Corn Analysis, Modeling, and Control for Ethanol Yield Optimization

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Key words: corn analyzer, ethanol production rate control, ethanol slurry solids control, fermentable starch, spectroscopy

ABSTRACT

Corn is over 50% of the operating cost for ethanol fuel manufacturing. The fermentable solids in corn vary with weather and storage conditions and the genetic capability of the seeds. A commercially validated NIR-T technology can provide non-destructive/high throughput analysis of corn for predicted fermentable starch. This technology in the form of a calibration equation is deployed to ethanol plants on a grain analyzer and used either in the receiving process or as operations support. A first principle model as part of a virtual plant in a DCS is developed to explore process control opportunities. The model uses material, energy, component, and charge balances, plus fermentation kinetics to provide process measurements and key compositions. The model runs much faster than real time so fermentation batches are completed in minutes. Study results show that an enhanced PID originally developed for wireless with a threshold sensitivity setting is able to handle the discontinuous updates, variable delays, and noise in the analysis. The PID is used as a production rate controller that optimizes corn feed rate based on predicted fermentable starch. The PID allows operations to set the front end slurry and liquefaction rate to drive production rate based on market demand or to match a change in fermentation rate or back end purification rate from operating constraints or abnormal conditions and maintenance. A second enhanced PID is used for slurry concentration control. The density measurement by Coriolis meter in a recirculation line is used with corn analysis to provide an inferential measurement of fermentable slurry solids. A feedforward calculation uses corn analysis and feed rate, backset recirculation rate, steam injection rate, and slurry concentration setpoint to set the water addition to the slurry tanks. The enhanced PID trims the feedforward calculation allowing for timing errors. Deadtime compensation is added to the slurry concentration PID to enable faster tuning settings despite the large process lag and deadtime. The slurry PID compensates for changes in corn moisture, water temperature, and backset recycle. A third enhanced PID is used to provide a gradual trim of the fermentable solids when a HPLC fermentation analysis indicates the ethanol batch cycle time has reached the end point. The control strategy automatically adjusts corn feed rate and solids concentration to optimize ethanol yield.

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INTRODUCTION

Fermentation batch cycle times are usually fixed. The ethanol concentration at the end of batch can vary from 11.8 to 12.2 per cent by weight during normal operation. Since the corn feed rate is typically constant and corn is the biggest cost, this variability in batch end point translates to variability of 2% in ethanol production cost. Since temperature and pH control is rather tight in the slurry preparation area, most of the variability in ethanol concentration is suspected to be caused by the differences in the corn. The actual opportunity for cost reduction is greater because ethanol inhibition of production of ethanol by yeast prevents achieving ethanol concentrations larger than a 12.2%. As the high limit is approached, yield is reduced by the diversion of glucose consumption from ethanol production to acetic and lactic acid formation. These acids lower the pH, which also reduces ethanol yield. The result is that increases in corn fermentable starch whether due to improved corn processing or corn genetic quality, do not show up as an increase in ethanol batch end point. Since fermentation batch cycle times are fixed, early achievement of the maximum ethanol concentration does not result in a faster fermentation production rate and yield improvements are lost. Even if plant design and automation were flexible enough to enable a variable batch cycle time, yield improvement would be delayed by 1 to 2 days till when the batch is completed. A supervisory loop to change front end operation would have a deadtime equal to 1.5 times this delay making direct control nearly impossible. Additionally, short term variations in front end operation would not be recognized and ethanol concentrations may not be confidently correlated to changes in corn quality. The availability of a NIT analyzer opens up opportunities for fast direct control of plant yield and demonstration of potential improvements in corn sourcing and processing through the online measurement of fermentable starch.

ANALYZER

To meet the demands of high throughput sampling, a Chemometrics model has been developed using Near Infrared Transmittance (NIR-T) technology allowing for non destructive analysis of whole corn. This calibration model is based on an industry developed lab/flask scale fermentation protocol designed to replicate commercial scale technology. Chemometrics allows HPLC analysis results to be correlated to the combination of known and unknown grain quality characteristics that ultimately determine the ethanol yield of a given sample. The calibration units are predicted ethanol yield on a gallons per bushel basis @ 15% moisture. Commercial validation of this calibration showed a 1% change in ethanol fermentor yield corresponded to a 1 +/-.4% change in predicted ethanol yield at a 95% confidence level. Operation of the instrument requires placing sample in the hopper and initiate run sequence. Each sample is analyzed in a series of sub-samples which are then averaged and the results immediately generated. The analysis process itself takes between 45 and 75 seconds depending on the number of sub-samples selected.

The whole corn sample should be representative of the entire fill time of any given fermentor. A sample is pulled at routine intervals based on fermentor fill time. For the process studied the corn feed rate is 88 bushels per minute, which means a sample is pulled roughly every 5 minutes with results being immediately processed and generated. A typical manual method simply dumps the subsample into a drum. When the drum is nearly full, samples are taken for analysis. The probe automatically collects samples at predefined depths in the drum. This method results in a large and variable delay and an essentially unknown feed time for the samples analyzed. While the proposed control system can deal with a large and variable update time, speed and timing is sacrificed. Perhaps even more of an issue is the severe limitation in the ability to track down changes in feed quality for improving process operations. An automated method of immediately submitting the half pound subsample to the NIR-T analyzer offers rapid recognition of changes in corn quality enabling faster optimization and offering knowledge for a continuous process improvement program. There is a synergy between control system and process design and operation because the control system will immediately take advantage of process and operational improvements by reducing corn feed rate for an increase in corn quality as soon as an analysis is communicated.

In this plant the time interval between subsample inputs is 5 minutes and the time until an analyzer output is communicated is about 1 minute. In process control, the 5 minutes time between inputs is called the sample time or scan time and the 1 minute delay until an output is communicated after an input is called the latency. In process control a phase shift is introduced equivalent to a deadtime of ½ the sample time plus the latency. The equivalent deadtime for the corn analyzer with an automated sample system in this plant is about 3 ½ minutes. This deadtime is small compared to the residence time in the slurry and liquefaction areas and the batch cycle time of the fermentor. However, for closed loop control, the deadtime is large compared to other common loop deadtimes and presents a challenge to conventional PID control. Also, despite the averaging of runs, the residual noise in the analysis results can translate into unnecessary or incorrect adjustments. A virtual plant is employed to explore process control challenges and opportunities. The virtual plant is used to develop and prototype control strategies employing an enhanced PID technology. The overall objective is to provide a simple robust optimization scheme using PID controllers whose standardized interface is exactly the same as what operators use and understand in the basic process control system.

VIRTUAL PLANT

A virtual plant shown conceptually in Figure 1 is used to quantify process control opportunities in the front end of ethanol production. The virtual plant consists of first principle dynamic process models, field instrumentation dynamics, and the actual DCS configuration and operator interface running in a virtual mode on a personal computer. The dynamic model integrates ordinary differential equations (ODE) for material, energy, and component balances to simulate compositions, levels, pressures, and temperatures. A charge balance is optimally solved to compute pH from acid and base concentrations. Transportation delays in piping and dip tubes are simulated via a deadtime equal to the volume divided by the flow rate. Deadtime blocks are also used to simulate mixing delays where the deadtime is ½ the vessel volume divided by the agitator pumping rate. An analyzer block comprised of DCS function blocks simulates the cycle time and noise. Similarly, blocks are configured to simulate field measurement and final control element dynamics. The field measurements are signals to the simulation input of analog input (AI) blocks and the outputs of the analog output (AO) blocks are signals to the field final control elements, such as control valves and variable speed drives. All of the control capabilities in a DCS including advanced control tools are available for exploring opportunities. For the ethanol plant, the enhanced PID (PIDPlus) is investigated that was originally developed for wireless measurements. Since wireless measurements and analyzers have discontinuous and potentially variable update times and possibly sensing noise, the PIDPlus with a threshold sensitivity setting (termed “deadband”) should be able to show performance advantages.

The residence time (volume divided by flow) in the continuous front end is about 188 minutes. The fermentor batch cycle time is 38 hours. Obviously a real time simulation takes too long for studies. A liquid speed-up factor of 24 for the integration of material, component, and energy balances reduced the residence time to about 2 minutes per vessel in the continuous front end. With a 24x speedup, the corn subsample time is 12 sec and the corn analysis time is 2 seconds rounded down to the nearest integer. In the fermentor, the liquid speedup factor of 24 and a biological kinetics speedup factor of 10 have a multiplicative effect providing a 240 speedup so that a 38 hour batch is completed in 8 minutes.

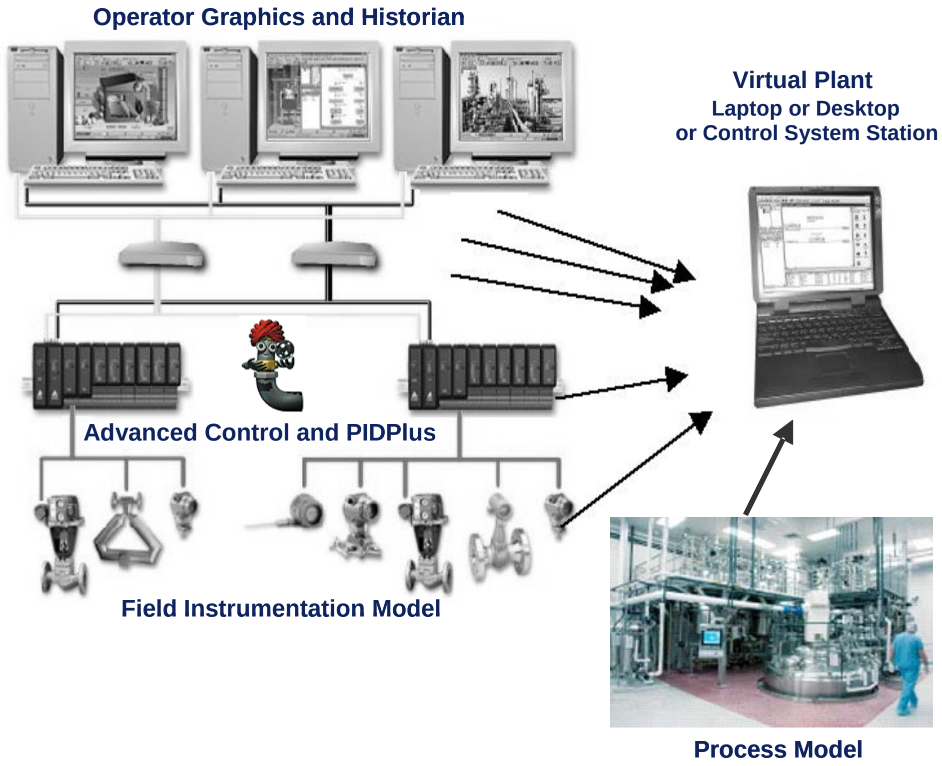
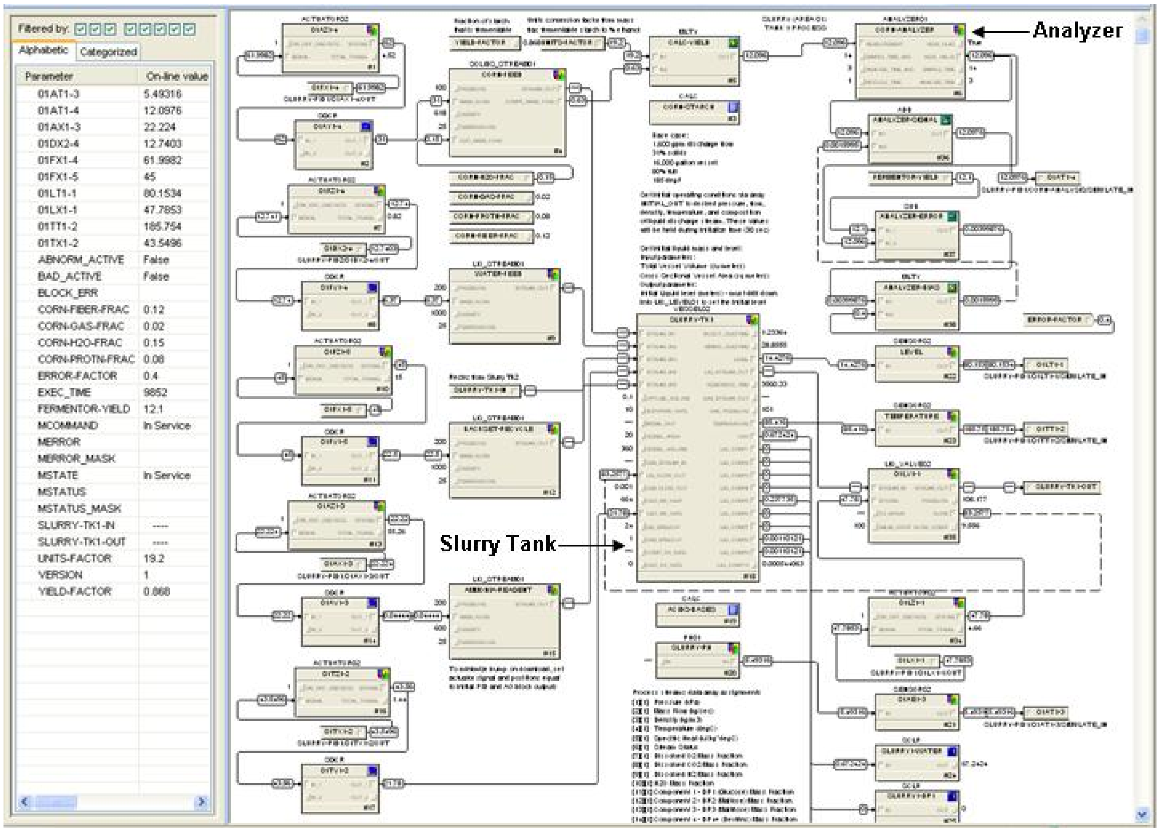


Figure 1. Virtual Plant integrates DCS Configuration with its advanced control and enhanced PID with models of the process and field instrumentation into a laptop.

A generic building block approach is used for the model that is applicable to any type of process and automation system. The models are graphically configured in the same control studio environment as the DCS control strategies. The primary difference is that the connections between model blocks are process connections. For equipment and final control elements, these connections are streams (e.g. pipes, conveyors, or ducts). For measurements, the connections are for sensors in sample lines, equipment, or streams as shown in Figure 2. The process conditions in equipment and streams are in a 20 x 1 dimensional array. For maximum visibility of operating conditions and vessel details and to show the flexibility of models, many parameters and connections are exposed. While this view adds to the visual complexity as seen in Figure 2, the exposure of details is useful for process understanding besides indicating the power and flexibility of the model. The models for the slurry tanks, liquefaction tanks, and fermenters use the same vessel block. If you drill down into the vessel block, you see generic blocks for blending, injection, mixing, heat transfer, level, and pressure. The difference between a vessel used for chemical or biological reaction, crystallization, evaporation, or just liquid storage is accomplished by the calculation and adjustment of parameters, reactions, and mass transfer. For the user, an operator graphic interface provides access to the model parameters and results.



Parameter	On-line value
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01AT1-4	12.0976
01AX1-3	22.224
01DX2-4	12.7403
01FX1-4	61.9982
01FX1-5	45
01LT1-1	80.1534
01LX1-1	47.7853
01TT1-2	185.754
01TX1-2	43.5496
ABNORM_ACTIVE	False
BAD_ACTIVE	False
BLOCK_ERR	
CORN-FIBER-FRAC	0.12
CORN-GAS-FRAC	0.02
CORN-H2O-FRAC	0.15
CORN-PROTN-FRAC	0.08
ERROR-FACTOR	0.4
EXEC_TIME	9852
FERMENTOR-YIELD	12.1
MCOMMAND	In Service
MERROR	
MERROR_MASK	
MSTATE	In Service
MSTATUS	
MSTATUS_MASK	
SLURRY-TK1-IN	----
SLURRY-TK1-OUT	----
UNITS-FACTOR	19.2
VERSION	1
YIELD-FACTOR	0.868

Figure 2. The slurry tank process model has process connections and streams with parameters exposed to show the flexibility of the generic building block method.

In the liquefaction tanks the kinetics provides a simple rate limited conversion of starch to maltose, maltriose, and higher order dextrin polymer. The conversion rates are set in the reaction array input to the vessel. In the vessel for simultaneous saccharification and fermentation (SSF) there is a much more complex set of kinetics. The Michaelis-Menten equation with dextrin polymer limitation and glucose inhibition is used for the maximum enzymatic reaction rates for conversion of dextrin polymers to glucose (saccharification). The limitation part of the Michaelis-Menten equation, a Monod equation with a product inhibition factor and maximum specific growth rate is used for viable yeast growth kinetics (fermentation). A Monod equation is also used for acetic and lactic acid formation. A power function is used to approximate death rate at high yeast concentrations. The effect of pH on growth rate and product formation is included by a convenient cardinal equation instead of the traditional Nielsen-Villadsen equation. Similarly a convenient cardinal equation is employed instead of the traditional Arrhenius equation to model the effect of temperature. The convenient cardinal equations eliminate the hyper sensitivity of parameters in the traditional equations that disable manual and automated identification methods. Also, the parameters of minimum, maximum, and optimum pH or temperature are more recognizable and easier to initialize based on process knowledge. Yield factors are used to compute glucose utilization from growth, ethanol production, and acid formation. The rate and mass transfer rate expressions for carbon dioxide production developed for bioreactor models were not used in this ethanol fermenter model. However, since carbon dioxide production rate as measured in the off gas is an inferential measurement of yeast growth rate, the model may be expanded to model carbon dioxide. A better documented opportunity is a dielectric spectroscopy measurement to provide a low cost, reliable, and fast measurement of viable yeast cell count whose slope is an inferential measurement of growth rate less death rate.

CONTROL SYSTEM

The control system for optimization of yield uses three enhanced PID controllers originally developed for wireless measurements. These enhanced PID do not make a feedback correction until there is a significant change in the process variable (PV). This normally occurs for proportional and rate action but not for reset action. The integral mode in a conventional PID will continue to ramp the PID output according to the difference between PV and setpoint (SP). Since the PV never exactly matches the SP, reset action is continually driving the PID output. In the enhanced PID, reset action is suspended unless there is new information, at which time a calculation is made based on the difference between the current and last PV update and the time since the last update to eliminate the error between PV and SP by reset action. By waiting and not continuing to act on the last PV, which is essentially old information, the PID has time to see the effect of the last change in output. For systems with analyzer updates times larger than the process response time, the enhanced PID can be tuned to provide a full correction for a setpoint change because no further feedback action will be taken until the correction is fully seen in the next analyzer update. For a feedforward signal change, the PID can wait till the full effect of the feedforward is seen eliminating any extraneous corrections from feedforward timing errors. Additionally if a threshold sensitivity limit (deadband) is used to only update the PV when there is a sustained significant change since the last update, the enhanced PID will not respond to measurement noise. Finally, changes in analyzer update time do not affect the enhanced PID because the PID execution time is not fixed but varies with the update time interval. Consequently, the enhanced PID helps deal with a variable analysis time that occurs when samples are manually handled.

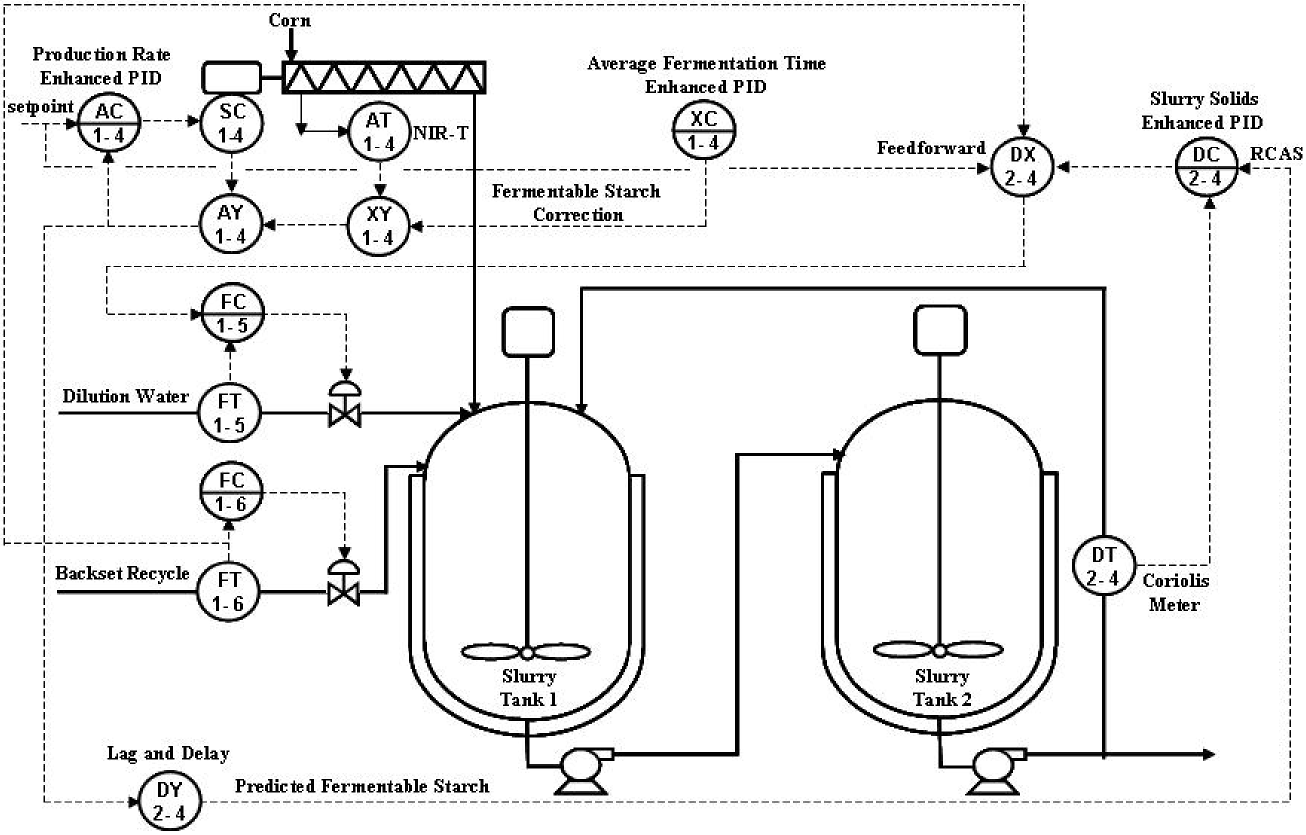
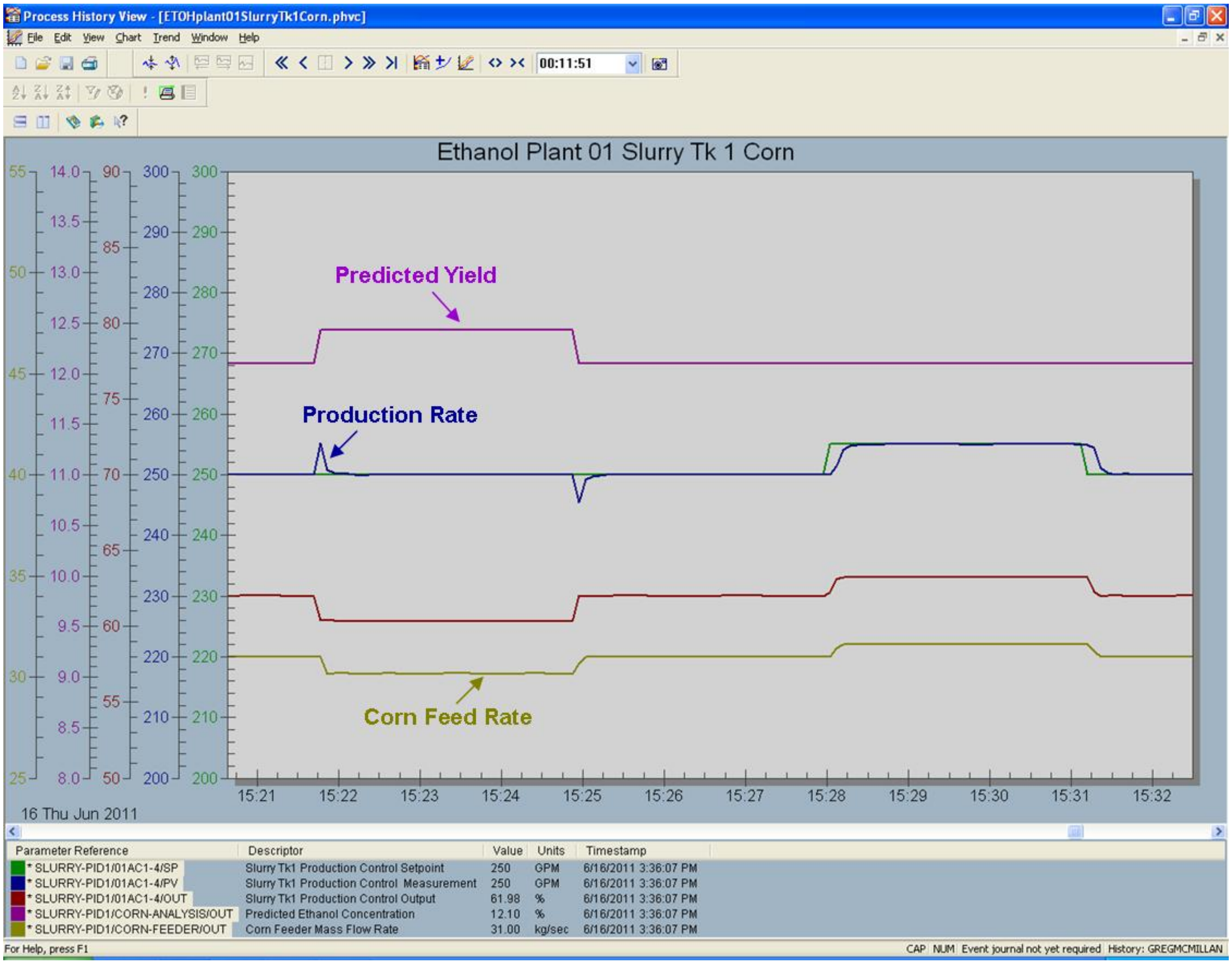


Figure 3. The control system provides rapid optimization of ethanol yield using the enhanced PID for control of production rate, slurry solids, and time to reach the ethanol endpoint (fermentation time).

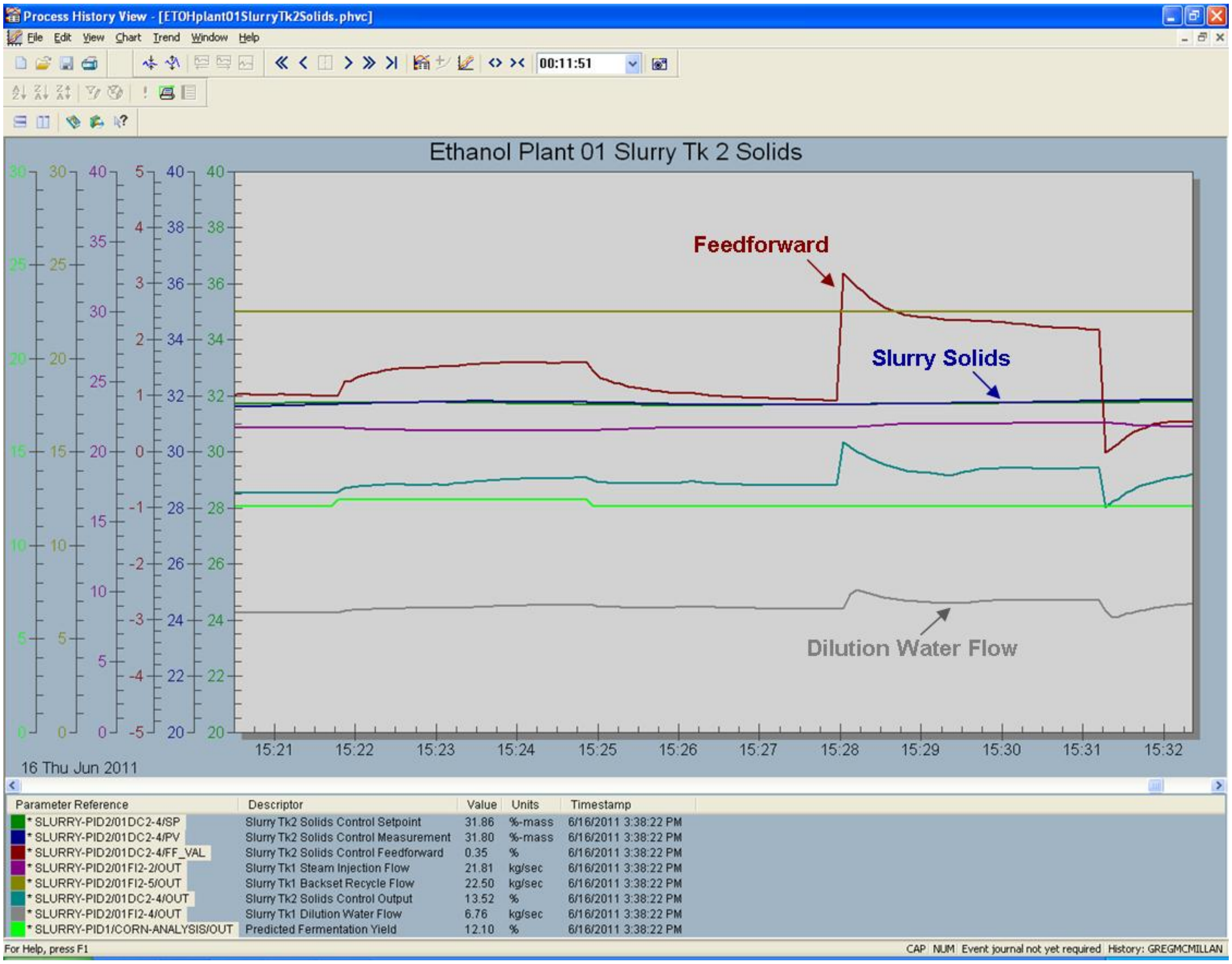
The front end of ethanol plant consists of slurry, liquefaction, cooling, and fermentation areas. The basic control system for the front end of an ethanol plant controls the temperature and pH of the fermenter feed. The fermenter may have temperature control as well. The pH in the fermenter will fall over the course of the batch from acetic acid and lactic acid formation. While there is an optimal pH for yeast growth and product formation, the effect of the change in fermentation batch cycle time is not thought to significant enough to warrant pH control in the fermenter. The control system developed for optimization of ethanol yield in the front end uses three enhanced PID controllers shown in Figure 3.

The first enhanced PID AC1-4 controller is on the first slurry tank. The PID is a production rate controller with its PV and SP scaled 0-400 gpm ethanol production rate. The PV is computed based on corn feed rate and corn analysis of the percent of fermentable solids, an inferential measurement of ethanol yield. The Dynamic Reset Limit is enabled so that PID does not try and drive its output faster than the corn feeder can respond. The output of the PID manipulates corn feeder speed. For the slurry tank model running 24x real time the analyzer will pull a sample every 4 seconds and communicate a result with a latency of 2 seconds. The PID refresh time is chosen to be 6 seconds. If the change in analyzer from the last significant change is less than the threshold sensitivity setting of 2 gpm for production rate, there is no update to the PV and no change in PID output. Since the PID will wait till the effect of its feedback correction is seen and will ignore noise, the PID gain can be set equal to the inverse of the process gain to provide a full immediate correction in feeder speed to a significant new analysis result or a new production rate setpoint. In order to prevent an oscillatory response from this great increase in gain, the reset time must also be decreased to be about equal to the loop deadtime. This decrease in reset time is counterintuitive because normally one would think of increasing the reset time to suppress oscillations. The increased reset action suppresses the proportional step when the measurement is reported returning to setpoint. Changes in analyzer sample time or communication latency do not affect the tuning because PID action is suspended until there is an update. Figure 4a shows that for changes in predicted yield (fermentable starch), the PID makes a single adjustment in corn feed rate bringing the production rate back to setpoint. The figure also shows that production setpoint changes can be easily made to match corn supply, market demands and back end constraints.



Parameter Reference	Descriptor	Value	Units	Timestamp
🟩 * SLURRY-PID1/01AC1-4/SP	Slurry Tk1 Production Control Setpoint	250	GPM	6/16/2011 3:36:07 PM
🟦 * SLURRY-PID1/01AC1-4/PV	Slurry Tk1 Production Control Measurement	250	GPM	6/16/2011 3:36:07 PM
🟥 * SLURRY-PID1/01AC1-4/OUT	Slurry Tk1 Production Control Output	61.98	%	6/16/2011 3:36:07 PM
🟪 * SLURRY-PID1/CORN-ANALYSIS/OUT	Predicted Ethanol Concentration	12.10	%	6/16/2011 3:36:07 PM
🟨 * SLURRY-PID1/CORN-FEEDER/OUT	Corn Feeder Mass Flow Rate	31.00	kg/sec	6/16/2011 3:36:07 PM

Figure 4a. Changes in fermentable starch or in production rate setpoint are rapidly handled by an enhanced PID for production rate control on slurry tank 1 by directly manipulating corn feed rate

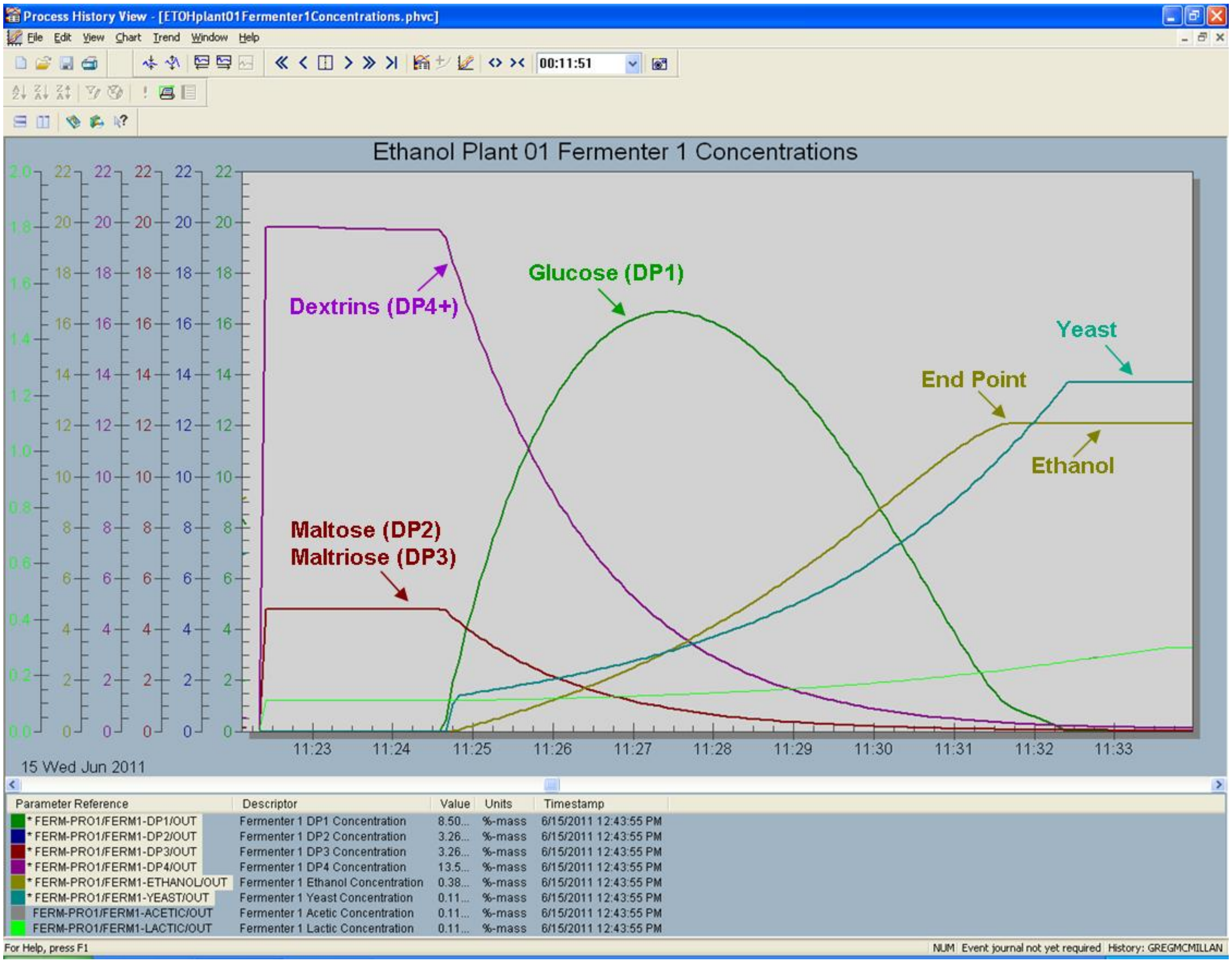


	Parameter Reference	Descriptor	Value	Units	Timestamp
🟩	* SLURRY-PID2/01DC2-4/SP	Slurry Tk2 Solids Control Setpoint	31.86	%-mass	6/16/2011 3:38:22 PM
🟦	* SLURRY-PID2/01DC2-4/PV	Slurry Tk2 Solids Control Measurement	31.80	%-mass	6/16/2011 3:38:22 PM
🟥	* SLURRY-PID2/01DC2-4/FF_VAL	Slurry Tk2 Solids Control Feedforward	0.35	%	6/16/2011 3:38:22 PM
🟪	* SLURRY-PID2/01FI2-2/OUT	Slurry Tk1 Steam Injection Flow	21.81	kg/sec	6/16/2011 3:38:22 PM
🟫	* SLURRY-PID2/01FI2-5/OUT	Slurry Tk1 Backset Recycle Flow	22.50	kg/sec	6/16/2011 3:38:22 PM
🟦	* SLURRY-PID2/01DC2-4/OUT	Slurry Tk2 Solids Control Output	13.52	%	6/16/2011 3:38:22 PM
⬜	* SLURRY-PID2/01FI2-4/OUT	Slurry Tk1 Dilution Water Flow	6.76	kg/sec	6/16/2011 3:38:22 PM
🟩	* SLURRY-PID1/CORN-ANALYSIS/OUT	Predicted Fermentation Yield	12.10	%	6/16/2011 3:38:22 PM

Figure 4b. Changes in fermentable starch or in production rated setpoint are rapidly handled by an enhanced PID for solids concentration control on slurry tank 2 by directly manipulating dilution rate

The second enhanced PID DC2-4 controller is on the second slurry tank. This PID is a slurry solids concentration controller with its PV and SP scaled 0-40% weight percent fermentable solids. Slurry solids inferred from a Coriolis meter density measurement in a recycle stream. The output of the PID manipulates the dilution water to the first slurry tank. Since the manipulation is to the first slurry tank while the solids is in the second slurry tank, there is an equivalent deadtime from the residence time of the two slurry tanks plus mixing and injection delays. The total loop deadtime measured online is about 80 seconds in the model. A feedforward signal is computed for the dilution water based on corn feed rate, steam injection, and backset recycle. An update time of 12 seconds is set on the inferential measurement of fermentable solids to ignore feedforward timing errors. A deadtime block with a deadtime parameter of 80 seconds in the external feedback path from the analog output to the PID provides deadtime compensation. A threshold sensitivity setting is used to ignore measurement noise.

Since the PID compensates for deadtime, ignores noise, and waits out feedforward timing errors, the PID gain can be increased to provide a faster setpoint response. The feedforward signal from the change in Slurry Tank 1 shown in Figure 4a prevent the changes in production rate from affecting the solid concentrations in Slurry Tank 2 as shown in Figure 4b. The feedforward signal is the production rate setpoint minus the water flow from other sources such as backset. The remote cascade (RCAS) setpoint is the desired solids concentration multiplied by a fermentable starch factor predicted by the corn analyzer. The prediction passes through a delay and lag set equal to the deadtime and residence time, respectively, so the change in setpoint coincides with the change in solids measurement from a change in corn feeder speed based fermentable starch.



Parameter Reference	Descriptor	Value	Units	Timestamp
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🟦 * FERM-PRO1/FERM1-DP2/OUT	Fermenter 1 DP2 Concentration	3.26...	%-mass	6/15/2011 12:43:55 PM
🟥 * FERM-PRO1/FERM1-DP3/OUT	Fermenter 1 DP3 Concentration	3.26...	%-mass	6/15/2011 12:43:55 PM
🟪 * FERM-PRO1/FERM1-DP4/OUT	Fermenter 1 DP4 Concentration	13.5...	%-mass	6/15/2011 12:43:55 PM
🟨 * FERM-PRO1/FERM1-ETHANOL/OUT	Fermenter 1 Ethanol Concentration	0.38...	%-mass	6/15/2011 12:43:55 PM
🟦 * FERM-PRO1/FERM1-YEAST/OUT	Fermenter 1 Yeast Concentration	0.11...	%-mass	6/15/2011 12:43:55 PM
⬜ FERM-PRO1/FERM1-ACETIC/OUT	Fermenter 1 Acetic Concentration	0.11...	%-mass	6/15/2011 12:43:55 PM
🟩 FERM-PRO1/FERM1-LACTIC/OUT	Fermenter 1 Lactic Concentration	0.11...	%-mass	6/15/2011 12:43:55 PM

Figure 5. A HPLC historization of SSF batch profiles shows glucose production in saccharification and the glucose consumption for ethanol production and the time to reach the end point in fermentation

The third enhanced PID XC1-4 controller uses a High Performance Liquid Chromatograph (HPLC) measurement of ethanol profiles in simultaneous saccharification and fermentation (SSF) batches.

Saccharification uses an enzymatic reaction to convert maltose, maltriose, and higher polymer dextrins to glucose. Fermentation employs yeast to produce ethanol from glucose. In older plants, the saccharification and fermentation are done in separate vessels. SSF decreases the total batch cycle. The HPLC provides an inferred measurement that is a running average of the fermentation time (time to reach ethanol endpoint) in the most recent SSF batches. The model has multiple SSF vessels each with a saccharification-fermentation time of 8 minutes (240x speedup), 80 seconds (24x speedup) for charging, and 40 seconds (24x speedup) for draining and preparing for next batch. When the HPLC indicates the ethanol has reached the desired end point as, the running average of batch times is updated. Note that the actual batch cycle time is fixed. The average is the time to the desired end point. After an initial delay of 10 minutes, a new batch time result is available and the running average is updated every 2 minutes in the model. The update is faster for a decrease in batch time from an increase in actual fermentable solids. The enhanced PID output biases a correction to analyzer measurement of fermentable solids, which changes the inferred production rate. The first slurry tank controller correspondingly adjusts the corn feeder rate to bring the production rate back to setpoint. An unmeasured increase in fermentable solids will show up as an early achievement of the batch end point resulting in a cutback in corn feed rate providing an immediate improvement in ethanol yield.

CONCLUSION

A corn analyzer can provide a rapid optimization of ethanol yield by reducing the corn feed rate for an increase in fermentable solids from higher seed genetic capability and improved corn processing. An innovative control strategy uses inferential measurements of production rate control, fermentable solids concentration, and fermentation time as the process variables for enhanced PID controllers originally developed for wireless applications. The enhanced PID ignores noise and by patiently waiting for an updated inferential measurement offers faster and more robust tuning that is not affected by long or variable discontinuous update times in the inferential measurements.

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