minimizing noise, maximizing sensor performance, selecting sensor technology, predicting sensor life, and developing inferential measurements. An example of the use wireless conductivity and pH measurements as inferential measurements of solvent and carbon dioxide is given to enable the optimization of absorber operation. The advantage of using spare wireless transmitters instead of lab meters for communicating test data for inferential measurements and calibration data from standardization methods with grab samples is offered. A simple enhancement of the PID algorithm for wireless control to extend battery life is explained and test results are presented for measurement failures, setpoint response, load upsets, and valve stiction. The effect of wireless transmitter settings such as "default update rate" and "trigger level" on control loop performance is estimated for unmeasured disturbances in terms of the additional deadtime added by wireless settings.

INTRODUCTION

The use of conductivity and pH in water and waste water covers a wide range of application conditions ranging from nearly pure water to wastewater with an incredible variety of chemicals. For condensate and de-ionized water, the low fluid conductivity poses special problems in terms of velocity effects, continuity, and sensitivity. For waste water streams chemicals can attack the electrodes and solids can coat the electrodes. Process and electrical noise are problems in all applications. The use of conductivity and pH in the measurement and control of carbon dioxide absorption is an emerging opportunity with special considerations due to the relatively high solvent concentration. Wireless measurement and control can play an important role in the design, installation, and performance of conductivity and pH in water and wastewater applications.

DESIGN

Wireless technology offers the opportunity to select the best electrode for an application. Spare wireless transmitters can be used to test electrodes in lab solutions set to mimic the concentrations and temperatures of the process. The process lab offers a controlled environment to vary the process conditions of interest and keep other conditions constant. The first through fourth variables of smart wireless transmitters can be readily made available for historization and analysis in the distributed control system (DCS). The slope, offset, and resistance of the electrodes can be studied. The accuracy and response time can be measured over an extended period of time to determine the performance and life of various electrode designs. For example, new high temperature glass formulations increase the life expectancy (Figure 1) and prevent the deterioration of electrode response time (Figure 2) from premature aging of the glass electrode.

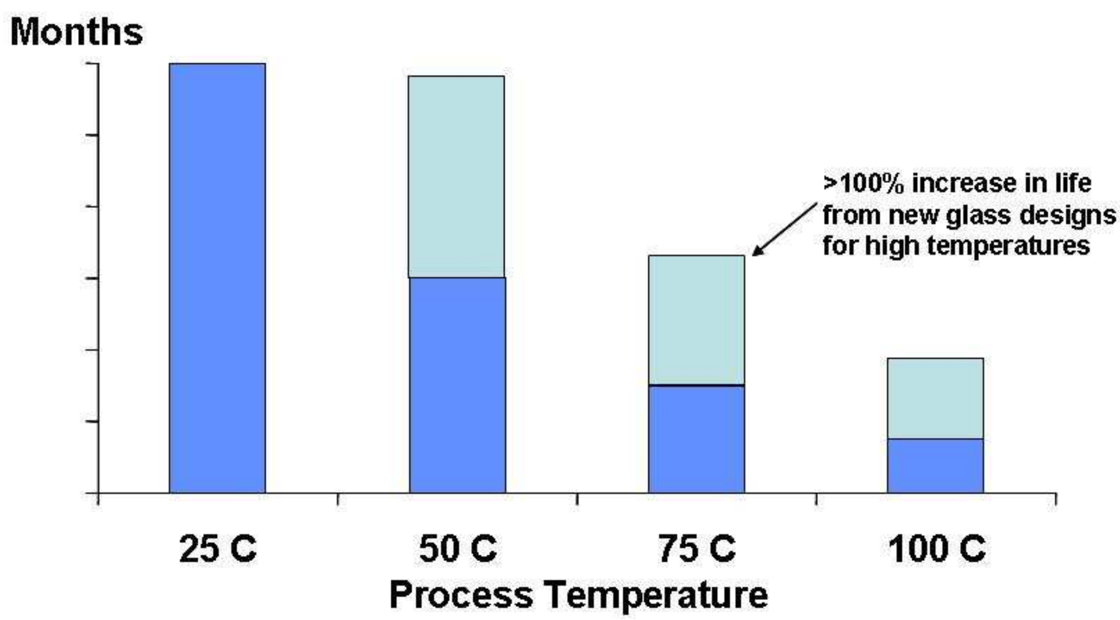


Figure 1. The life expectancy that decreases with temperature can be doubled by the use of new high temperature glass formulations.

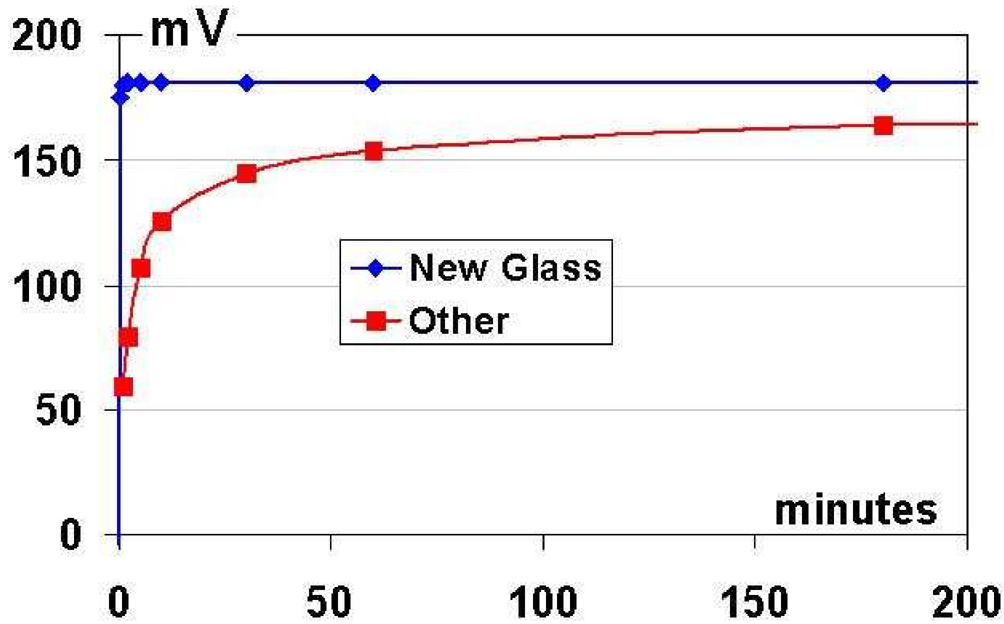


Figure 2. The onset of premature aging of the glass that greatly increases the response time can be delayed by the use of new high temperature glass formulations

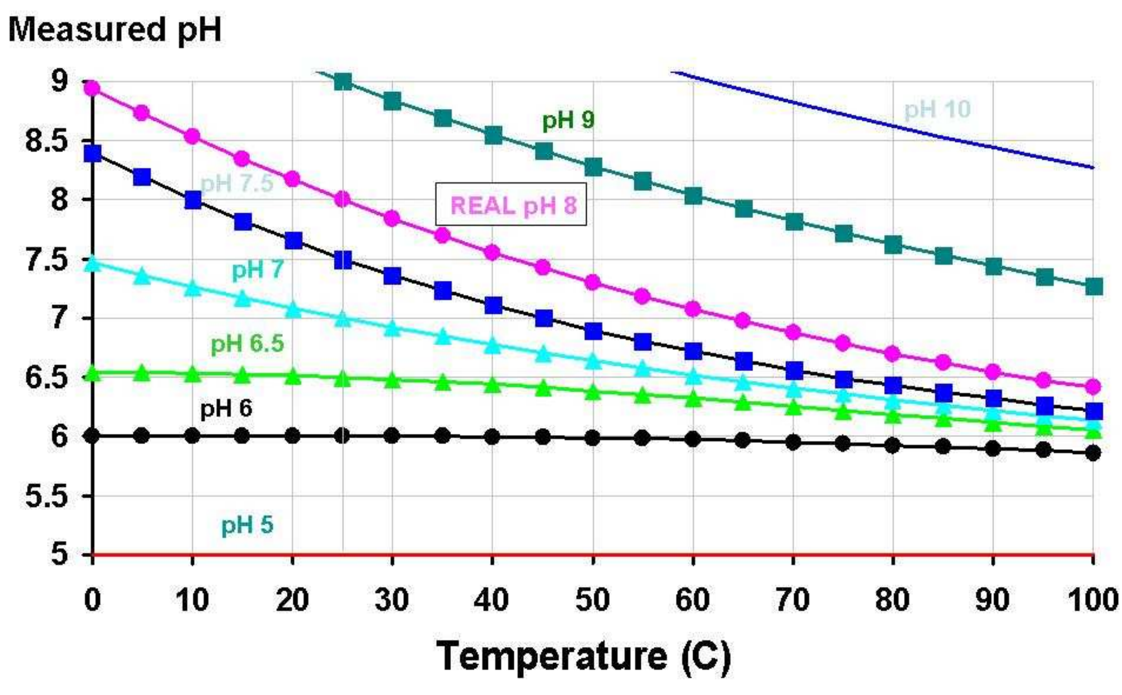


Figure 3. The change in water dissociation constant will decrease the pH with temperature by an amount that increases as the pH approaches the dissociation constant

Process temperature changes the dissociation constants and mobility of the ions and thus the actual solution pH and conductivity. For complex mixtures, the best way to determine the effect of process temperature is to vary the process sample temperature over the expected operating range. The change in the water dissociation constant (pK_w) with temperature causes a change in solution pH that increases as the pH approaches the pK_w (Figure 3). Smart wireless transmitters have the ability to configure solution temperature compensation. However, lab meters often cannot provide more than the standard temperature compensation for the electrode per the Nernst equation. Wireless transmitters could be used instead of lab meters for standardization with grab samples, the preferred method of calibration. Standardization is safer and more effective since it does not require removal of the process electrodes eliminating the associated risk of personnel exposure and damage to the glass, and disruption of the reference junction equilibrium.

Conductivity can provide an inferential measurement of the concentration of an acid, base, or salt by measuring the concentration and mobility of ions. Plots of conductivity versus ion concentration will increase from zero concentration to a maximum as the number of ions in solution increases. The conductivity then falls off to the right of the maximum as the ions get crowded and start to interact or associate (group) reducing the ion mobility (Figure 4). The peak must be found from process samples and measurements made for all possible operating conditions to insure operation on one side or the other of the peak. If the conductivity approaches the peak, the inferential measurement can lose sensitivity and change sign invalidating it for process control.

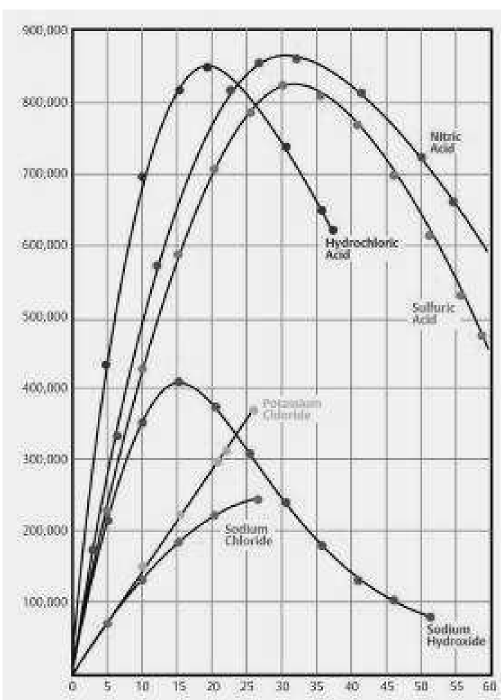


Figure 4. Conductivity as an inferential measurement of concentration can be used if the operating range can be verified to be always on one side of the peak.

For the maximum efficiency of carbon dioxide reduction in powerhouse stacks, the solvent and carbon dioxide concentration in the absorber must be measured and controlled. The absorber is never at steady state but is in a constant state of transition because boiler emissions vary significantly with weather and day to night load swings. Conductivity and pH were studied with wireless transmitters in the University of Texas (UT) Separations Research Facility with a reactive absorption system and solvent recovery column (Figure 5). The operation of the UT pilot plant boiler was varied to emulate the type of load changes experienced in a powerhouse.

Figure 5. UT Separations Research Facility for Carbon Dioxide Recovery

Wireless conductivity and pH transmitters were used in a process sample UT Separations Research lab representative of absorber operation (Figure 6). The use of a new glass formulation and reference design was found to increase the life of the pH electrode from 2 weeks to over 6 months. The relationships between pH and conductivity and the solvent and carbon dioxide concentrations were quantified by tests at concentrations representative of the range of powerhouse operation.

Figure 6. Wireless Test Setup of Conductivity and pH Transmitters for CO_2 Recovery

The use of conductivity as an inferential measurement of solvent concentration turned out to be not viable due to operation at the peak in the conductivity versus concentration plot (Figure 7). The maximum was a rounded hump rather than a sharp peak causing poor sensitivity (small change in conductivity for a change in concentration). Even more problematic was the reversal of the conductivity response that would lead to saturation of a controller output due to reversal of the direction of the process action.

Conductivity was found to be a possible inferential measurement of CO_2 loading if proper process temperature compensation is applied (Figure 8). Coriolis density and viscosity measurements also showed sufficient sensitivity to CO_2 loading. However, wireless conductivity is more portable and affordable. Since smart wireless conductivity like pH transmitters offer solution temperature compensation and auxiliary variables, these transmitters are preferable to lab meters for standardization with grab samples.

Tests of the wireless pH transmitter in the UT lab showed a linear relationship between pH and CO_2 concentration for a given solvent concentration with good sensitivity (Figures 9 and 10). Again solution pH temperature compensation was important. The change in pH with solvent is due to the change in the concentration and the mobility of the hydrogen ion with the change in water concentration.

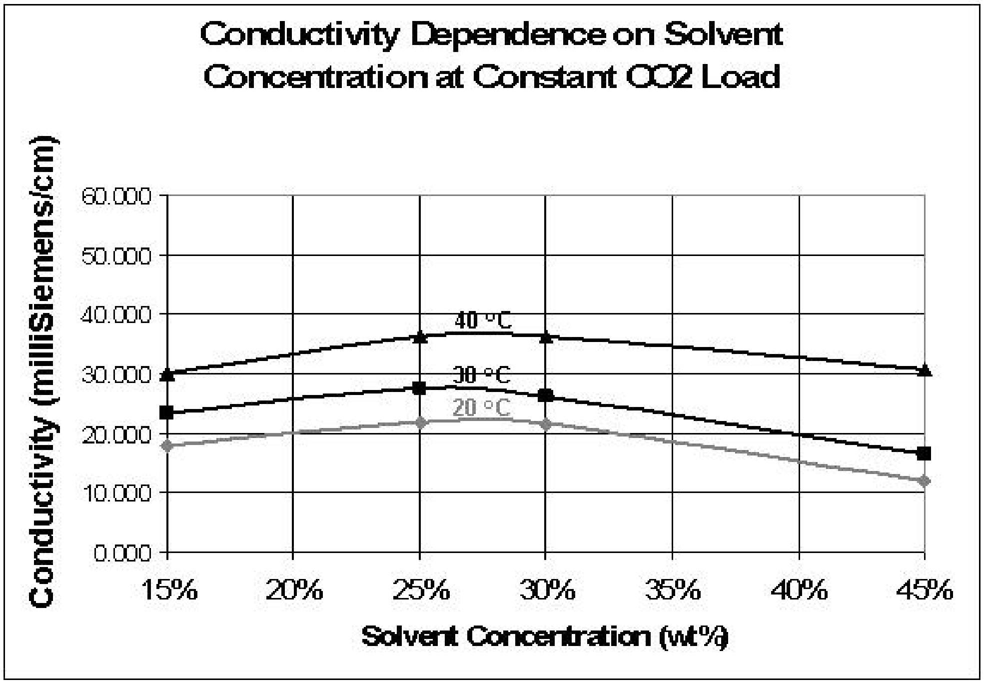


Figure 7. Conductivity for Inferential Measurement of Solvent Concentration had Poor Process Sensitivity and Reversal of Process Action Sign

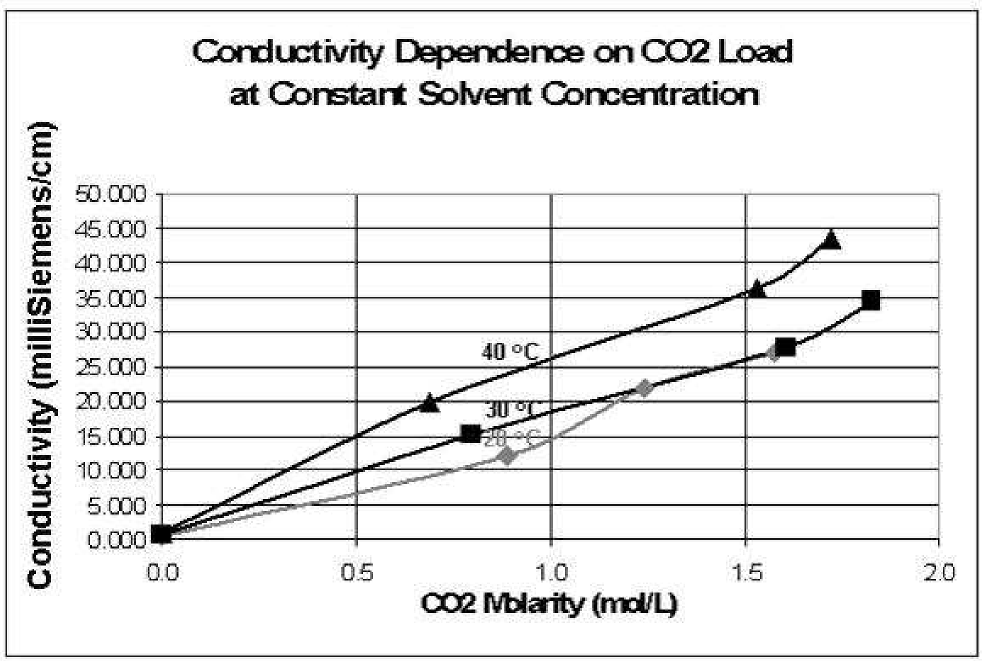


Figure 8. Conductivity for Inferential Measurement of CO_2 Loading Showed Promise if Proper Temperature Compensation is Developed and Automated.

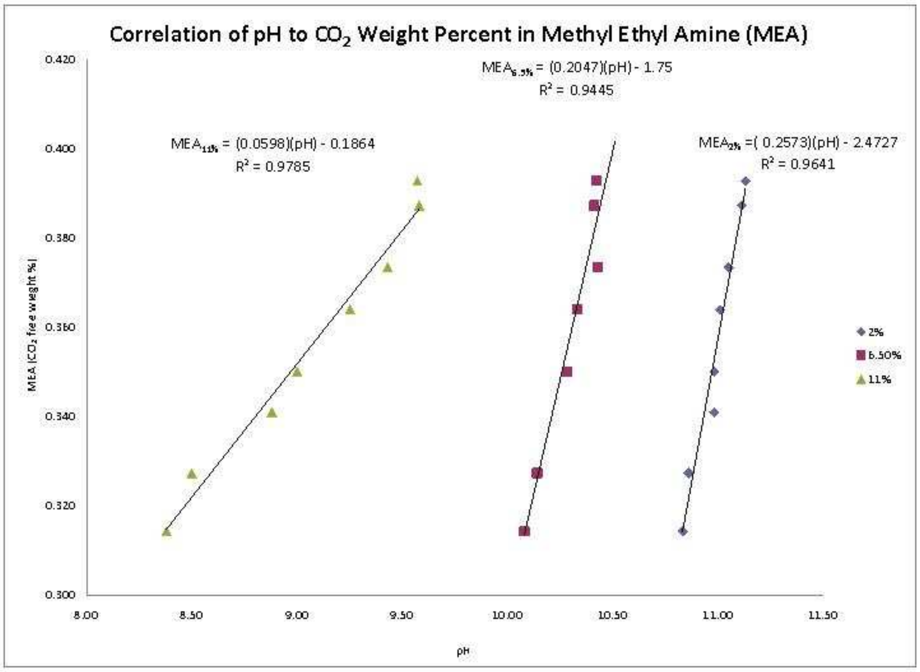


Figure 9. pH can be an Inferential Measurement of Methyl Ethyl Amine (MEA) Solvent Concentration if the Solution pH is Compensated for CO_2 Loading and Temperature

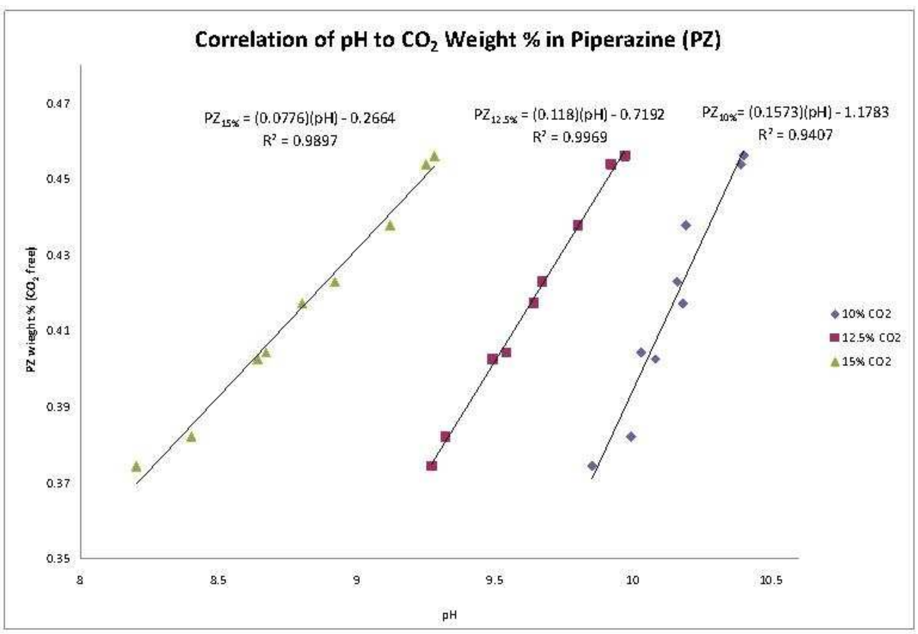


Figure 10. pH can be an Inferential Measurement of Piperazine (PZ) Solvent Concentration if the Solution pH is Compensated for CO_2 Loading and Temperature

INSTALLATION AND MAINTENANCE

pH measurements are susceptible to spikes from the start of motors and the change in speed of variable frequency drives. The fact these spikes are not observed when the electrode is connected to a laboratory meter is clue that transmitter output wiring may be a significant contributing factor to ground loops. When a wireless pH transmitter was used on a “single use bioreactor” (Figure 11), the spikes in the wired transmitter left in service did not appear in the wireless transmitter trend chart (Figure 12).

Figure 11. Wireless pH Transmitter on a Single Use Bioreactor

Wireless pH measurements eliminate the inevitable questions as to whether there is a problem with the wiring or terminations in troubleshooting the measurement. Also, wireless pH transmitters with automated solution temperature compensation and measurements of electrode resistance can be used to provide more intelligent grab sample calibrations that can be historized and analyzed in the DCS. Most pH systems suffer from over calibration with calibration adjustments chasing previous adjustments. If you compare the readings of two pH electrodes inline over several days, what may be high to day may be low tomorrow due to concentration gradients (Figure 13).

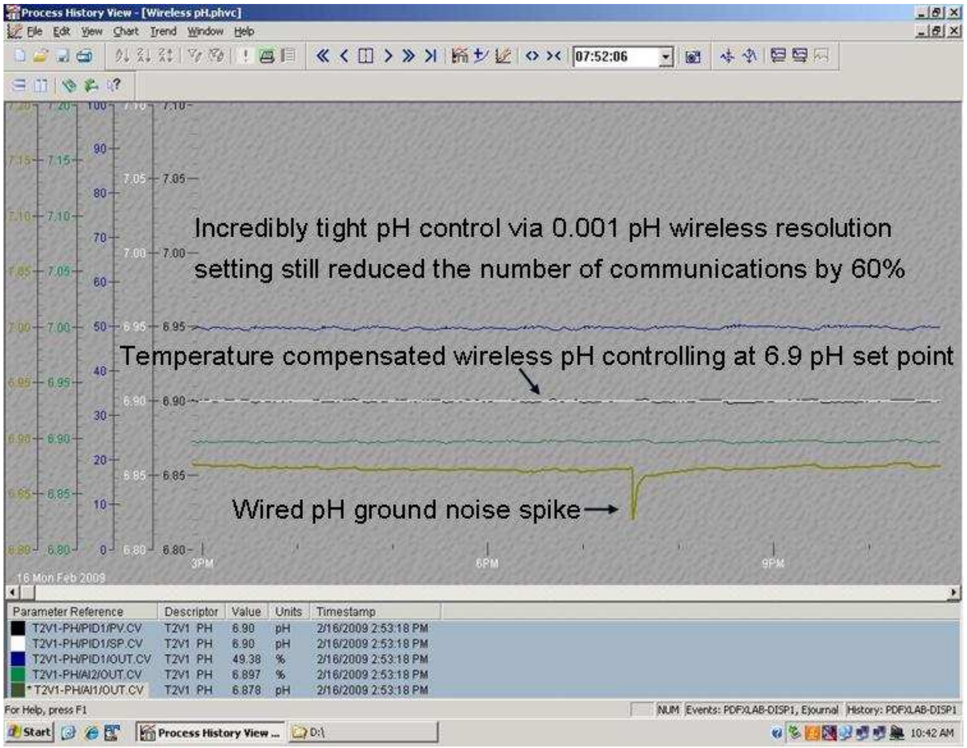


Figure 12. Wireless pH Transmitters Do Not Exhibit Spikes Seen in Wired Transmitters

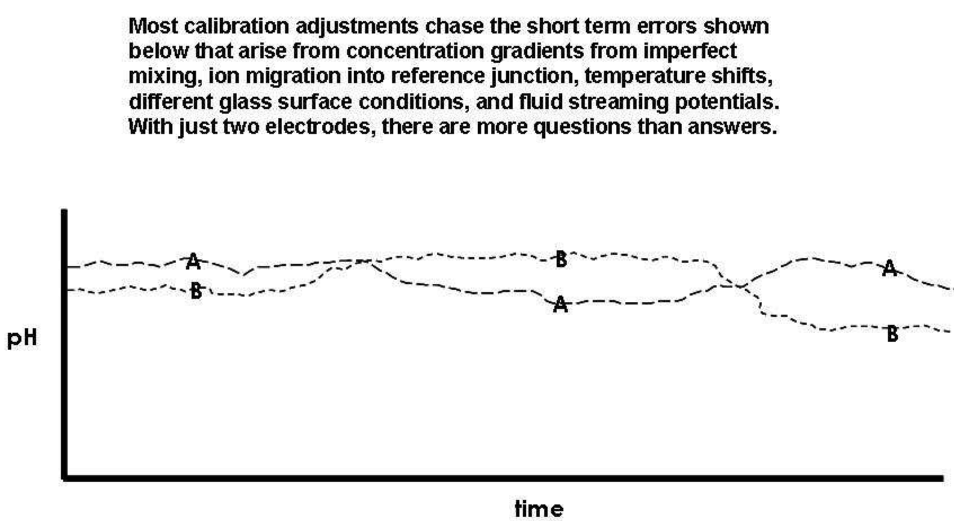


Figure 13. The pH Electrode that is High Today may be Low Tomorrow

The portability of wireless conductivity and pH measurements offer the opportunity to find the best location by plant trials. If several process connections are provided, the connection that offers the most representative measurement with the least noise and deadtime can be found. Noise is minimized by finding the location with the best mixing and least bubbles. Deadtime is minimized by reducing the transportation delay and increasing the velocity at the electrode, decreasing the electrode lag and coatings.

CONTROL

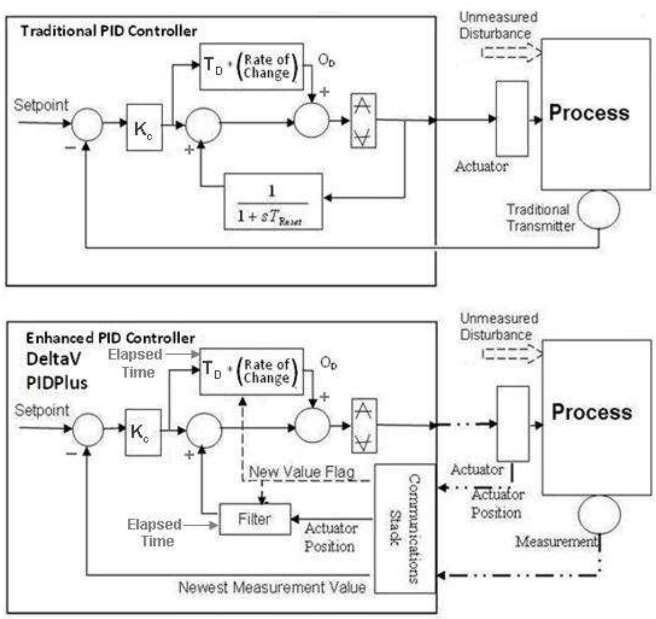
Wireless measurement devices have a “default update rate” (time interval for periodic reporting) and a “trigger level” (sensitivity limit for exception reporting) set as large as possible to conserve battery life. The integral mode in the traditional PID will continue to ramp while the PID is waiting for an updated measurement from a wireless device. Also, when an update is received, the traditional PID considers the entire change to have occurred within the PID execution time interval. If derivative mode is used, the rate of change of the measurement is the difference between the new and old measurement divided by the PID execution time interval. The result is a spike in the controller output.

The non-continuous update scenario occurs for many applications besides wireless devices. During the time when a measurement is not updated due to a failure, resolution limit, sensitivity limit, or backlash, the PID output continues to ramp from the integral mode. Failures, resolution limits, and sensitivity limits can originate in an analyzer, sensor, transmitter, communication system, or control valve. Analyzers also have a time interval between updates determined by the sample time and cycle time.

The enhanced PID for wireless executes the PID algorithm as fast as wired devices. A change in setpoint, feedforward signal, and remote output translates immediately (within PID execution time interval) to a change in PID output. However, integral action does not make a change in the output until there is an update. When an update occurs, the elapsed time between the updates is used in an exponential calculation that mimics the action of the filter block in the positive feedback implementation of integral action. If derivative action is used, the elapsed time rather than the PID execution time interval is used to calculate the rate of change of the process variable. The integral and derivative calculations are executed only once upon a change in setpoint or measurement compares a simplified block diagram of the traditional PID to the enhanced PID (Figure 14).

A traditional PID will have to be detuned to prevent instability for a large increase in the time between updates. The enhanced PID will continue to be stable for even the longest update time interval. For a measurement update time interval larger than the process response time, the enhanced PID controller gain can be set equal to the inverse of the open loop gain (product of valve, process, and measurement gain) to provide a complete correction for setpoint change or update. Tests show the enhanced PID can suppress oscillations from a wide variety of sources. This reduction in variability results from the suspension of integral action and the wait in feedback correction till there is a more complete response. To achieve these benefits, the user simply enables the enhanced PID option in the PID block, which automatically enables the dynamic reset limit option. No retuning is necessary to achieve a smooth response but if the update time is larger than the process response time the enhanced PID can be tuned with a much higher gain. For cascade control of static mixer pH to reagent flow control, the static mixer is able to make a single correction for a load disturbance (Figure 15) and a setpoint change (Figure 16) compared to the slow response of traditional PID. The enhanced PID also eliminated the ramp off toward the output limit by a traditional PID for a communication failure or broken electrode glass or wire (Figure 17).

Stick-slip and backlash cause limit cycles because integral action in a traditional PID continues to ramp when there is an offset. The exceptional sensitivity of the pH measurement can result in extremely large limit cycles on the steep portion of the titration curve. The stick-slip is also greatest at the split range point because the reagent valves are operating near the seat where the friction from seating and sealing is greatest. The enhanced PID inherently prevents the limit cycles from stick-slip and backlash if a noise band is used to prevent an update to the PID pH due to measurement noise (Figure 17).



- PID integral mode is restructured to provide integral action to match the process response in the elapsed time (reset time set equal to process time constant)
- PID derivative mode is modified to compute a rate of change over the elapsed time from the last new measurement value
- PID reset and rate action are only computed when there is a new value
- If transmitter damping is set to make noise amplitude less than communication trigger level, valve packing and battery life is dramatically improved
- Enhancement compensates for measurement sample time suppressing oscillations and enabling a smooth recovery from a loss in communications further extending packing - battery life

Figure 14. Enhancements of PID for Wireless Prevent the Ramping from Integral Action and the Spikes from Derivative Action for Discontinuous Updates

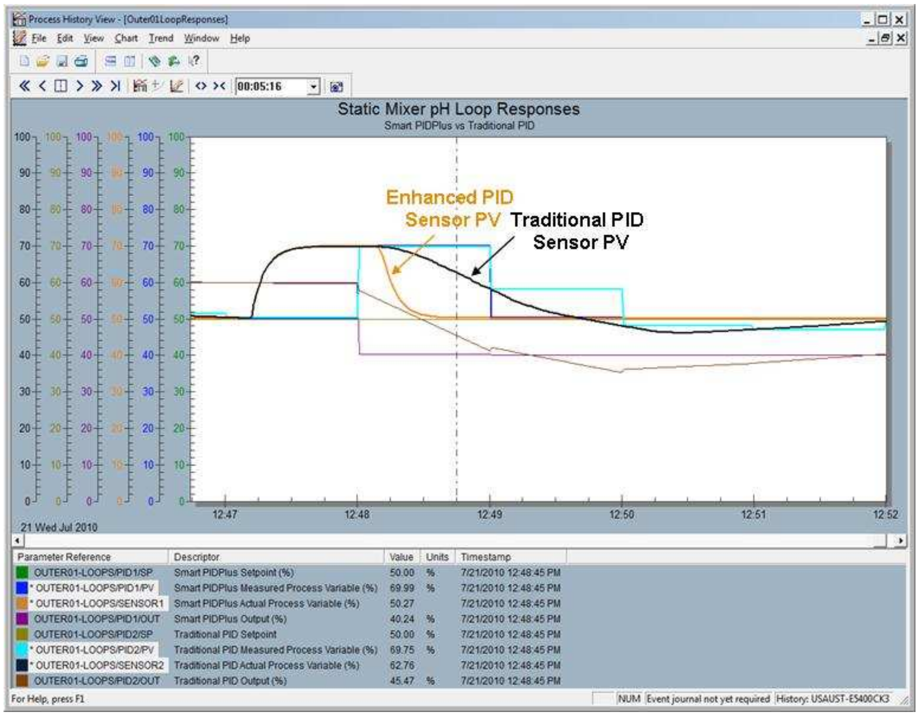


Figure 15. For a Wireless pH Loop Load Upset, the Enhanced PID Makes a Single Reagent Correction whereas the Traditional PID Slowly Makes a Series of Corrections

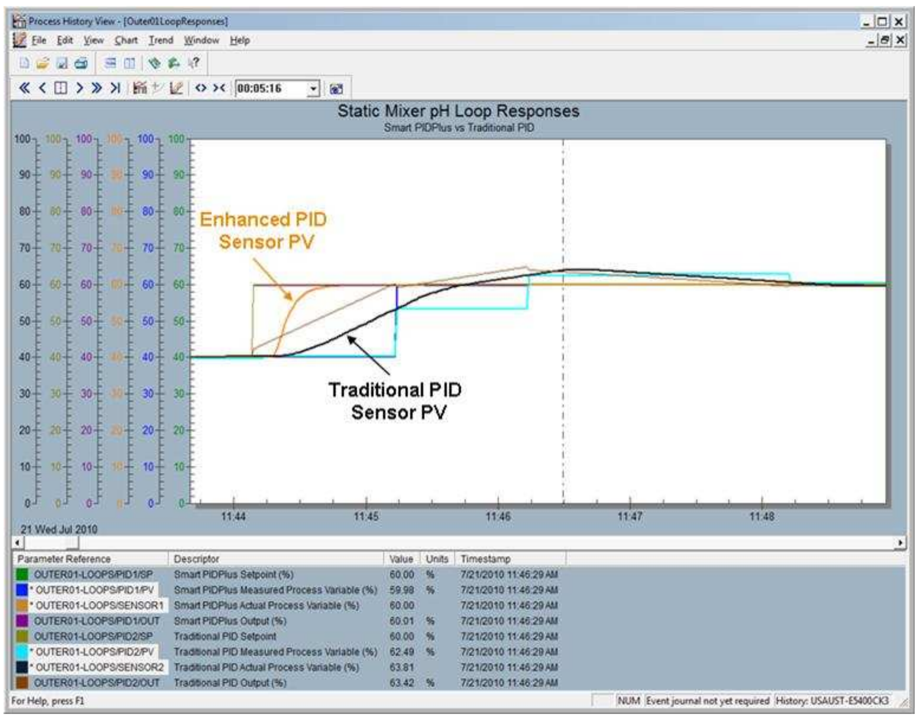


Figure 16. For a Wireless pH Loop Setpoint Change, the Enhanced PID Makes a Single Reagent Correction whereas the Traditional PID Slowly Makes a Series of Corrections

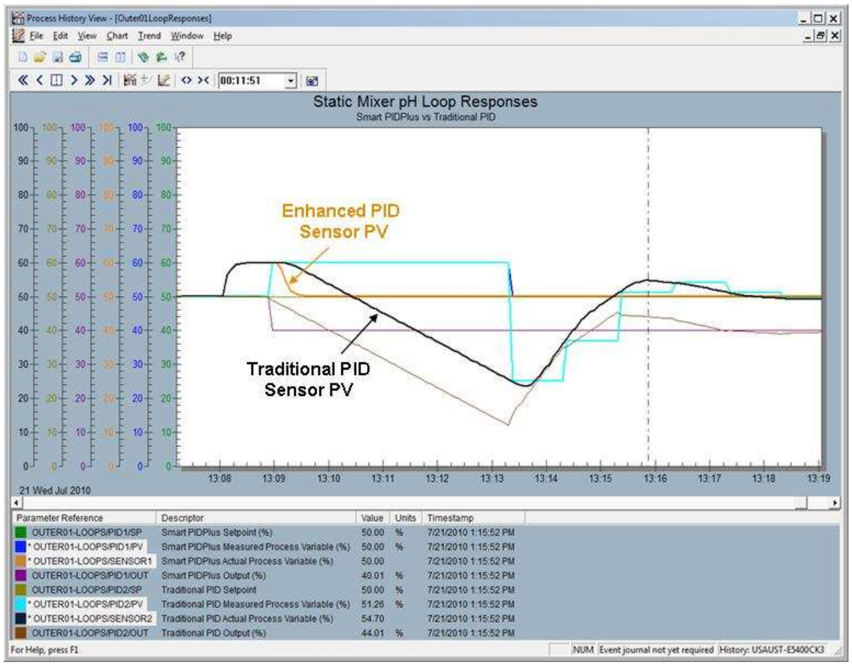


Figure 17. For a Wireless pH Loop, the Enhanced PID Rides out a Communication Failure or Broken Electrode whereas the Traditional PID Ramps to its Output Limit

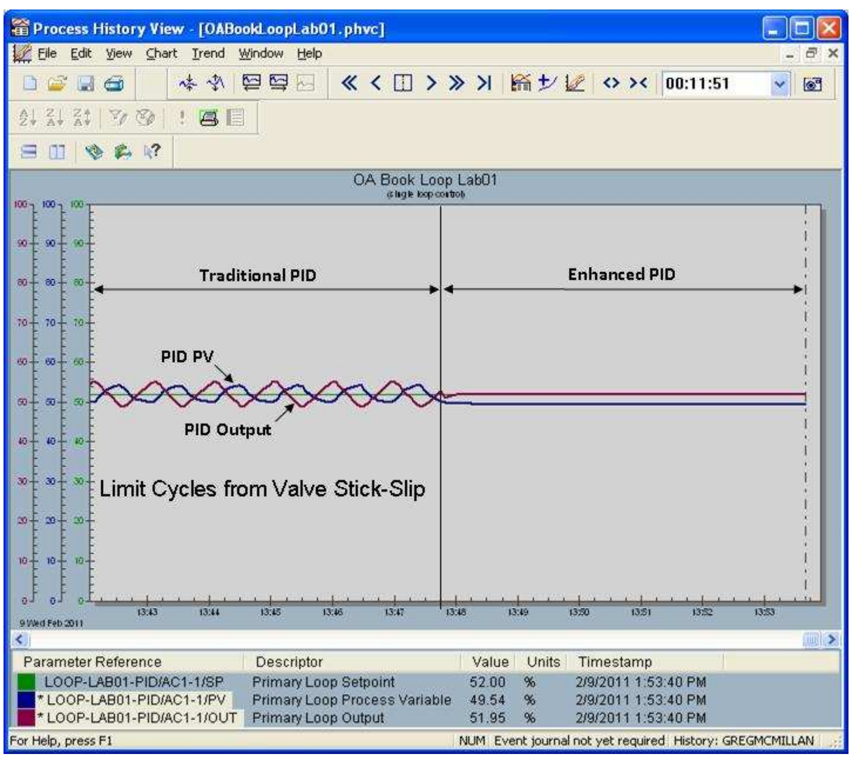


Figure 18. The Enabling of the Enhanced PID option for Wireless Control Eliminates Limit Cycles from Valve Stick-Slip and Backlash

For a step change in an unmeasured disturbance that would cause an open loop error of (E_o), the minimum peak error (E_x) (Equation 1) is proportional to the ratio of the total loop deadtime to the 63% response time (T_{63}). The minimum integrated error (E_i) (Equation 2) is approximately the peak error multiplied by the total loop deadtime that is the original deadtime (θ_o) plus the additional deadtime from a wireless measurement (θ_w) and a control valve (θ_v). The 63% response time (Equation 3) is simply the sum of the original loop deadtime plus the wireless measurement deadtime and the open loop time constant (τ_o), which is hopefully the primary process time constant. Note that the valve deadtime from stiction and backlash does not appear in the 63% open loop step response time because the step change occurs within the controller execution and must be larger than the valve resolution, sensitivity, and deadband to create a response. Consequently, on open loop step response trend charts, the deadtime from valve stiction and backlash is not seen. However, in closed loop operation, the controller output is ramping for an unmeasured disturbance and the time the controller takes to ramp through the valve resolution, sensitivity, and deadband is additional deadtime.

$$E_x = \frac{\theta_o + \theta_w + \theta_v}{T_{63}} * E_o \qquad (1)$$

$$E_i = \frac{(\theta_o + \theta_w + \theta_v)^2}{T_{63}} * E_o \qquad (2)$$

$$T_{63} = \theta_o + \theta_w + \tau_o \qquad (3)$$

The additional deadtime from a wireless measurement (Equation 4) is the smallest of the deadtimes from the wireless "default update rate" (update time interval) for periodic reporting (ΔT_w), and the wireless "trigger level" (threshold sensitivity) for exception reporting (S_w). The deadtime from periodic reporting ($\theta_{\Delta T}$) (Equation 5) is one half of the update time interval. The deadtime from exception reporting (θ_S) (Equation 6a) is one half of the sensitivity setting divided by the maximum rate of change of the % process variable $(\%\Delta PV/\Delta t)_{\max}$. Half of the interval and sensitivity settings are used because on the average the disturbance starts halfway in the interval and halfway in the sensitivity.

The rate of change is a maximum during the beginning of the disturbance before the control loop has had any effect. This maximum rate of change is dictated by the size of the disturbance and process dynamics. The maximum ramp rate (Equation 6b) can be approximated by a near integrator gain multiplied by the equivalent change in controller for the disturbance. The equivalent change in controller output is the open loop error (E_o) divided by the open loop gain (K_o). The near integrator gain (Equation 6c) is the open loop gain divided by the open loop time constant (τ_o). The substitution of Equation 6c into Equation 6b cancels out the open loop gains giving the maximum ramp rate (Equation 6d) as simply the open loop error divided by the open loop time constant. The substitution of Equation 6d into Equation 6a yields Equation 6e where we see the deadtime from the sensitivity setting decreases as the size of the disturbance increases and the open loop time constant decreases, both of which cause a faster rate of change.

$$\theta_w = Min(\theta_{\Delta T}, \theta_S) \tag{4}$$

$$\theta_{\Delta T} = 0.5 * \Delta T_w \tag{5}$$

$$\theta_S = \frac{0.5 * S_m}{(\Delta\% PV / \Delta t)_{\max}} \tag{6a}$$

$$(\Delta\% PV / \Delta t)_{\max} = K_i * (E_o / K_o) \tag{6b}$$

$$K_i = \frac{K_o}{\tau_o} \tag{6c}$$

$$(\Delta\% PV / \Delta t)_{\max} = \frac{E_o}{\tau_o} \tag{6d}$$

$$\theta_S = \frac{0.5 * S_m * \tau_o}{E_o} \tag{6e}$$

Similarly, the deadtime from valve sensitivity (S_v) can be estimated (Equation 7a) as half of the sensitivity divided by the maximum rate of change of the controller output that is initially mostly due to the proportional mode. This rate of change of controller output (Equation 7b) is the rate of change of the process variable multiplied by the controller gain (K_c). The controller gain (Equation 7c) can be approximated as the Ziegler Nichols gain multiplied by a detuning factor (K_x) to provide robustness and a smoother response. However, the gain should not inflict disturbances from fluctuations in the PID output from exceeding the control valve sensitivity. An enhanced PID noise band expressed as measurement sensitivity (S_m) can reduce this noise allowing a higher controller gain. The substitution of Equation 7c into Equation 7b cancels out the open loop time constant (Equation 7d). The substitution of Equation 7d into Equation 7a yields Equation 7e where the deadtime is proportional to the product of the open loop gain and original deadtime and inversely proportional to the product of the detuning factor and open loop error.

$$\theta_v = \frac{0.5 * S_v}{(\Delta\% CO / \Delta t)_{\max}} \tag{7a}$$

$$(\Delta\% CO / \Delta t)_{\max} = K_c * (\Delta\% PV / \Delta t)_{\max} \tag{7b}$$

$$K_c = \min\left[\frac{K_x * \tau_o}{K_o * \theta_o}, \frac{S_v}{\max[(N_m - S_m), 0.002]}\right] \tag{7c}$$

$$(\Delta\%CO/\Delta t)_{\max} = \frac{K_x * E_o}{K_o * \theta_o} \tag{7d}$$

$$\theta_v = \frac{0.5 * S_v * K_o * \theta_o}{K_x * E_o} \tag{7e}$$

CONCLUSION

The portability and connectivity of smart wireless transmitters creates new possibilities of using spare transmitters to get data into the DCS from lab testing and field calibration and for developing inferential measurements and selecting the best sensor technology and location. The elimination of wiring reduces the susceptibility to electrical noise especially for wireless pH. An enhancement to the PID algorithm provides protection for delays and interruptions in communication and offers a nearly perfect setpoint response when the default update rate is slower than the process response time. The effect of wireless settings on the peak and integrated errors for unmeasured disturbances can be estimated.

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BIOGRAPHY

Greg is a retired Senior Fellow from Solutia/Monsanto and an ISA Fellow. Presently, Greg contracts in Emerson DeltaV R&D via CDI Process & Industrial in Austin and is a part time employee of Experitec and MYNAH in Saint Louis. Greg received the ISA "Kermit Fischer Environmental" Award for pH control in 1991, the Control Magazine "Engineer of the Year" Award for the Process Industry in 1994, was inducted into the Control "Process Automation Hall of Fame" in 2001, was honored by InTech Magazine in 2003 as one of the most influential innovators in automation, and received the ISA Life Achievement Award in 2010. Greg is the author of numerous books on process control, his most recent being *Advanced Temperature Measurement and Control.* Greg has been the monthly "Control Talk" columnist for *Control* magazine since 2002. Greg's expertise and virtual plants are available on the web sites:
http://www.modelingandcontrol.com/ http://www.processcontrollab.com/