Flexible Distributed Energy & Water from Waste for Food and Beverage Industry

Phase II Final Report

March 2014

Ruijie Shi
GE Global Research
Schenectady NY 12303

Acknowledgment: “This material is based upon work supported by the Department of Energy under Award Number DE-FC26-08NT05870”

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1 Introduction

Food and beverage plants inherently consume a large quantity of water and generate a high volume of wastewater rich in organic content. On one hand, water discharge regulations are getting more stringent over the time, necessitating the use of different technologies to reduce the amount of wastewater and improve the effluent water quality. On the other hand, growing energy and water costs are driving the plants to extract and reuse valuable energy and water from the wastewater stream. An integrated waste-to-value system uses a combination of anaerobic digester (AD), reciprocating gas engine/boiler, membrane bioreactor (MBR), and reverse osmosis (RO) to recover valuable energy as heat and/or electricity as well as purify the water for reuse. While individual anaerobic digestion and membrane bioreactors are being used in increasing numbers, there is a growing need to integrate them together in a waste-to-value system for enhanced energy and water recovery. However, currently operation of these systems relies heavily on the plant operator to perform periodic sampling and off-line lab analysis to monitor the system performance, detect any abnormal condition due to variations in the wastewater and decide on appropriate remedial action needed. This leads to a conservative design and operation of these systems to avoid any potential upsets that can destabilize the system.

1.1 Program Introduction

This DOE sponsored project aims at developing and demonstrating an advanced monitoring and controls solution that optimizes the process operation for enhanced energy and water recovery with reduced chemical and energy consumption, while maintaining reliable operation through continuous online monitoring and automation. The proposed monitoring and control technology was developed in Phase I of the program. In particular, the proposed solution employs a combination of online sensors, simplified physics-based models of key process units, and supervisory control for smooth operation of the integrated system combining both feedback regulation as well as feedforward correction for measured/estimated variations or disturbances. The monitoring and control solution is developed with an initial focus on the brewery industry, which comprise a large segment of the food and beverage industry generating large volumes of wastewater with high organic content, with the produced biogas capably to replace 10% ~ 25% the plant energy need. However, the solution was developed within a generic framework that allows rapid extension to other segments of the food and beverage industry.

In Phase I of the program (mainly in 2009 and 2010), the foundation of the monitoring and control technology for wastewater from Food and Beverage plants was developed, referring to Phase I final report (submitted in 2011). The overall scheme of the monitoring and control solution is based on Extended Kalman Filter (EKF), which takes in the process input measurements, simulate the process outputs based on the process model and compare the calculated process outputs with the measured outputs, then use the difference to adjust the process model and estimate the process disturbances and the process model parameter changes, therefore the estimated process states and parameters can provide better information about the process unknown quantities and trends.

Phase II of the program is to demonstrate the technology in a wastewater treatment plant in food and beverage industry. In the first half of 2011, work progress towards this goal led to collaboration with the largest beer brewer Anheuser-Busch InBev. (ABI) to implement the technology in their effluent treatment facility located in Van Nuys, CA. The proposal for Phase II was approved by Department of Energy (DOE) in September 2011 and the Phase II kicked off in October 2011, and finished by the end of 2013. This report is to summarize the technical progression and achievements as well as what learned from the Phase II of the program.

The goal of Phase II of the program is to implement the advanced online monitoring and control technologies developed in Phase I into the industrial wastewater treatment plant, modify the technologies to fit to the particular industrial application requirements, test the technology in the plant site field operation and observe the benefits. This pilot demonstration in a real-world plant is to mature the technology, enhance the plant overall system stability and reliability, and to accelerate acceptance of the technology in broad food and beverage industry.

1.2 Program Phase II Plant Demonstration

Plant demonstration of the monitoring and control solution in Phase II of the program requires to prepare the wastewater plant ready for installation of some online instruments, modify the existing process model to fit to the plant operation, test run and analyze the results. Iterations may be in need to improve the performance of the solution in the field application for better use in real plant operation. It provides the opportunity to test all the assumptions and theoretical models developed in Phase I of the program, and promote the readiness of the technology for acceptance of the technology in broad food and beverage industry.

To apply the solution developed in Phase I of the program, the plant was required to install extra instruments in additional to the existing flow and pH online measurements, mainly Total Organic Carbon (TOC) and total Inorganic Carbon (TIC) contents in the inlet and outlet streams in the plant, the biogas composition measurements and the communication and computer system, including the Programmable Logic Controller (PLC); so the first step of the project was to prepare the plant ready to install these online instruments.

The second step was then to install these online instruments and equipment, obtain other related process measurements to the computer running the EKF. In the meanwhile, the model inside the EKF was modified to follow the real plant process, and ran the tests with real process data.

The following step was to analyze the results, based on the extra information provided by the EKF scheme, provide the operational trends for process monitoring and supervisory control suggestions to the plant operator to make the plant more reliable and better performance.

Phase II of the program is a cost-share project, sponsored by DOE with cost share from GE as well as ABI. The project has been carried out by a team from GE Global Research Center, GE Water Process Technology and ABI cooperation and LA plant. The team worked together to overcome various technical and practical difficulties and finished tasks in the project in about two years.

1.3 Phase II Plan and Execution

The overall plan for Phase II is shown in Figure 1 below for the tasks and the timeline. The five main tasks include (1) installation of sensors and PLC, (2) analyzing the process data and updating the model, (3) updating and implementing the monitoring algorithm, (4) updating and implementing the control algorithm, and (5) quantifying and documenting the benefits of the technology.

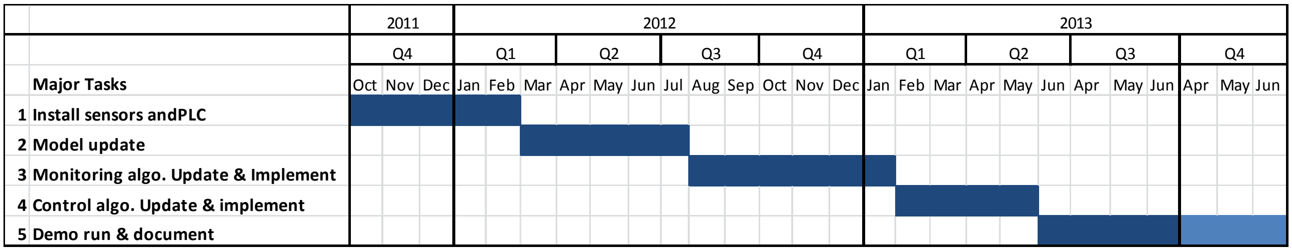

Figure 1 Overall Program Plan for Phase II

Phase II of the program stated in October 2011 and the original plan was to finish the project in Q1 2013. Due to the delay in the beginning of signing service agreement and limited resources on PLC implementation, the program was extended to end of 2013 (no-cost extension).During the execution process, the team sent out quarterly report to DOE for project progress as required in the program.

The online TOC analyzer and the Biogas analyzer were installed in the ABI Van Nuys, CA plant in February 2012. The process model update was finished in summer 2012. The task for EKF software update and PLC code implementation were finished by the end of 2012. In February 2013, the online EKF monitoring solution was installed in the ABI plant. In the following months, the team tried hard to maintain the online instruments, modified the software to adapt to the plant changes, ran the tests online with the plant operation. The results were analyzed and supervisory suggestions were provided to the plant operator.

The plant tests indicated that the EKF monitoring solution is capable to run real-time in the plant site on the PLC platform. It can match up the majority process measurements, such as biogas flow and compositions, reactor pH and Alkalinity, TOC and TIC, but it showed a relative large difference in prediction of the reactor VFA. The monitoring solution is able to detect the unmeasured distances to the plant, and able to trace the source of the disturbances; The EKF solution has been further developed to include the lab measurements. Based on the EKF results, suggestions for process control and changes were given to the plant operator. Some of the suggestions were carried out indicating improvements on process performance.

The plant tests showed that the biogas analyzer can work fine in the plant with special design to mitigate the condensate problem. The TOC analyzer can work for about one year time in the field without much problem, then it shows many issues with worn out parts and operation reliability issues. A constant operational problem in the wastewater plant application environment is that the TOC analyzer sampling subsystem is prone to get clogged and insufficient sample stream to the analyzer sensor. More design improvements are required to mature the TOC analyzer enough for WWTP real plant applications. The

PLC hardware and the communication system work fine, but extra measures on software execution was required to avoid the occasional Watch-Dog time out problems. To effective implement the supervisory control suggestions, some essential process changes are in need to verify the effectiveness of the supervisory control solution.

2 Plant Site Preparation and Installation

2.1 Plant site Introduction

The generic wastewater treatment process studied in Phase I includes the two-stage anaerobic digestion process, which can be simply described as EQ (Equalization tank) + AD + recycle, where the influent wastewater enters a EQ tank (buffer tank, or called PA tank, Pre-Acidification tank), then goes into an AD reactor followed by part of the AD effluent flow recycled back to EQ/PA tank, as shown in the following Figure 2.

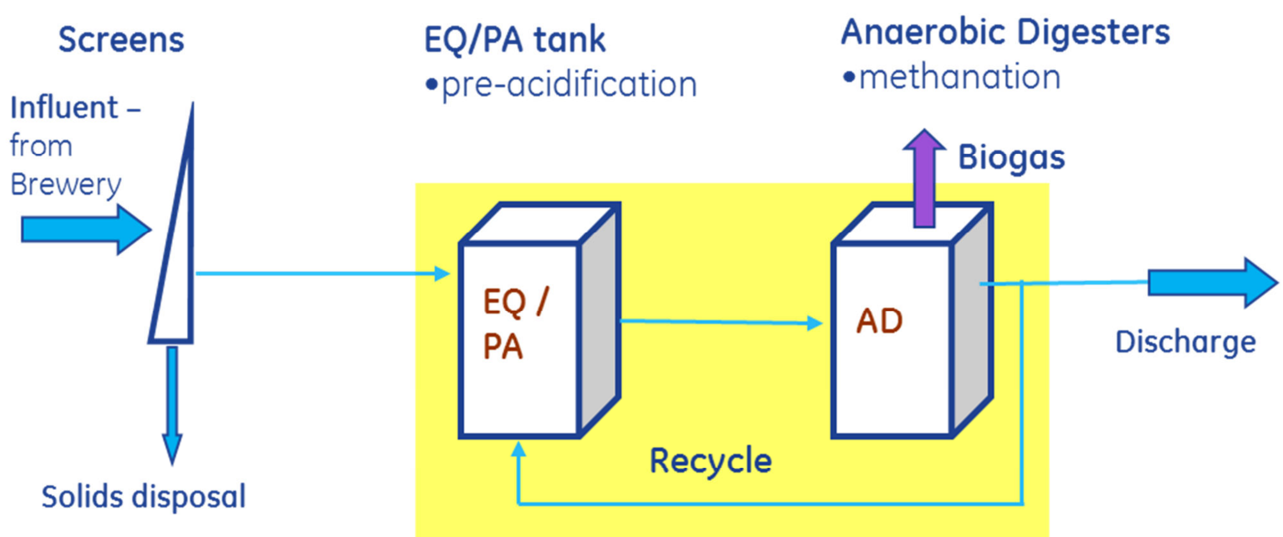

Figure 2 General diagram of a wastewater treatment plant with AD reactor

The AB's BERS (Bio-Energy Recovery Systems, see Figure 3) turns the nutrients in wastewater into renewable biogas. AB started BERS in their New Jersey yeast facility in 1985 and now has installations in ten breweries in the US. BERS now provides AB 9.5% of their fuel needs (all refer to website www.anheuser-busch.com/s/index.php/our-responsibility/environment-our-earth-our-natural-resources/energy/). The generic process configuration used in Phase I study of the program is generally applicable to the ABI BERS plant in Van Nuys, CA for the Phase II plant demonstration of the process monitoring and control solution.

Figure 3 BERS Plant in Anheuser-Busch plant

This BERS plant is the Waste Water Treatment Plant (WWTP) for the wastewater from the main beer production process. the wastewater stream is generally of flow in 1~2 million gallons per day, and has a high level of COD (typically 2000-6000 mg/L). The process in the plant has 2 equalization (EQ) tanks and 4 USAB anaerobic digester (AD) reactors (tagged as R1, R2, R3 and R4 respectively). The effluent stream from this WWTP plant goes to the local municipality wastewater treatment plant. The plant generally runs well in treating the wastewater and turn most of the organic in the influent stream to biogas, which has about 70~80% of CH_4 and 15~25% of CO_2 with a trace amount of H_2S. The generated biogas is used for combustion in boilers in the main plant to substitute Natural Gas (NG), and it can replace about 10% of the NG demand for the main plant operation.

In the daily operation, the BERS plant is subject to huge disturbances from the main plant operations, especially any large discharges or leaks, sometimes, the startup and shutdown processes or product shifting. Occasionally, the plant may need to bypass some of the influent flow directly to the outlet stream to cope with large disturbances. The BERS plant may also suffer the excessive biomass loss problem in some of the reactors over some operation periods, this may lead to operational stability issues and a biomass washout, and cause a completely AD reactor shutdown.

As many typical WWTP's, this plant has the online flow measurements for the influent, the feed flow to each reactor, the effluent from each reactor, and the biogas flow. It has the liquid level and temperature online measurements of the EQ tank as well as the pH measurements of EQ and each UASB reactor. The plant also conducts lab measurements once a day or once a week for COD, TSS, VSS, Alkalinity, VFA and biomass content in the reactor. However, it lacks of online measurements of wastewater strength just like most other WWTP's. This is a key limiting factor for online process monitoring and control applications. This is the reason we start with installing more online instruments in the customer plant.

The ABI plant is driving to reduce the water usage, increase the biogas production and reduce the chemicals used in the BERS plant to reduce the overall operation cost. Our effort in the project provides extra paths for the customer to achieve their ultimate goals.

2.2 Plant Site Preparation

Customer plant site preparation was required to install the online instruments and PLC system in the beginning of the project. It was mainly the mechanical (piping) work and electrical work.

2.2.1 Mechanical and piping preparation

The mechanical work includes to draw process sample liquid flows and biogas flow to locations identified for the online TOC analyzers and the Biogas analyzer, add additional pipe for compressed air to the instruments, as well as to draw the exhaust flows from the sensors to proper places for safe disposal. It is also in need to add proper flow control devices (such as valves) as well to tie in all the piping connections.

One local subcontractor was obtained to perform the onsite mechanical preparation. The work was completed in early February 2012 to provide the necessary condition for online instrument installation.

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2.2.2 Electrical and signal wire preparation

The electrical work includes to draw power lines to the instrument locations, to install wires and terminal blocks to connect instrument output signals to the plant PLC, and install the communication equipment to connect the existing plant PLC and the PLC for this plant demonstration.

Working with ABI, the schematic layout of the preparation work was completed by the end of 2011, and a qualified subcontractor was also identified for the electrical work. The majority work was done by mid February 2012. The remaining connection work was finished during the hardware installation time period in late February 2012.

2.2.3 Historical Data Collection

To calibrate the process model and identify the proper model parameters, with the help from ABI, the team was able to obtain some historical operation data, including 3-year daily plant operation data, and some daily report data. These data were used for model validation study, plant working condition analysis and historical performance analysis.

2.3 Instrumentation Preparation and Installation

According to the requirements of the monitoring and supervisory control solution developed in Phase I, Biogas analyzer, two units of TOC analyzer and PLC are in need for the plant demonstration project.

By end of 2011, the TOC/TIC analyzers were identified, purchased and delivered to the customer plant site; the biogas sensors were purchased, assembled and tested; the PLC and the associated connection hardware were purchased and shipped to the destinations. The plant installation was planned in late February 2012.

2.3.1 Biogas analyzer

Similar as lab experiment setup in Phase I, infrared gas sensors GasCard NG from Edinburgh Instruments were chosen to measure methane and carbon dioxide concentrations in the biogas sampled from plant, see Figure 4. The choice was the latest generation in the product series with better stability and lower power consumption, furthermore, several aspects for the biogas sensor application were enhanced through engineering design for better adaptation to the plant environments, such as enclosure box, sample gas pressure and flow regulation, moisture and corrosion solutions.

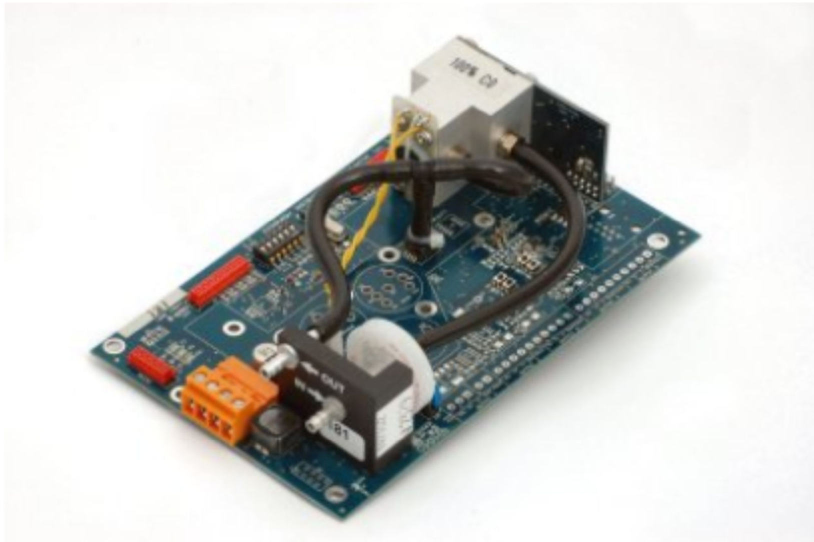

Figure 4 Edinburgh NG Gascard for CH_4 and CO_2

Figure 5 Biogas Analyzer Installed in ABI Plant (Feb., 2012)

In quarter 2011 Q4, Tech Engineering & Construction Inc. (TEC), a US distributor for Edinburgh Instruments, was attained to assemble the sensing system together, make offline tests and perform the calibration. The unit was installed in late February 2012 as shown in Figure 5.

The Biogas Analyzer includes two sensor elements, for CH_4 and CO_2 respectively, and biogas sample pre-processing elements. It was specially designed, assembled and tested for the application. The analyzer measures the volumetric concentrations of CH_4 and CO_2 components respectively in the biogas from the reactors. The real-time online measurement data are transferred to plant control PLC and the PC historian.

2.3.2 TOC/TIC analyzer

As other wastewater treatment facilities, the wastewater treatment plant for the ABI brewery is to reduce the organic content of the wastewater to a desirable level. As shown in Phase I simulation study, the organic and inorganic carbon balance is crucial to indicate the performance of the bio-chemical process. Real-time measurements of TOC/TIC (Total Organic Carbon/Total Inorganic Carbon) of the wastewater influent, final effluent and intermediate flow are critical for monitoring and control of the process.

With further survey and comparison of the instruments available in the market, the Sievers InnovOx online TOC analyzer (see Figure 6) from GE Analytical Instrument was identified to measure the TOC/TIC of the wastewater for Phase II. The same type analyzer had been used in the lab tests in Phase I of the program. According to the needs of implementation of the monitoring and control technology, two units of the analyzer, each with a capacity of 5 streams, are required for the program.

Two units of the Sievers InnovOx online TOC analyzer from GE Analytical Instrument were installed in the plant just next the process line. One unit was designated to test the raw influent and the effluent for the EQ tank, and the other unit was used to test the effluent streams from two reactors. These analyzers were equipped with filter panels, sample cups and sampling devices. For each sample stream, the analyzer measures the Total Organic Carbon (TOC), Total Inorganic Carbon (TIC), Total Carbon (TC) and Non-Purgeable Organic Carbon (NPOC).

Figure 6 TOC/TIC Analyzer: 5 stream InnovOX online TOC/TIC Analyzer

With the assistance from personnel at the AB brewery BERS facility, the team was able to install and test the online TOC/TIC analyzers in February 2012

2.3.3 PLC system

To run the monitoring and control algorithms while avoid any interference with the normal production operation, a dedicated PLC was planned to be installed onsite the plant to make online data communication and the computation, and another PLC was planned to facilitate the improvement work and offline tests. To connect the sensor output signals to the plant operation system, electrical terminal blocks and communication items are also required to be installed onsite the plant. The PLCs were contribution from GE Intelligent Platforms.

To connect the online PLC for this program to the plant existing operation PLC, a set of TCP-Data Highway Plus gateway and items of Flex IO terminal block, power supply, remote I/O adapter and analog input adapter were also identified, purchased and shipped to the plant for installation in February 2012.

One PLC from GE Intelligent Platforms was installed in the plant control room with cable connection to the existing plant control PLC, which collects all the process data, including the measurements from the TOC analyzers and the biogas analyzer. The GE PLC is also connected to the PC Historian where selected plant operation data and all the online measurement data were recorded. The Historian software was installed to a separate PC machine.

2.4 Software Preparation and Installation

2.4.1 Process model modification

The process model used in Phase I development of the program was based on the general process configuration and not specific to the ABI plant configuration. One obvious difference is that the general configuration has just one AD reactor, but the real ABI plant has 4 AD reactors. In plant operation, each reactor may work online or shut off at any given time. Though these reactors are feed with the same feedstock, but they may have significant different operation status and characteristics, e.g., the accumulated biomass amount in one reactor may be quite different from the other reactors; some reactor seems more prone to lose biomass than other reactors. The plant operation data recorded in Q2 and Q3 2012 showed that the two AD reactors can have significant performance difference under the same operation conditions. Therefore, one lumped general reactor cannot represent the different operational states of different reactors. It is necessary to modify the process model to have multiple reactors.

In the historical operation data, the plant ran mostly with only two AD reactors online in the same time. So the process model was modified to have two different reactors: each has its own states and specific parameters related to particular reactor. The biochemical reaction parameters are treated into two different categories: if they are not subject much variation with special conditions, they are s treated as common parameters and have the same values for the two reactors; if they are prone to get affected by reactor specific conditions, they have different values for the two reactors, such as biomass decay rate and biomass growth rate.

The process modification work was carried out in the summer 2012, and then the EKF and associated functions in the algorithms were also modified to accommodate the changes in the process model.

2.4.2 Offline simulation, parameter setting

Before the hardware installation, the model parameters were only adjusted based on lab tests and operation data in other plant. Directly using those model parameters for Van Nuys plant operation conditions led to large discrepancy between the simulation results and the plant measurements, e.g., the open loop simulation results gave more than 20% difference on biogas production rates compared to the plant measurement values.

With the collected online measurements and daily operation data from the plant, offline parameter identification work was performed in Q2 2012. The preliminary results were promising. The model with the identified parameters from multiple weeks of pseudo steady state operation data was able to match most of the measurements much closer, e.g., the difference between calculated biogas production rates and the measurement values was reduced to about 5%.

With the online data collection functionality available after February 2012, some process operation data was collected and used for offline preliminary model validation and parameter identification. Multiple weeks of the plant collected data were used as pseudo steady state operation conditions, and the EKF was used to tune the model parameters, especially the reaction kinetic parameters and the feed compositions.

The tuned PA and AD models were able to fit closer to the process data collected from the plant. As one example, for the week of 3/18 to 3/24 2012, Table 1 below shows the measured and estimated process variables. As can be seen, most of the 24 measured variables are closed matched up by the model estimated values with very small difference or the percentage differences; a few small quantity output variables (e.g., AD effluent SCOD content) have relatively larger mismatch of about 15%. Only the AD effluent VFA has significant difference. These differences come from the model approximations and measurement errors. Small quantity variables are hard to be measured accurately and tend to have relatively larger percentage differences between measured values and model estimated values. Overall, the model can match up the real plant process measured variables relatively close.

Table 1 Measured and Model Estimated Process Variables

Measured Value	Final estimated	Difference(%)	Output Variable
6.82	6.82	0	MixPAIn_pH
0.00017214	0.00017214	0	MixPAInf_SIN (mol/L)
144.03	148.78	3.2993	MixPAInf_TOC (mmol/L)
6.0962	6.0962	0.00056287	MixPAInf_TIC (mmol/L)
5.089	5.0878	-0.022795	MixPAInf_SCOD (gCODl/L)
6.131	6.1298	-0.018921	MixPAInf_TCOD (gCODl/L)
4.8829	4.8817	-0.023757	MixPAInf_SBOD (gCODl/L)
6.372	6.3846	0.19786	PA_pH
70	70	0	PA_level (%)
1.2225e+007	1.2302e+007	0.62416	PA2MixAD_Flow (L/day)
88.4	86.326	-2.3465	PA_TOC (mmol/L)
15.909	16.157	1.5563	PA_TIC (mmol/L)
14153	15081	6.5551	AD_biogas (m^3/day)
0.71	0.70586	-0.58357	AD_CH4gas_molfrac
0.2832	0.24564	-13.263	AD_CO2gas_molfrac
6.87	6.7997	-1.0226	AD_pH
0.0005	0.0021908	338.16	AD_VFA_mol (mol/L)
0.0227	0.023551	3.7483	AD_Alk_mol (mol/L)
27.263	23.137	-15.134	AD_MLVSS (g/L)
1.804	1.502	-16.739	AD_TCODeff (gCOD/L)
0.31	0.35946	15.955	AD_SCODeff (gCOD/L)
0.952	0.80462	-15.481	AD_VSSeff (g/L)
36.988	32.835	-11.229	AD_TOCeff (mmol/L)
23.582	28.198	19.574	AD_TICeff (mmol/L)

2.4.3 Software implementation on PLC platform

In Q3 2012, the EKF software was compiled into C language format, some interface wrapper was modified for PLC application. Then the code was converted to the PLC machine language. Due to the resource limitation on particular expertise, the test of this PLC machine language was postponed and carried out in Q4 2012. This work was limited by the license availability of the Matlab/Simulink Real-time Workshop toolbox and the Embedded Coder. The compiled EKF software was tested on GE Intelligent Platform. The simulation on the PLC was observed to run smoothly without issue. The results were compared with what came from the Matlab/Simulink simulation results. The two results overlap well and the difference no more than 0.1%.

For plant application, HMI (Human Machine Interface) was also designed. The HMI allows the operator to tune the EKF online without shutdown the operation, and also show the operator all the results from the EKF software, including the estimated unmeasured performance indexes, feed compositions and reaction parameters as well as other process parameters to facility the monitoring of the system. Figure 7 below is a screen copy of the initial setting of the tuning parameters in the HMI.

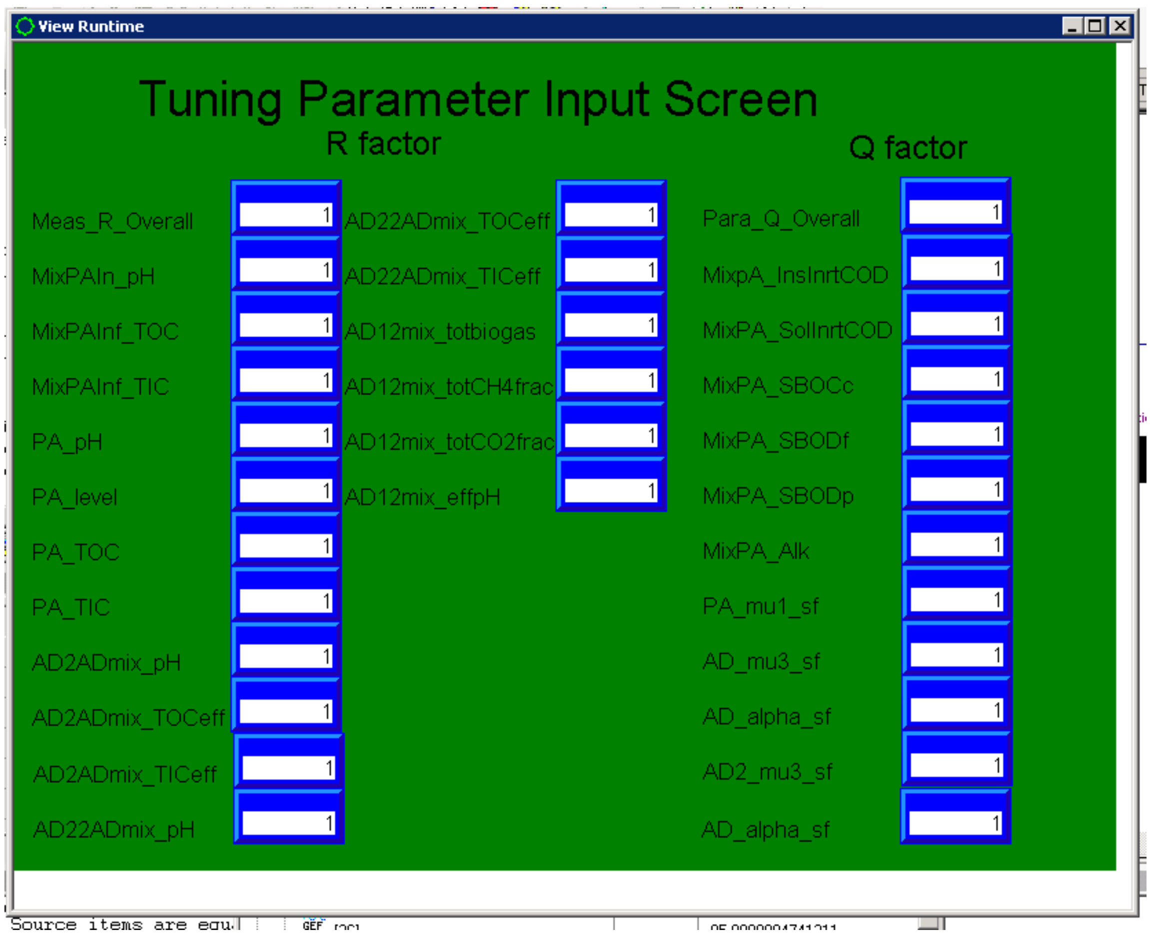

Figure 7 HMI Installed for Online EKF Tuning Factors

With all the necessary modification of the process model, identifying the proper model parameter for the ABI plant, update the EKF software and conversion of the software for the PLC platform, the EKF software became ready for online installation, which happed in February 2013. With the online operation of the software, the project then focused on the EKF real-time operation and improvements.

3 Plant Site Operation and Improvements

3.1 Hardware Operation and Improvements

3.1.1 Biogas analyzer issues and improvements

The Biogas Analyzer was a new design based on lab-validated core components (CH_4 and CO_2 Gascards) for online application. This type of instrument had been used in other applications (e.g., landfill gas measurement). However, the assembly was the first application for AD biogas measurement. The biogas analyzer worked well continuously in the first one and half month, and then calibrations and maintenance were required to be functional.

The main issue was found that water condensate was accumulated in the inlet tubing to the Gascards, which was believed to be entrained into the cards and affected the function of the measurements. The OEM manufacturer was called to check one card, and the other card was shipped to the plant to back online after re-calibration at the vendor's workshop. For the online test data, it was found that the percentages of CH_4 and CO_2 only vary within a relatively small range over the operation conditions, the average values are used as approximates for model validation for the time period when the Biogas Analyzer was not available online.

The methane card was calibrated with air and 50% span gas correctly but the analog signal was found out of the range when the process sample gas was switched in. After care examination, issue was determined to be within the electronic part of the card. It was still under warranty, so a new methane card was replaced.

In the meanwhile, the vendor was retained to work together for root cause analysis and approaches to overcome the issue. The sample biogas coming from the plant main pipeline with saturated moisture may carry water droplets. When passing through the gas pre-processing units (water-trap, H_2S scrubber), the temperature of the sample biogas drops, and conversion of H_2S in the scrubber increases its moisture level, more condensate forms. Most of the condensate was removed at the bottom of the scrubber, but the biogas sample gas still keep 100% RH (Relative Humidity) when entering into the pump (blower). The pressure increment though the pump leads to further condensation when the biogas exits the pump and the condensate accumulates in the tubing before getting into the Gascard.

Some design modifications were implemented in the plant field, such as bypassing the pump, straightening the flexible tubing inside the sensor box. Other design modifications were suggested to the vendor for further evaluation. For example, a second water trap together with a riser was introduced after the H_2S scrubber to separate out possible water droplets and drain away from the system. These mechanical approaches can move the condensate away but could not drive the sample gas away from saturation condition. Other approaches, mainly absorption and heating were also investigated in Q3.

For absorption approach, a quick study was done for several absorbents, such as Silica Gel, calcium-based material, Molecular Sieve, etc. Molecular Sieve has the best fit for the application due to the capacity and CO_2 presence. Then several grades of Molecular Sieve, mainly the different pore sizes, were deeply analyzed and contacted vendors to learn more details. At the end, it was found that, due to its capacity, the absorption approach incurs frequently media change services which is difficult for this continuous industrial plant application. So no further action was done for this approach.

The heating approach is to increase the sample gas temperature above its saturation temperature so that the sample gas is significantly under saturation even with the same amount of vapor. Two different heating elements are selected in the application, heating tape and box heater. In the filed modification, both elements were installed in the biogas analyzer.

Figure 8 below shows the improved biogas analyzer, which has been working in the field for approximately since September 2012. No condensate issue was noticed by the plant operator any more. In the newly improved system, the CH_4 and CO_2 cards are able to give proper signals and give reasonable measured values.

Figure 8 Improved Biogas Analyzer in the Plant

The Biogas Analyzer showed reliable performance after the modifications with the the above modifications for one year. There was no report of the moisture issue with the Biogas Analyzer in the winter season. The biogas CH_4 and CO_2 concentrations were well measured and the results have been recorded in the PC Historian.

Starting 9/21/2013, the cards for CH_4 and CO_2 could not give the results reliably, the readings becoming jumpy or kept as 103.1%, which is an indication of no signal from the detection cards. The two cards were removed out of the biogas analyzer and shipped back to the vendor. The vendor checked the two cards in his workshop and could not find any obvious reason for the malfunction, only found pollution on the IR windows and then cleaned the IR window.

After shipped back to the ABI plant, the cards were installed in the Biogas Analyzer. The methane card measures the biogas CH_4 composition correctly after troubleshooting in the initial period. However, the CO_2 card became totally non-functional after about one day time. The vendor stopped by the plant and examined/tested the card at the site and could not recover its functionality, so the vendor brought the CO_2 card back to his workshop to troubleshoot in consulting with the manufacturer or to swap for a new card for the application. The H_2S absorption column used in the biogas analyzer sample pre-treatment was opened and examined, and the results indicated that the H_2S absorbent was still in good condition. It was turned out to be a malfunctioned chip in the card, and after the key

component on the card was repaired, it began to function normally again (refer to Figure 9)
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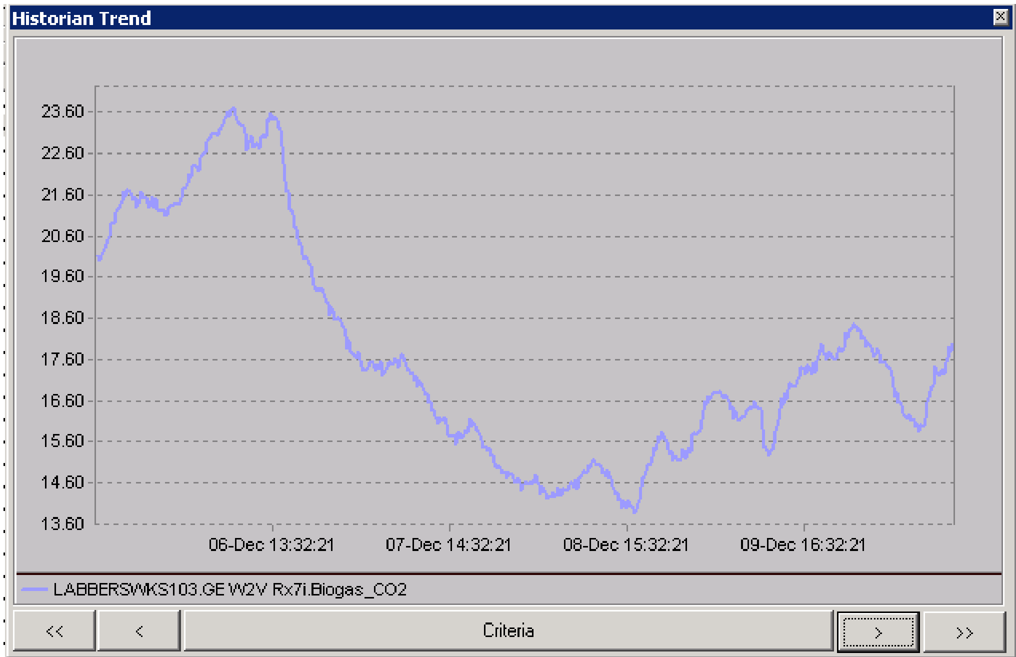

Figure 9 Biogas CO_2% Measurements after Repair

3.1.2 TOC analyzer issues and improvements

The TOC analyzers worked well in the first year in the field expect a few small hiccups, however, there were heavy maintenance work required for the two units during the online operation of the units. The sampling subsystem is prone to get clogged very easily with the organic solids in the wastewater stream, and back pulse mechanism inside the filter panel can not work well, so it requires the operator to manually the filter screen several times in a week.

In Q1 2013, a preventive maintenance was performed on the two units of the Sievers InnovOx online TOC analyzer installed in ABI plant. The unit which measures the raw influent and the EQ effluent has been working properly with most of its results in the expected range. The unit which measures the reactor effluents (R1 and R2 respectively) has recorded high frequency of results near to zero (out of expected range). Onsite observations indicated that it was often due to not enough sample liquid to flow into the sample cups.

Based on the observations, it was concluded that the main issue with the TOC analyzer unit for reactors was the sampling system. Working together with ABI personnel, the team cleaned the filter panel meshes several times, made filter panel valve position adjustments, rearranged the sampling tubing to bypass the peristaltic pumps (refer to Figure 10 and Figure 11 for pictures taken during the onsite trip). With these modifications, the sample has more chances to flow into the sample cups, and the resultant TOC and TIC measurements got improved. The long-term reliability of the improvement performance has been tested in the plant operation.

Figure 10 TOC Analyzer

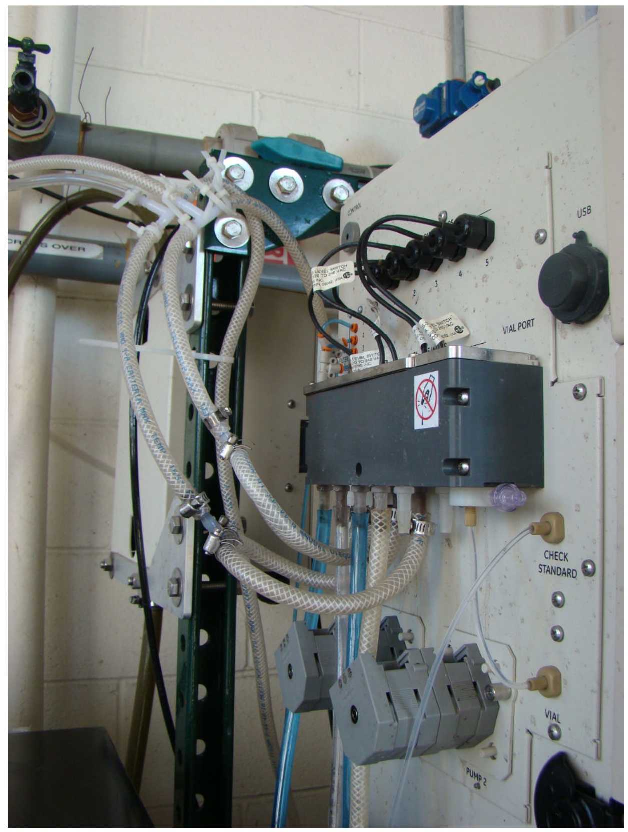

Figure 11 Modifcation of the Sampling Tubing

In Q2 2013, in one of the two units of the Sievers InnovOx online TOC analyzer installed in ABI plant, a test reactor leakage problem was detected in middle May 2013 and could not function. The instrument fault disabled the TOC/TIC measurements of the AD reactor effluent streams. A new oxidization reaction tube inside the TOC analyzer was replaced and the system could function well again.

In Q4 2013, the unit of the Sievers InnovOx online TOC analyzer installed in ABI plant for EQ influent stream and effluent stream showing reading results near zero all the time. With the onsite troubleshooting and remote consultation, the team was able to identify the issues with the internal tubes and external pump. Onsite vendor services were performed in December and the issues were finally corrected in January 2014, and the TOC analyzer unit became functional again (refer to Figure 12 and Figure 13).

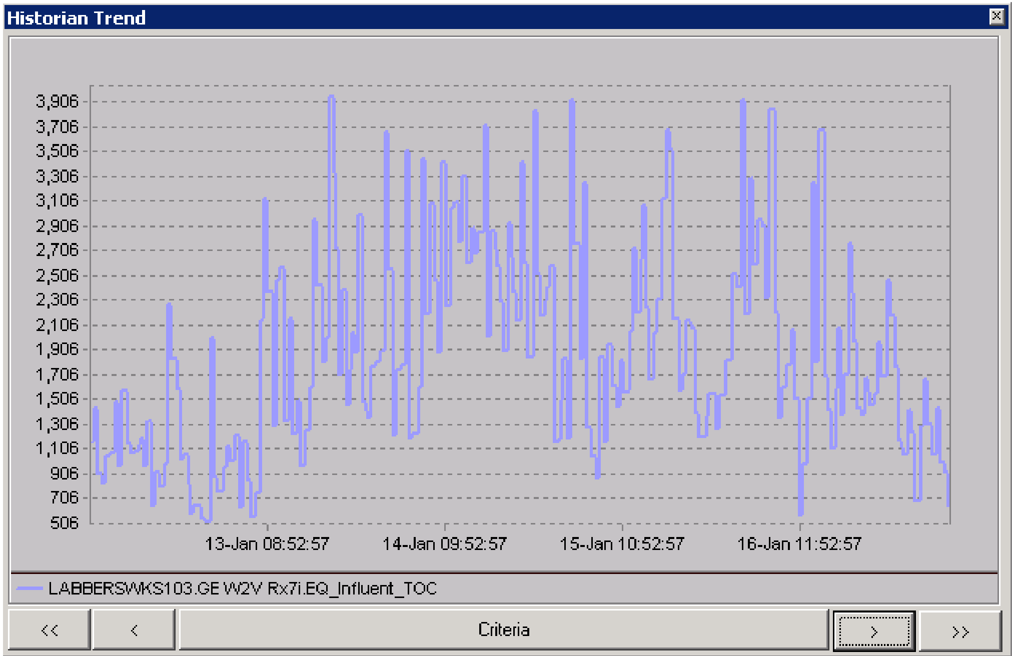

Figure 12 TOC (mg/L) Measurements of Influent Stream after Repair

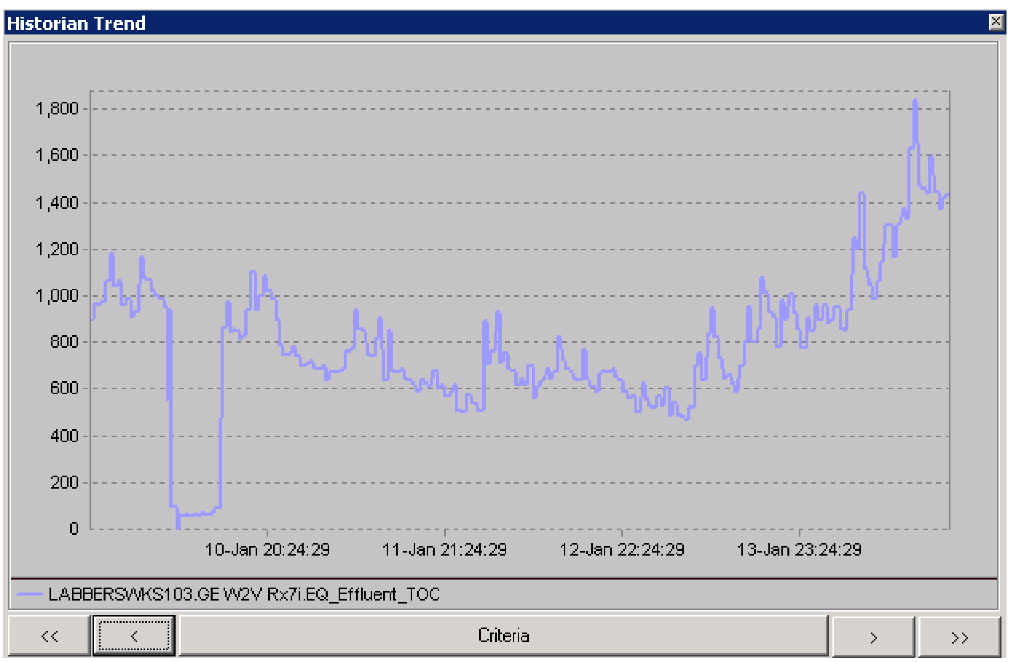

Figure 13 TOC (mg/L) Measurements of EQ Effluent Stream after Repair

3.1.3 Plant operation mode changes

The plant changed its operation mode during the field test period and the process model also need make the corresponding changes. One particular change was that the number of reactors online increased from 2 to 3 while our TOC analyzers have limited input channel and cannot have the extra reactor effluent TOC/TIC measured. In a compromised solution, the process model keeps two reactors but have the 3rd reactor volume and feed flow rate of the plant split into the two existing reactor in the model. And this makes the two reactors in the EKF model can handle the three reactors in the plant operation. All the corresponding changes were made to the EKF algorithm.

3.2 Software Operation and Improvements

3.2.1 Data Pre-processing

Early observation of the measured process data indicates significant process variations and measurement noises. For example, the raw feed influent flow can have large variations or noise (Figure 14) due to the stochastic nature of the wastewater discharged from the upstream, and the flow measurement noise introduced by the sensors. The flow process has the high frequency large noise, while many other measurements in the process are quite slow (e.g. slow TIC/TOC analyzer, which runs at 72 minutes/cycle). The EKF estimator cannot run at a high frequency. The large instant variation of variables, such as the raw influent flow rate, can introduce large error for the EKF at simulation time point if the instantaneous measured values are used for EKF estimation. Some other measured variables, like the measured EQ pH show in Figure 15, have spikes or outliers apparently due to sensor or transducer temporary malfunctions. A data pre-conditioning (pre-processing) process is necessary for the instant measured values with large noises or errors for the EKF application to avoid extra discrepancy.

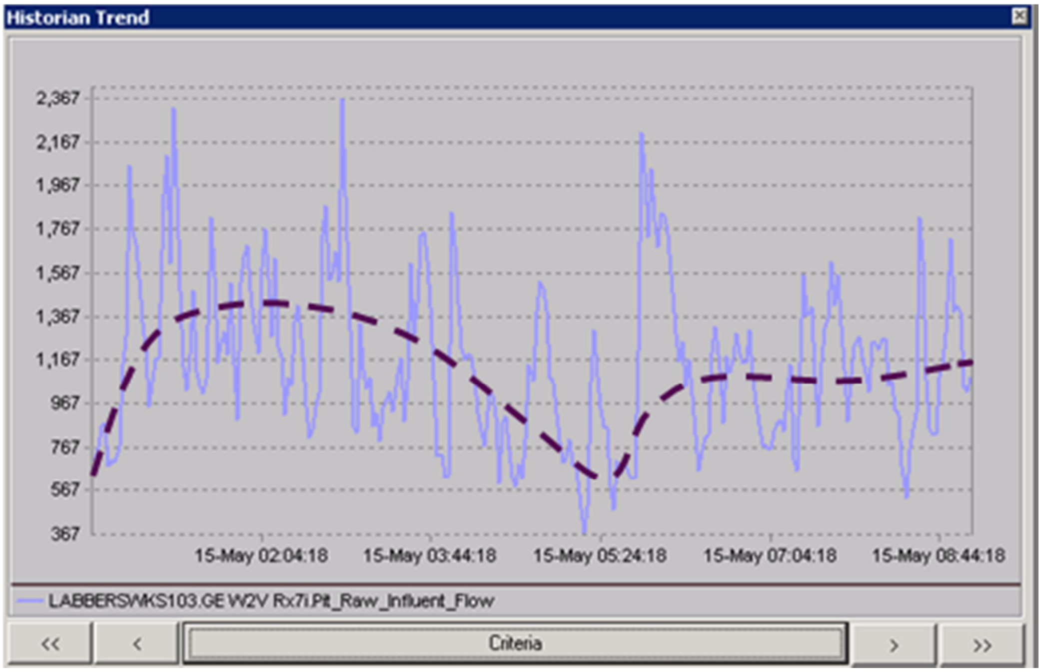

Figure 14 Raw Influent flow rate recorded by PC Historian with 2 minutes sampling interval for 9 hours. Dashed line is a smoothed process for the influent flow rate variation.

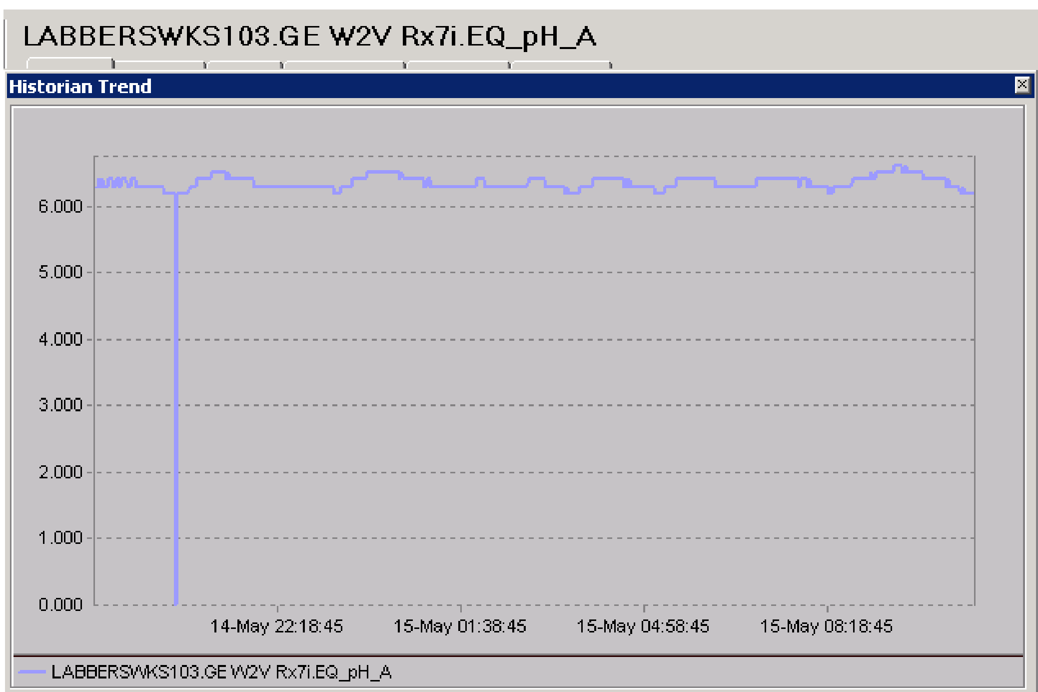

Figure 15 EQ pH sensor measured values recorded by PC Historian with 2 minutes sampling interval for 16 hours. Instant spike to zero is due to sensor or transducer temporary malfunction.

For the online operation of the EKF software, the measured data pre-conditioning Simulink blocks were developed and integrated into the online EKF simulation model. The functions includes data range check, change rate check and data filtering. A later improvement in the aspect is to include a memory block to remember the value of last good measurement (based on range check). If the current measurement is bad (out of reasonable range), then the last good value is used so that bad measurement data points (such as spikes or jumping out of range) are filtered out, and avoid the EKF measurement update affected by the bad data. With the function block, large variations or spikes are greatly reduced and the probability of measurement error introduced to EKF is also greatly reduced. One example is shown in Figure 16, where the spikes of the recorded pH values are essentially removed and the process normal variations are kept in the resultant signal.

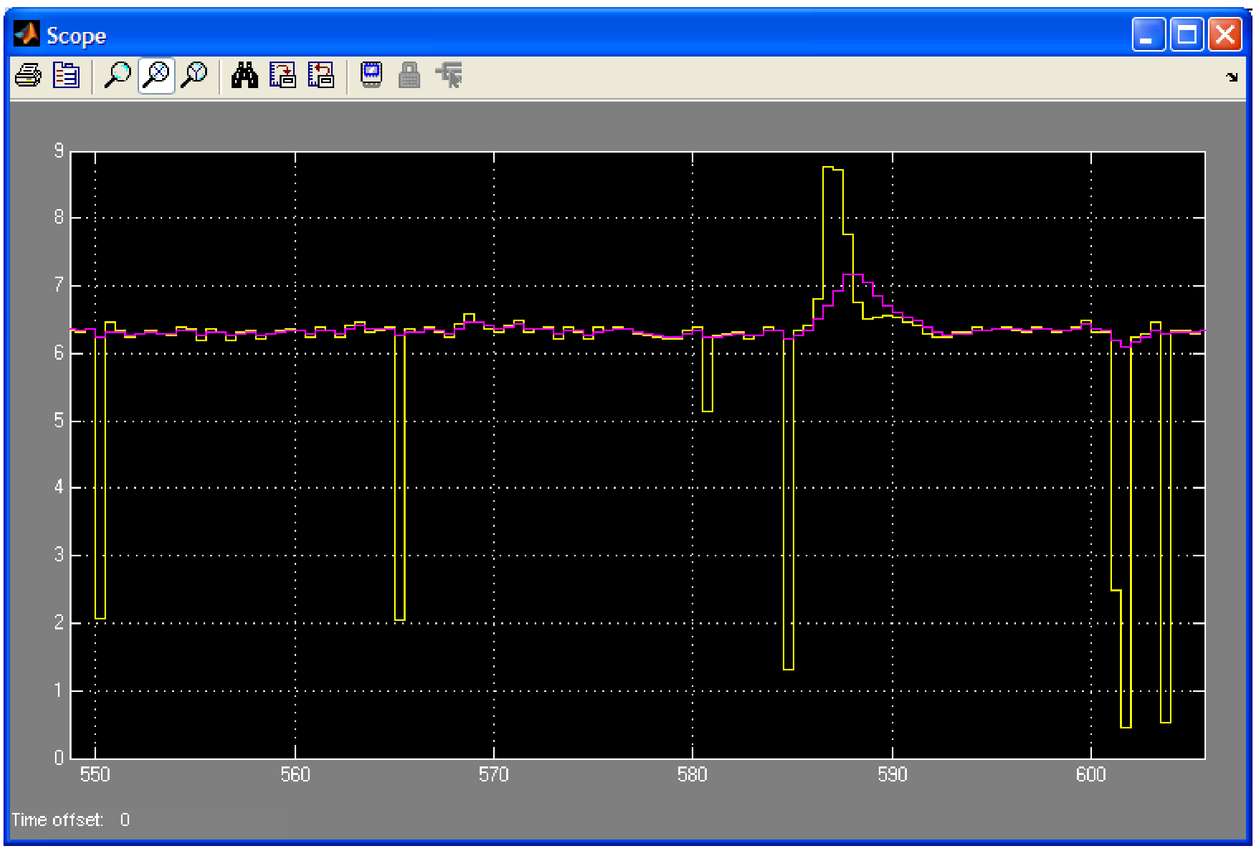

Figure 16 EQ pH sensor measured values (yellow line) recorded by PC Historian passing the data pre-processing function, and the magenta line shows the results. (X axis is the data point sequence)

3.2.2 Process model improvement

The process model used in the Online EKF installed in the ABI plant was developed for normal operation. The model could handle the bypass flow but it deemed the bypass flow to be discharged to the sewer. However, the in the plant the bypass flow joins the AD effluent flows before the recycle flow is drawn. In the operation period of 3/16~3/18 2013, for a period of time, the feed flows to the AD reactors were totally shut off, therefore the normal operation model cannot have the recycle flow at the special operation condition and could not maintain the EQ tank level.

A modification was performed to original plant model so that the special shutdown operation situation is also covered by the model. The changes in the process model include mixing bypass flow with the AD effluents before the recycle split lock as well as the corresponding changes in the linearization model block. After the modifications, the simulation with the new model can maintain the EQ tank level with the same operation data, referring to Figure 17 below.

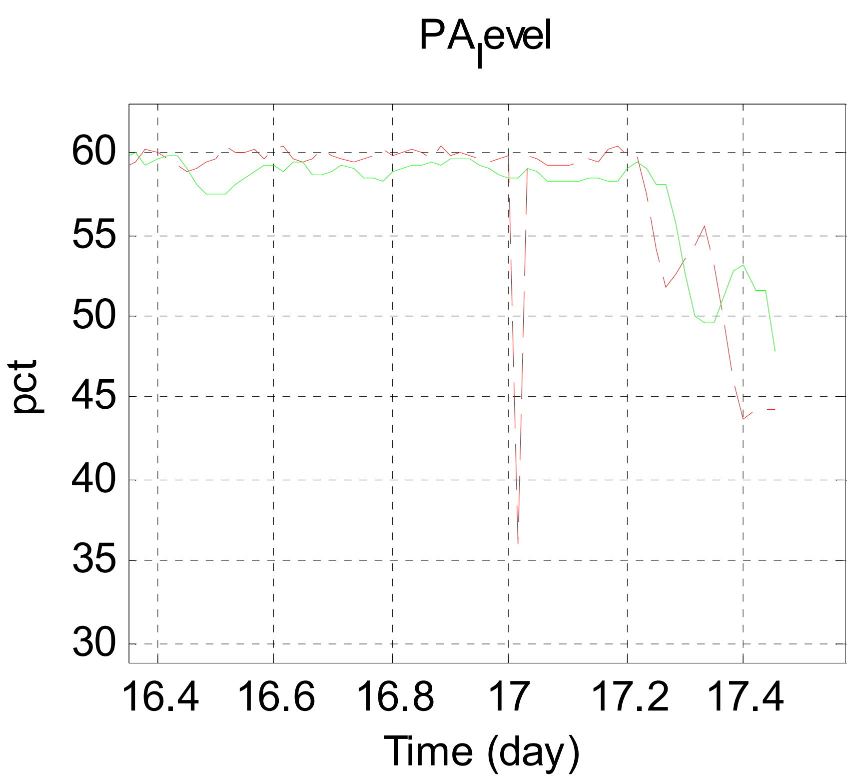

Figure 17 EQ Tank Level Simulation (green) Vs. Meaurements

3.2.3 EKF monitoring algorithm

During the online test operation of the EKF software, lots of parameter tuning was done to filter out the process noise and show the real process changes due to disturbances or plant operation. For example, Figure 18 shows a plot for comparison of estimated raw Influent TOC and TIC (green lines) with their corresponding measured values (read lines) for the week of 3/18~3/24 2012. It is observed that the estimated values follow the measured values generally. The TOC has a higher value and larger variation while TIC has a smaller value and relatively larger variation. The EKF estimated TOC follows the measured values closer (more aggressive) than what the EKF estimated TIC does. These estimated values help TOC to estimate other process variables (e.g., contents of carbohydrate, fat and protein in the feed, the reaction kinetic parameters).

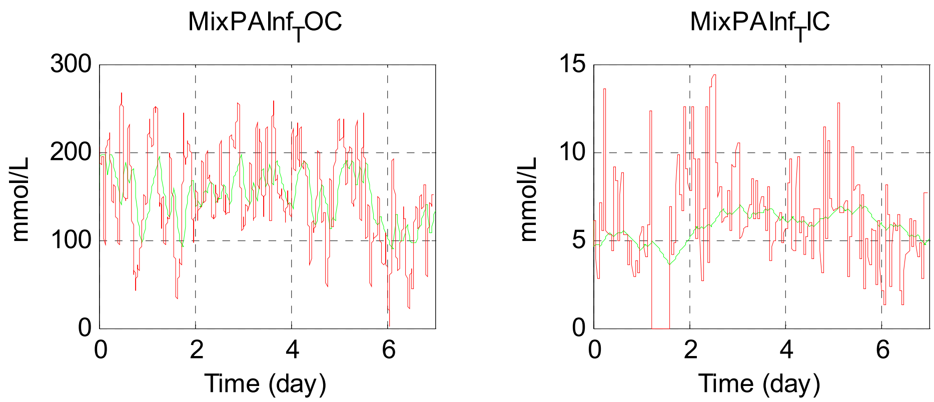

Figure 18 EKF estimated TOC and TIC (green) vs. the measured values (red)

In Q2 2012, the transient EKF was further developed as the Online EKF which takes only the online measured process inputs and outputs. It was implemented on the PLC platform and deployed in the plant field in February 2013.

In Q4 2012, the Online EKF model was also modified to fit to plant real field application environment, mainly unifying input and output connection to the PLC installed in the plant and adding the functionality to run real-time tuning. The Online EKF system in Simulink environment was finally compiled and converted to PLC code and deployed into the ABI plant in Q1 2013.

The process inputs to the Online EKF model are unified to a vector of 35 variables, which includes the 27 process online measurements and 8 null variables in reserve for future extension. Most of the process online measurements are directly corresponding values from communication from ABI PLC with the units used in the plant. The outputs from the Online EKF model consists of a vector of 191 variables, which includes estimated process states, estimated process parameters and the estimated process unmeasured key variables (raw influent properties, each reactor and its effluent stream properties, etc.). These outputs provide direct information for operators to better understand the status of the process as well as performance trends, such as the biomass amount in each reactor, so that operator can have a high confidence about the plant operation status, can have a better idea about the process disturbances coming into the process and can pin point to the locations where abnormalities approach the process hidden. The values of the EKF outputs are also converted to be consistent with the units used in the plant.

The Online EKF is able to accept the tuning factors that user can specifies on fly during the plant application without shutdown the Online EKF. This functionality allows the user to tune the Online EKF to match the overall process measurements more aggressively or to be more stable or to match closer to individual particular process measurement. This functionality also allows the user to specify the relative variation sizes of different process parameters. For each measured process output, there is a tuning factor for its standard deviation. There is also an overall tuning factor for EKF to select a balance between closeness matching the outputs and algorithm stability. For each process parameter there is a tuning factor for its variation size. There is also an overall tuning factor for all the parameter variation size. In current Online EKF, there are a total 17 measured outputs and 11 process parameters. Together with the two overall tuning scale factor, there are a total 30 tuning factors to fine tune the EKF algorithm. In the input vector for tuning factors, there also are 32 reserved signals for future expansion. The input vector can accommodate a maximum 62 tuning factors in the current EKF model block.

The Online EKF results are shown in the outputs, mainly including estimated process states, estimated process parameters and calculated process unmeasured outputs. All the states in EA tank and two AD reactors are estimated in the Online EKF outputs. The estimated process parameters include estimated raw influent properties (process main disturbances) and scale factor for reaction kinetics in EQ tank and AD reactors. In the current setting, the Online EKF refresh the calculated unmeasured outputs every 30 minutes, these outputs includes many important process variables for monitoring, such as biomass concentration (total amount), VFA, Alkalinity, TCOD, SCOD, biogas generation rate and compositions in each reactor.

The Online EKF was then tested extensively in the plant for real process operation data. The results shows that the Online EKF could predict some process variables, such as reactor pH, alkalinity, biogas flow and compositions, but it was hard for Online EKF to predict variables related to detail qualities, such as reactor VFA, biomass inside in the reactors etc., which have been used by plant operator to find the operation trend and adjust the operation. This is due to the limited process quality variables that online EKF model can use for calibration over the time. With lab test data, as simulated in the offline EKF studied last year, the EKF should give better prediction about the process quality variables.

Modifications were done in Q3 2013 to have the EKF taking in both online and lab test data by expanding the port size from 35 to 50 for process input measurements. These process input measurements are processed and input to EKF (average of duplicated measurements, etc.). The ultimate variables input into the EKF increases from 17 to 32. Therefore, the online EKF was modified to take all the possible measured data from the process including the once a day lab test data, and it becomes the all-data EKF algorithm. In November 2013, the team was able to build the extra communication capability to flow the lab test data (except 4 reactor biomass measurements) from the ABI plant side to GE PLC via Data Highway Plus (DH+) connection and transfer those data into the PC Historian via Modbus TCP Network. The GE team worked with ABI personnel to transfer over the 4 reactor biomass measurements. With the installed all-data EKF, both the online measurements and the lab test data are used in the EKF scheme and utilized for process variable estimation and operation status monitoring.

In Q4 2013, the team installed and tested the all-date EKF monitoring software in the demonstration plant, repaired and maintained the TOC analyzers and the biogas analyzer, modified the data communication and PC Historian, collected operation data and compared the operation results. The team also summarized the materials used in the program and the labor spending by the end of the year for the program.

3.2.4 Execution time and redistributing computation load

In Q1 2013, the online EKF was loaded into the GE PLC machine and was tested to run for about one month. During the field test, the Online EKF could run for a long time (e.g., for a few weeks continuously), but it may experience a couple of times of the Watchdog Timer timed out fault and led the GE PLC halt during the test run. The GE team took a few actions to address the issue, such as reducing the maximum iteration number in solving the pH and other equilibrium conditions in the model, introducing the sweep timers in PLC as well as the block numbers to track the current running block in PLC. These improvements helped to reduce the Watchdog problem but could not eliminate it completely.

Through a deeper analysis, the Watch-Dog-Timer (WDT) timeout fault was identified to come from that the EKF software computation time is longer than the set limit for the WDT, which is set to its maximum of 2.55 seconds. Normally the maximum PLC computation time in the cycle for linearization and EKF update period is about 1.5 seconds, therefore there is a buffer room about 1 second for any extra calculation load or system CPU usage. The PLC execution time for the EKF algorithm is very consistent over time. However, due to some operation variation in the process or system implementation, if the PLC execution time for one cycle is longer than the WDT limit time, then the PLC automatically causes a WDT timeout fault and shuts down.

Due to the hardware limit, it is not feasible to set a longer WDT time limit or disable the WDT function, the most possibly approach to solve the issue is to reduce the computation load needed for the longest cycle and track every block in the EKF that is running inside the PLC (so that to trace the point or block that causes extra-long computation time). In Q2 2013, the team performed extensive computation load analysis and took great efforts to reduce the cycle computation time. First, separate the EKF update calculation load away from the EKF propagation and model linearization calculation, and put the EKF update calculation into a subsequent cycle. Second, split the linearization computation load into 3 different cycles so that to reduce the load for each cycle. Therefore the main calculation load is spreads into 4 different PLC execution time cycles: 3 cycles for EKF propagation and linearization and one subsequent cycle for EKF update. The efforts lead to reduce the maximum cycle computation time from 1.5 seconds to about 0.5 seconds, and the buffer time for extra PLC computation time get doubled from 1 second to about 2 seconds. This improvement eliminated the WDT fault, and online test runs do not suffer the problem anymore.

Another improvement of the PLC implementation was to build a runtime view to observe the EKF calculation performance on the PLC platform, mainly including the overall maximum cycle time (millisecond), the maximum cycle time (millisecond) for last EKF period as well as the total number of times the EKF has been called to run. Refer to Figure 19 for the runtime view, which is shown with real time update on the PC Historian machine screen.

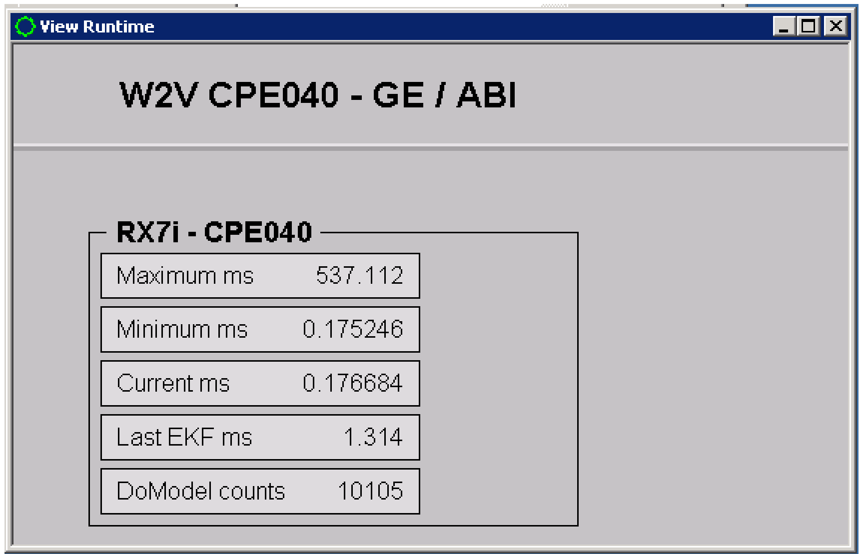

Figure 19 Runtime View of EKF Computation Performance

4 Plant Site Tests and Results

After the hardware and software installed in the plant site in February 2012 and February 2013 respectively, continuous improvements were made in the online test runs whenever there was an issue surfaced. The plant site real-time test runs over the time and some of the results are summarized below to show the capability of the EKF based process monitoring and supervisory control solution in the plant demonstration tests.

4.1 Two-reactor Model EKF for Plant Operation Data

In Q3 and Q4 2012, the two-reactor process model was modified and incorporated in the EKF algorithm, but the online EKF was not ready to implemented to the ABI plant due to delay in PLC implementation. The EKF model was tested with the recorded ABI plant operation data in the offline simulation studies to verify its performance. During the simulation study, all the recorded plant data with both online measurements and offline measurements were feed to the EKF software as if it ran online in the plant.

The ABI plant data indicated that the two reactors (R1 and R3 at that time) had difference performance in the summer 2012. Intensive data was collected from the recording of the plant control PLC for a time span of ten weeks, from May 27, 2012 to August 4, 2012, where R1 experienced a short-term stress but was able to recover to normal operation, while R3 struggled for several weeks and finally had to shutdown at the end of the 7th week of the time period, then another reactor (R2) was brought online.

For the preliminary study, a special treatment was done to make sure the process EQ tank was running with proper pH level, then every other process measured outputs were tried to be matched with the model calculated outputs by adjusting the process states and parameters, mainly the parameters which includes unknown properties of process feed flow and the process reaction parameters. In general, these outputs were matched relatively close. The values or trends calculated from the EKF were consistent with measured values. For examples, Figures 20, 21 and 22 below are the EQ TOC, R1 pH and R3 effluent TOC, where red line is for the raw measured data, cyan color for the filtered value to remove the large noise or spikes in the raw measured values, and green line is for the EKF results.

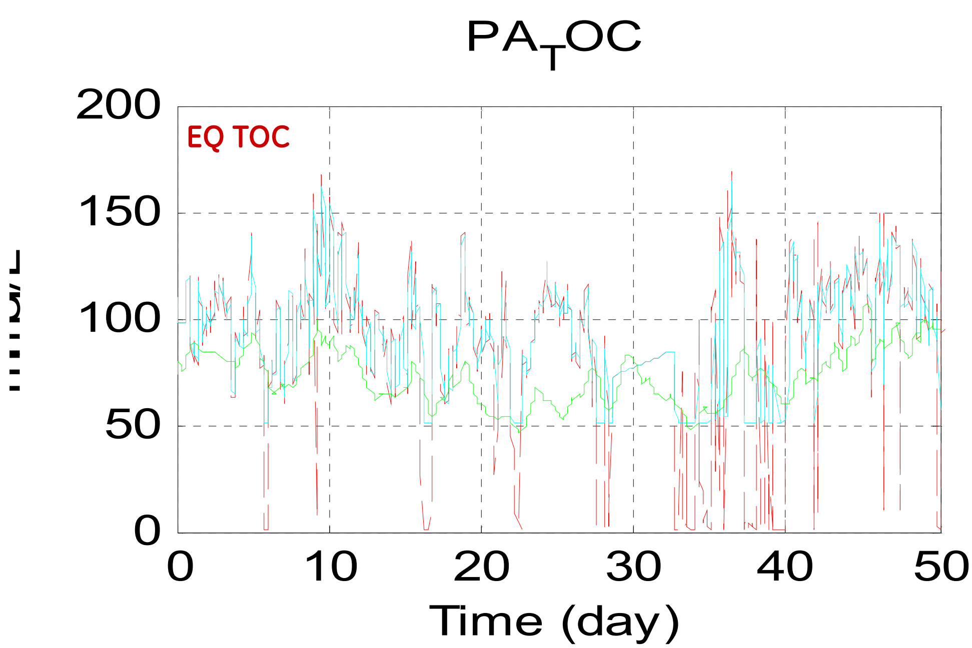

Figure 20 EQ Tank TOC: measured (red), filtered (cyan) and EKF (green)

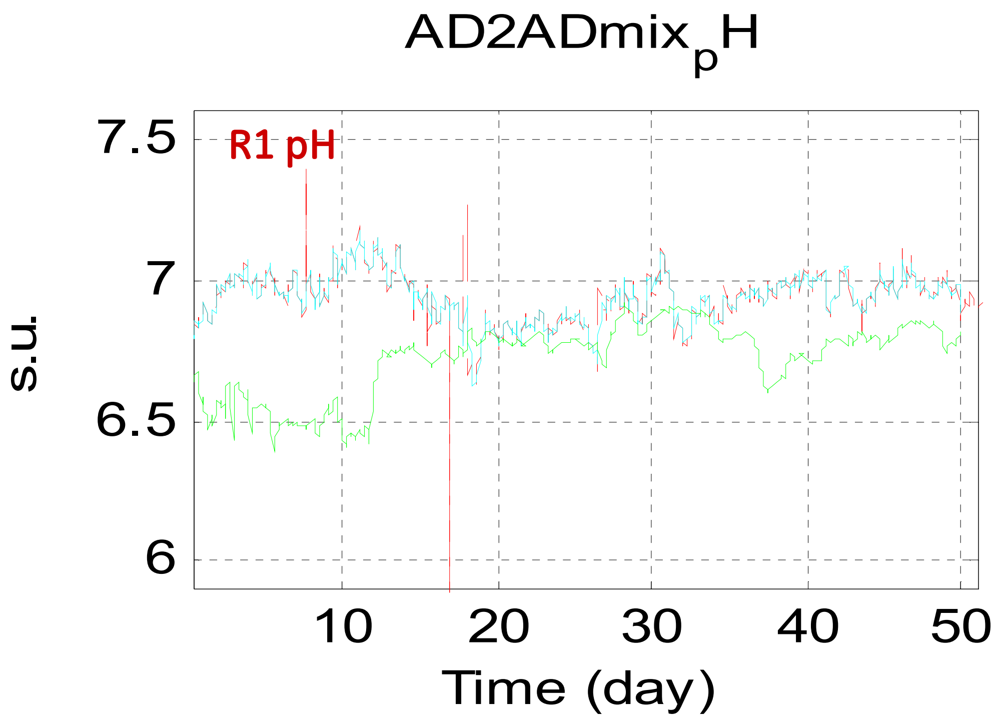

Figure 21 R1 Reactor pH: measure, filtered and from EKF

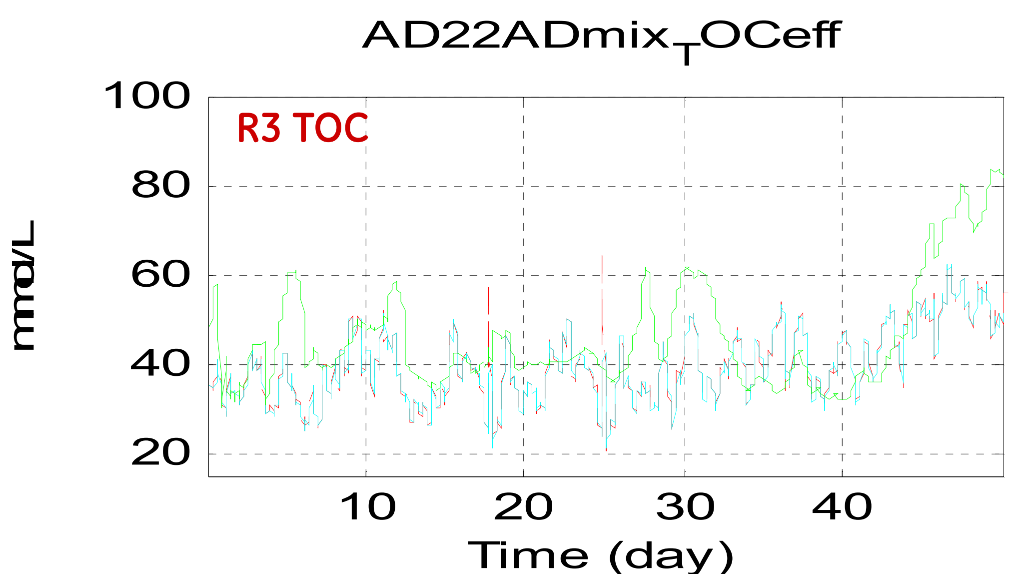

Figure 22 R3 Reactor TOC: measured, filtered and from EKF

The KEF can estimate the feed compositions in the feed flow. As one example, Figure 23 is for the soluble BOD in the feed flow calculated from daily lab measurements and the EKF estimation. This matching up for most of the time indicates EKF capability to estimate the soluble BOD in operation when the lab measurements are not available, or for online EKF operation where soluble BOD is estimated real time.

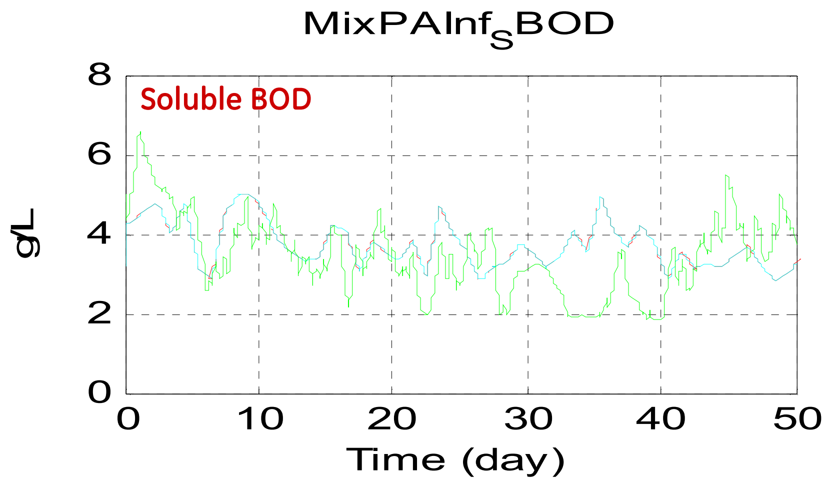

Figure 23 Estimated Influent Soluble BOD

The EKF estimated reaction parameters reveal important information of the underline process changes during the operation period. One may have particular interests in the biomass changes in the process. When a reactor suffers performance degradation, it may convert less COD in the feed, generate more VFA I the effluent and see a biomass reduction in a long run. One may have two different hypotheses: biomass got loss from the reactor or biomass did not generation enough in the first place. It is hard to know what happed in the process. If particular situation can be determined, then corresponding action can be taken to improve its performance effectively. Figure 24 is a preliminary results showing how the two key estimated parameters change over the time: methanogensis biomass growth scale factor and biomass loss from the reactor scale factor. The results indicate that R1 reactor got a temporary growth issue I the 2nd and 3rd week and it did not suffer much biomass loss problem, while R3 reactor mainly hit by biomass loss problem.

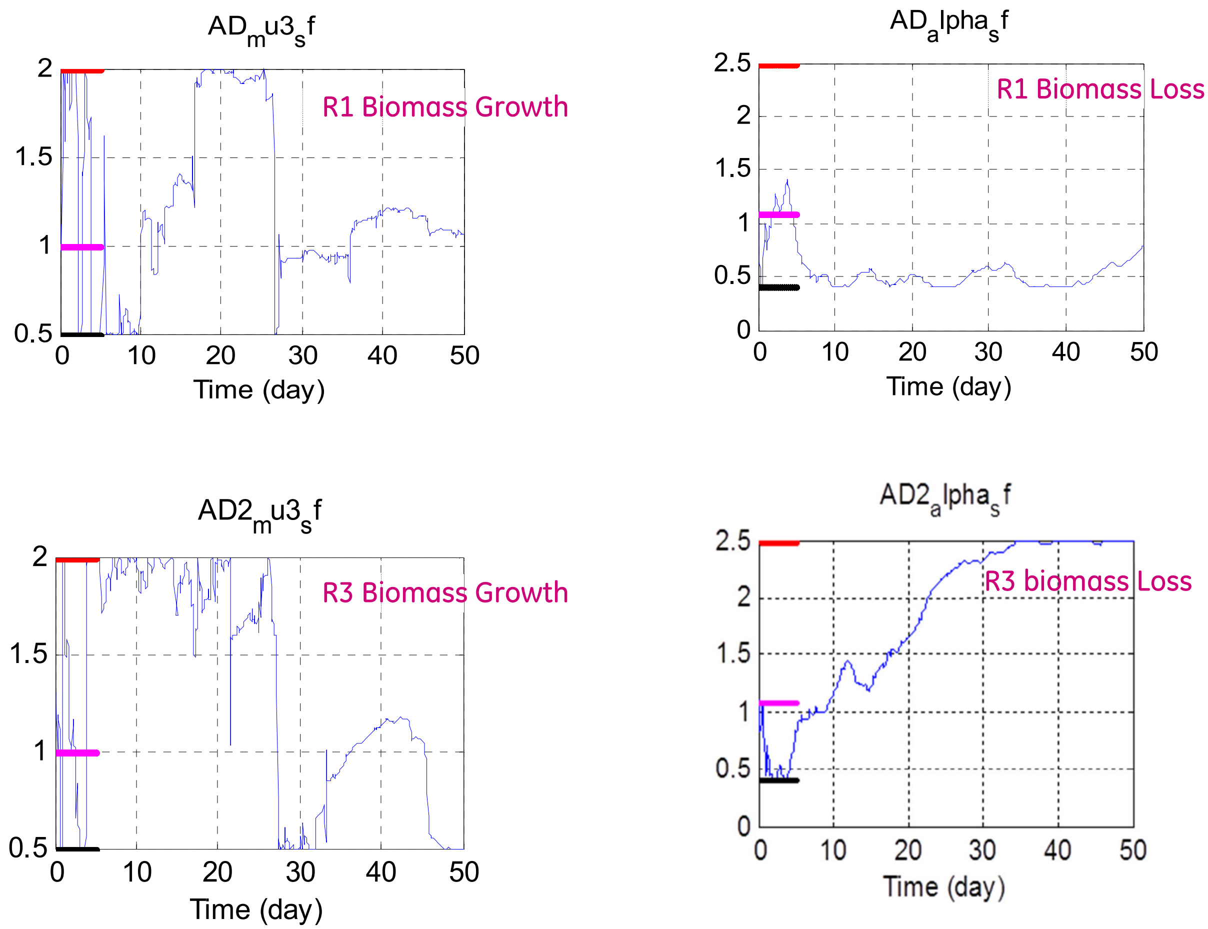

Figure 24 EKF Estimation of R1 and R3 Biomass Growth and Loss

4.2 Online EKF for Plant Operation Data

In Q3 2012, the EKF algorithm was applied to the plant data with both the online measurements and offline measurements. This is called Offline EKF for its taking the rich additional information from offline measurements. This nature of the Offline EKF makes it easy for batch application after collecting data for a period of time and is used for tuning a larger set of process parameters with the rich information in both online and offline measurements.

All the measurements from the plant can be classified into two categories: online measurements and offline measurements. The online measurements are obtained in real-time, such as feed flow rates, temperatures, pH readings, TOC and TIC measurements as well as biogas flow and compositions. These measurements are available for the EKF algorithm running real-time online. The offline measurements are mainly the measurements obtained through lab analysis and the values of these measurements are typically available hours after taking the samples from the production lines, such as TCOD, SCOD, VFA, Alkalinity, VSS and MLVSS. Due to the delay and not readily available in PLC system in the plant, the offline lab measurements can be used for offline EKF, but exposes difficulties for online application. The Online EKF was developed with only the online available process measurements.

In Q4 2012, the online data set of the transition operation period from May 27, 2012 to August 4, 2012 was used for Online EKF algorithm. In simulation studies, there are a total 27 online measurements that can be used in the Online EKF, including feed flow rates to 2 AD reactors, temperatures of EQ tank and AD reactors, pH readings of raw influent, EA tank, AD tank and AD effluent, TOC and TIC measurements of raw influent, EQ tank effluent and two AD reactor effluents, as well as the overall biogas flow rate and CH_4 and CO_2 compositions. These measurements are available online real-time in the plant operation. Compared with Offline EKF application, the Online EKF cannot utilize the lab test measurements (such as TCOD, SCOD, VFA, Alkalinity, VSS). With less information in the data utilized, the Online EKF performance is expected to be inferior compared to that of the Offline EKF, in terms of the EKF results to follow and indicate the true process changes. In the current setting, the Online EKF takes in the process measurements every two minutes, and gives out the estimated results every 30 minutes. Figure 25 is the summary results of the Online EKF for biomass growth and biomass loss of Reactor R1 and R3 during the summer operation period. The overall trends from the Online EKF are similar to what observed in the Offline EKF results in general, however, the Online EKF conclusions were not as definite as the Offline EKF due to the limited information availability (no lab test data for the Online EKF). Fine tuning was done towards the onsite implementation of the Online EKF software package.

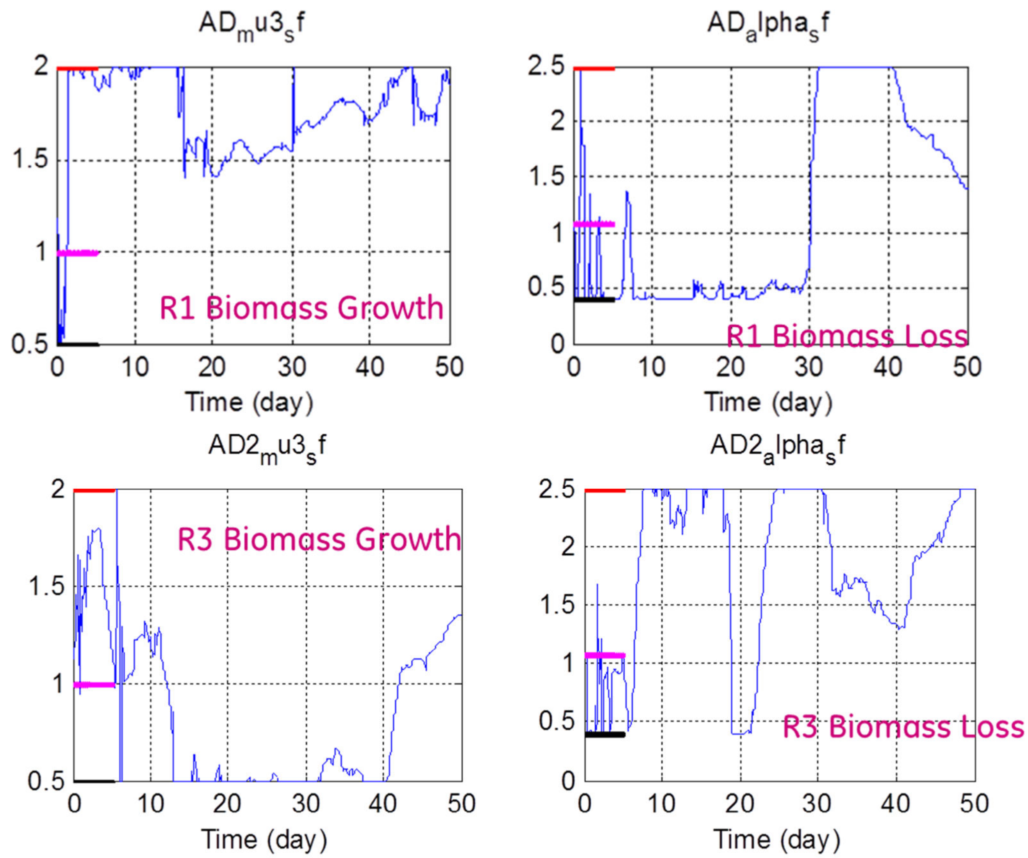

Figure 25 Online EKF Estimation of R1 and R3 Biomass Growth and Loss

4.3 Online EKF Field Test Results

In early part of Q1 2013, the GE team implemented the Online EKF algorithm into the PLC platform. The implementation efforts mainly included compiling the Matlab/Simulink block into the C code, building wrappers for the C code, converting the C code to the PLC executable code and the building the ladder logic for the PLC to run the executable code. After that, the PLC code was tested in a bench-top PLC machine running with 7 weeks of recorded plant operation data. The emulation test went well with the operation data.

In late February 2013, the GE team traveled onsite to the ABI plant in Van Nuys, CA. In the plant, the prepared PLC executable code of the Online EKF was downloaded into the GE PLC machine, and internal connections within the PLC were made to receive the plant operation data and pass the Online EKF results to the PC Historian. In the meanwhile, some Machine-Human-Interface was built to enable changes of tuning factors be set from the PC machine for the PLC. The Online EKF was tested with the real-time field operation data. The results from the Online EKF were recorded in the PC Historian. Plant operators can observe the process trends and the EKF estimates on the PC Historian. Figure 26 is a screen shot of the PC historian as well as the PLC program installed in the ABI plant taken during the onsite trip.

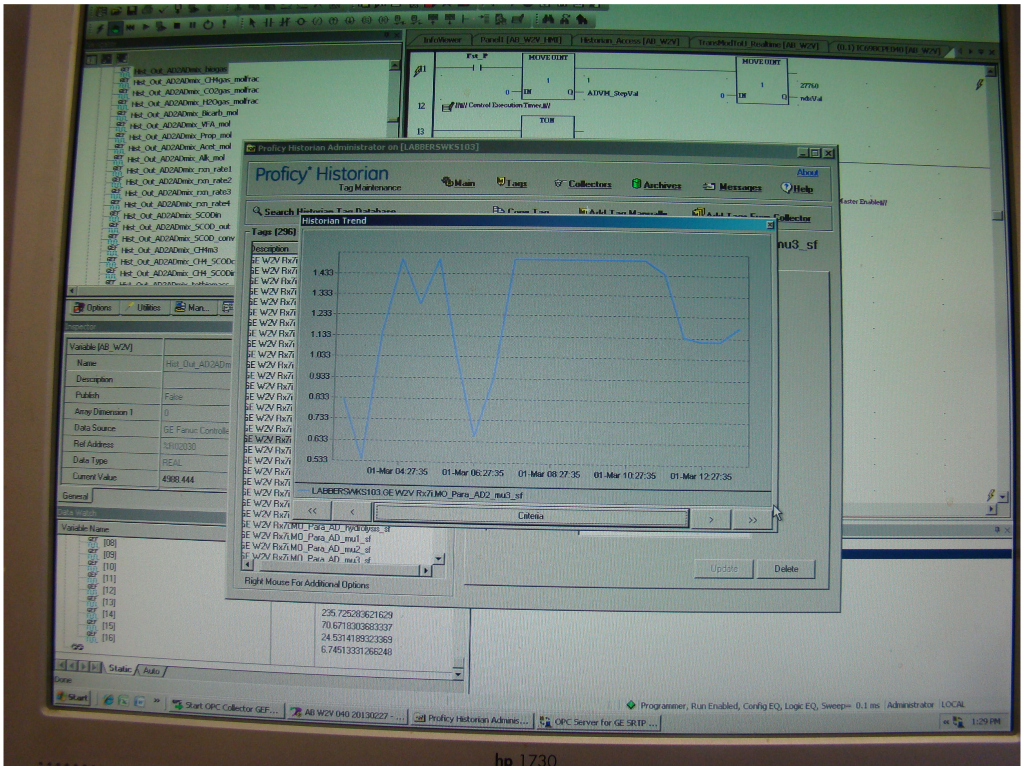

Figure 26 PC Historian and PLC Program Installed in the ABI Plant

The field tests with real-time plant operation data were performed for most time of March 2013. The results of the Online EKF showed a relatively close match between the estimated plant outputs and the measured values, especially after the initial transient period. Figure 27 shows the comparison of the Online EKF results (green color) to the plant measurements (red color) of the Influent pH, TOC, TIC and EQ pH over the operation period of 3/1 to 3/18 (first downloaded data set; horizontal axis start at time of 3/1/2013 1:10 AM; lack of measured data for 3/4~3/7 and 3/11~3/13 which are filled with liear interpolation lines for plant measurements). The EKF can match up to the plant meaurements closely but without so much measurement noise. Figure 28 mainly shows the comparison of bogas flow, biogas CH_4 percent and CO_2 percent estimated by the Online EKF (green) to those values directly measured by online sensors. Overall, the Online EKF has a relatively close match with the field measurements, indicating that the model represents the real process generally well over a large scope of operation conditions.

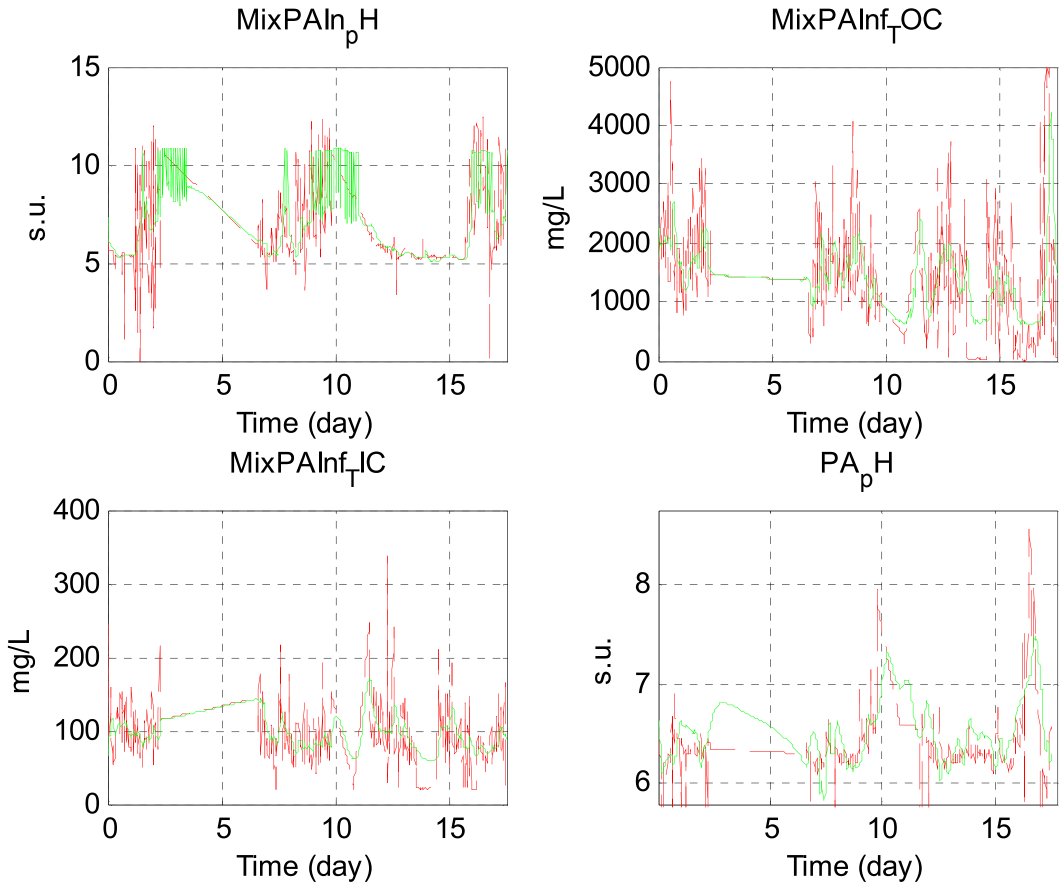

Figure 27 EKF Estiates (green) Vs.Plant measurements (red) for Influent and EQ pH

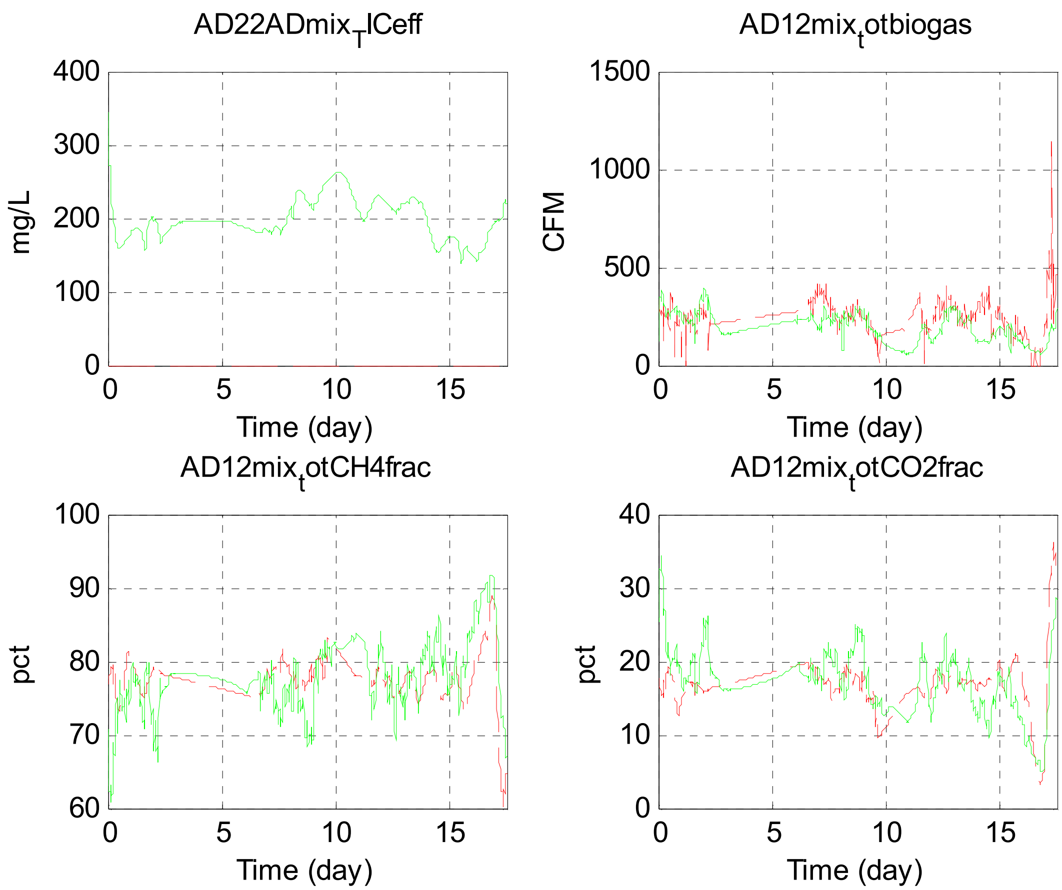

Figure 28 EKF Estiates (green) Vs.Plant Measurements (red) for Biogas

The Online EKF not only tries to match up the measured outputs, but also estimates the unmeasured process variables and some process parameter. For example, the Online EKF can estimate the unmeasured raw influent qualities and the biochemical reaction process parameters. The EKF estimates the raw influent contents of solid inert COD, soluble inert COD, Soluble biodegradable COD (carbohydrate, fat/alcohol and protein respectively) and the alkalinity. Figure 29 shows the variations of solid insert COD, soluble inert COD, soluble carbohydrate BOD and fat/alcohol BOD respectively estimated by the Online EKF over the period of 3/1~3/18. The large variations in the estimated feed parameters indicated the huge changes of wastewater qualities over the operation period. Early detection of these variations can lead to early actions to cope with the disturbances and enhance the plant performance.

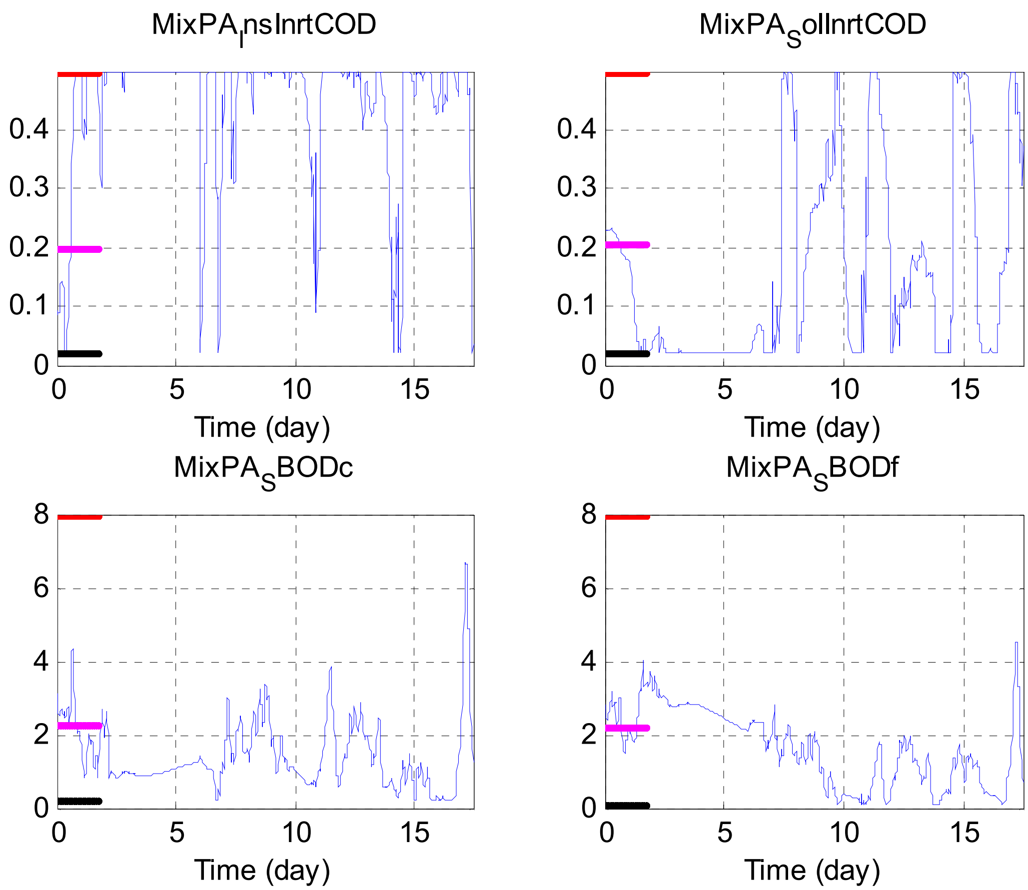

Figure 29 EKF Estiated Raw Influent Qulities

The estimated biochemical reaction process parameters include reaction rate scale factor for EQ acidification reaction, acetoclastic methanogenesis reactions in two AD reactors respectively and the biomass washout factors for two AD reactors respectively. As one example, Figure 30 shows the estimated EQ acidification reaction scale factor for the test period of 3/1~3/18. Large variation indicates considerable changes in the reaction conditions in the EQ tank over the operation period.

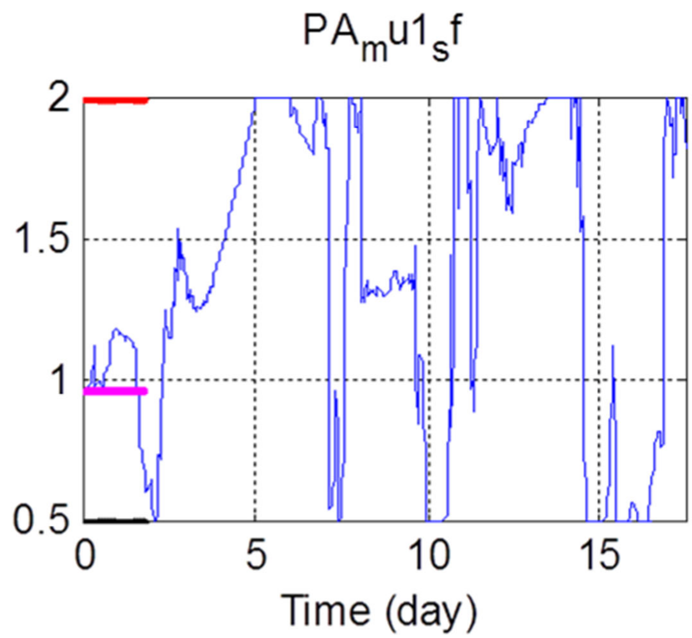

Figure 30 EKF Estiated Scale Factor for EQ Tank Reaction

4.4 Online EKF for Disturbance Detection

During the weekend of 3/16, the upstream brewery plant was preparing to change the type of beer to be produced, therefore lower flow rate of waste water stream and lower content of COD was initially introduced to the wastewater treatment plant (BERS), then the raw influent has a period of high pH due to the use of base for cleaning. At the time around 3/17 Sunday evening, an incident happened in the upstream. One tank of dextrose leaked and was discharged to the wastewater flow to the BERS plant. The BERS plant experienced a series of large disturbances from 3/16 to 3/18, as shown in Figure 31, indicated by the variations in the raw influent TOC, raw influent pH, EQ effluent TOC, CO2 concentration in biogas and reactor pH values. It became even necessary to shutdown the feed flows to the AD reactors for a couple of hours and bypass the wastewater flow to the sewage to keep the plant safe.

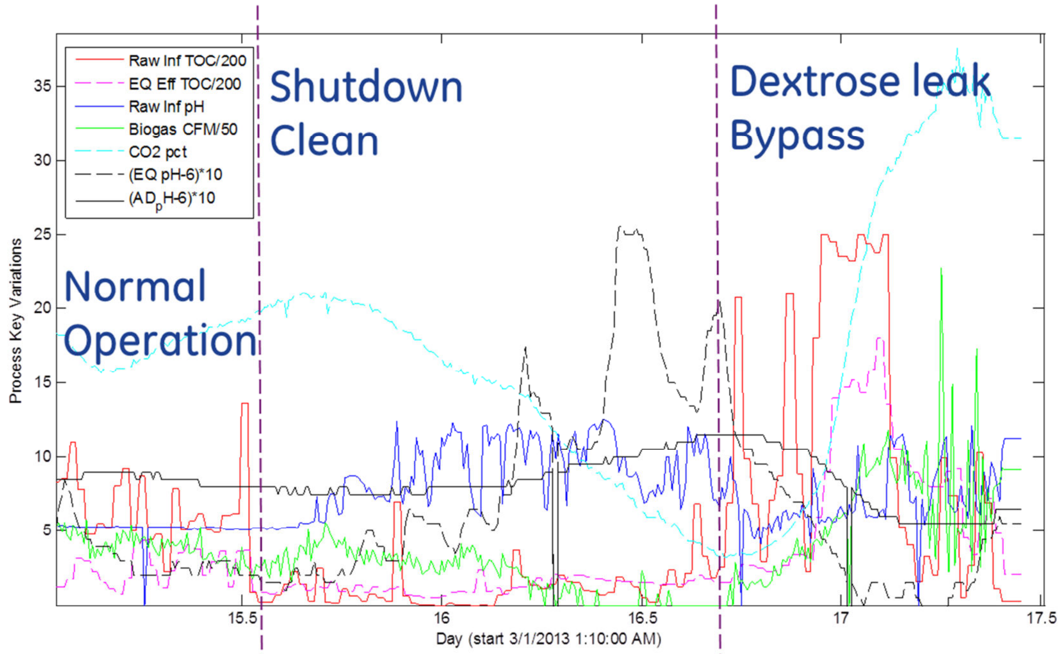

Figure 31 Normal Operation and Disturbances 3/16~3/18

The plant operation data during the period of disturbances was feed to the Online EKF and the results from the EKF indicated the series of disturbances in the operation. Figure 32 shows the estimated alkalinity in the raw influent feed to the BERS for 3/1 to 3/18, and the periods with the high estimated alkalinity are consistent with the plant operation (3/8~3/10 for high pH influent, and 3/17 for base cleaning in the upstream). Figure 33 shows the soluble BOD of carbohydrate category in the raw influent estimated by the Online EKF during 3/16~3/18, and the high peak is corresponding to the dextrose leakage from the upstream brewery process. These results have been shared with the ABI plant personnel and got confirmed by the plant operator for the disturbances and the time sequences of the disturbances.

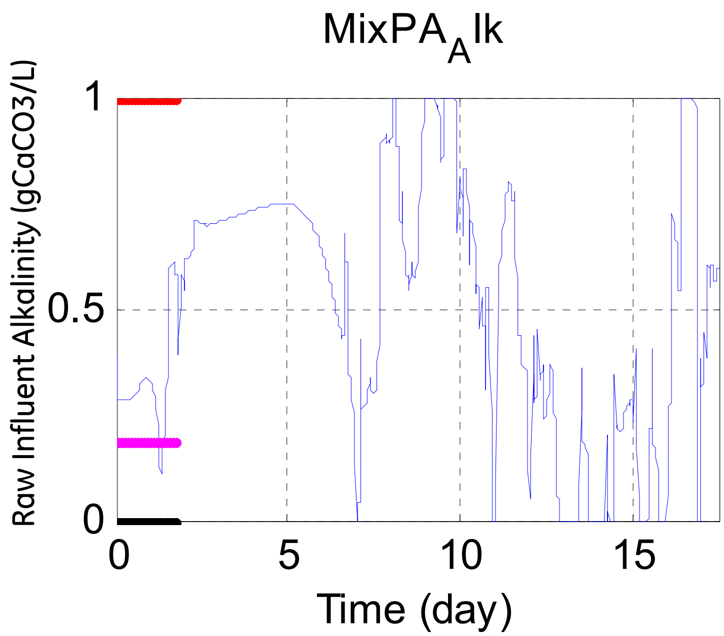

Figure 32 Estimated Raw Inluent Alkalinity

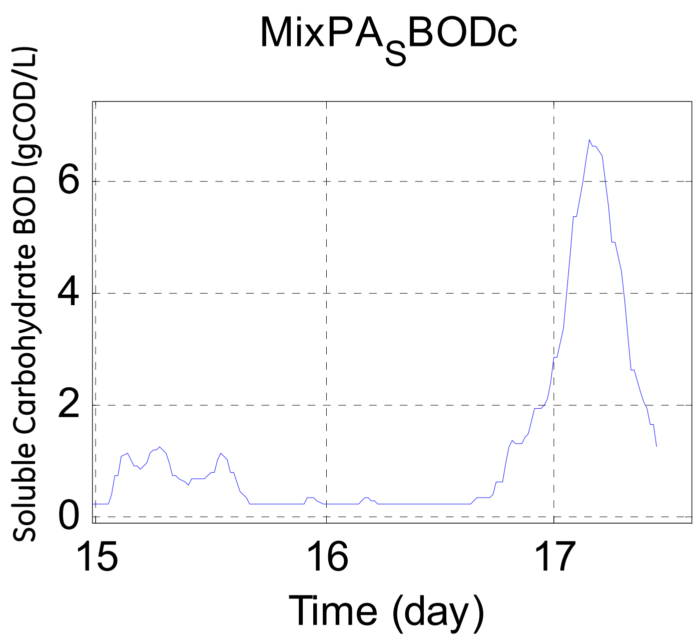

Figure 33 Carbohydrate SBOD in the RawInfluent for 3/16~3/18 Estimated by Onlin EKF

4.5 All-data EKF Test Results

In Q3 2013, the new version of EKF for both online data and lab data was also simulated with plant operation data, collected in 2012 summer operation time as well as collected in 2013 July to August operation. Tuning modifications were also done by intensive simulations. The new tuning gives less weight on TIC/TOC online measurements due to the large variations in the measurements, and gives more weight on biogas flow and compositions. Figure 34 shows the simulation results of biogas flow for 50 days beginning 5/27 2012. The red line is the field measurement and the green line is the EKF model calculation results. After an initial period, the EKF can predict closely to the real plant measurements.

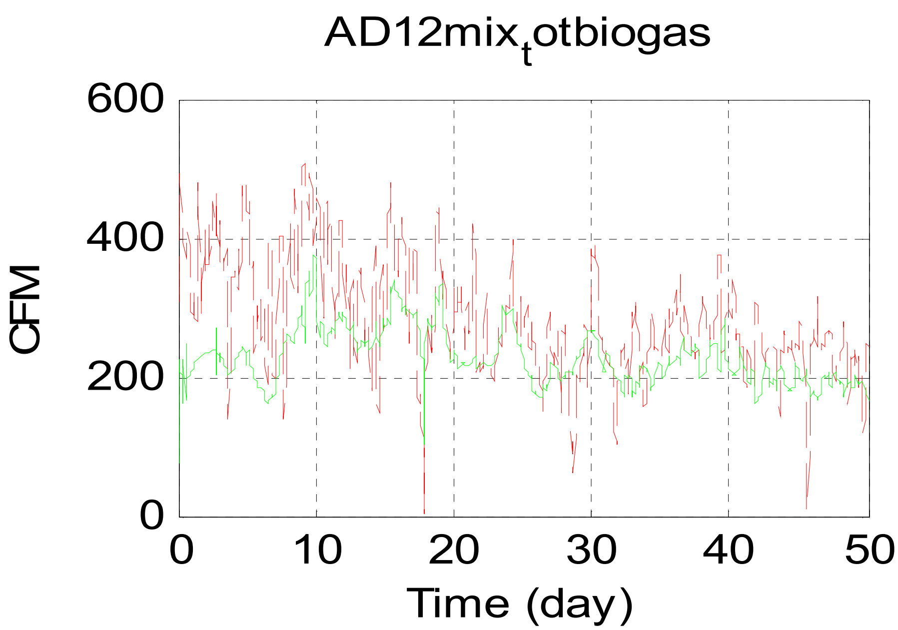

Figure 34 Results of the new EKF for biogas flow

The new version EKF was implemented in the ABI plant in late October 2013 for test. Figure 35 is a screen catch for the EKF running status, indicating it has successfully run about 2200 cycles by 10/28/2013 noon time. The CO_2 measurement card went bad and could not function at all, but the EKF model can continue to predict the process CO_2 variation, refer to Figure 36 (the large jump on 10/25 morning was due to the installation). Figure 37 and Figure 38 respectively are the measured and EKF calculated Biogas flow in the initial few days after the installation. It indicates that the new EKF is capable to match up the biogas flow rate in a relative short time period.

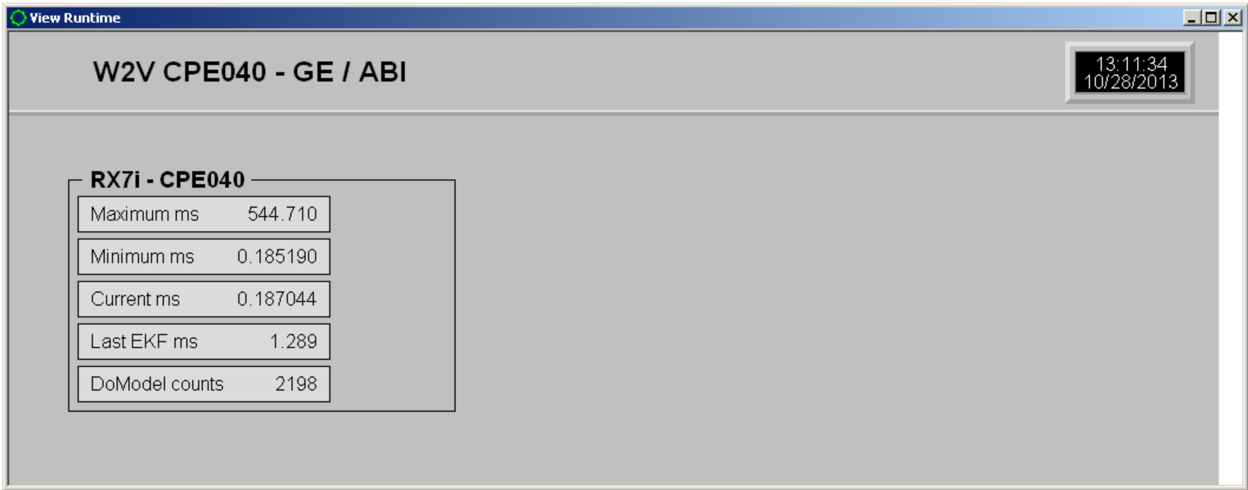

Figure 35 Runtime View of EKF Computation Performance

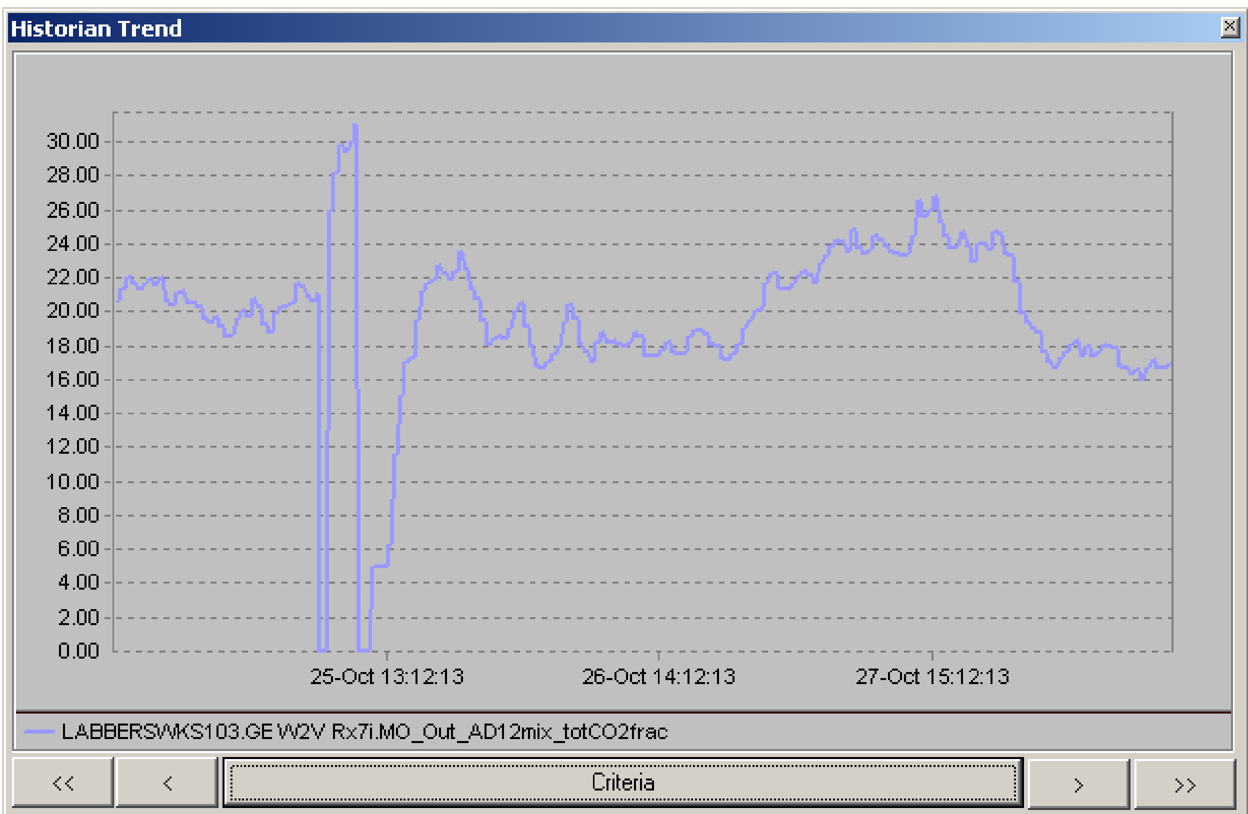

Figure 36 CO_2 prediction from the new version EKF

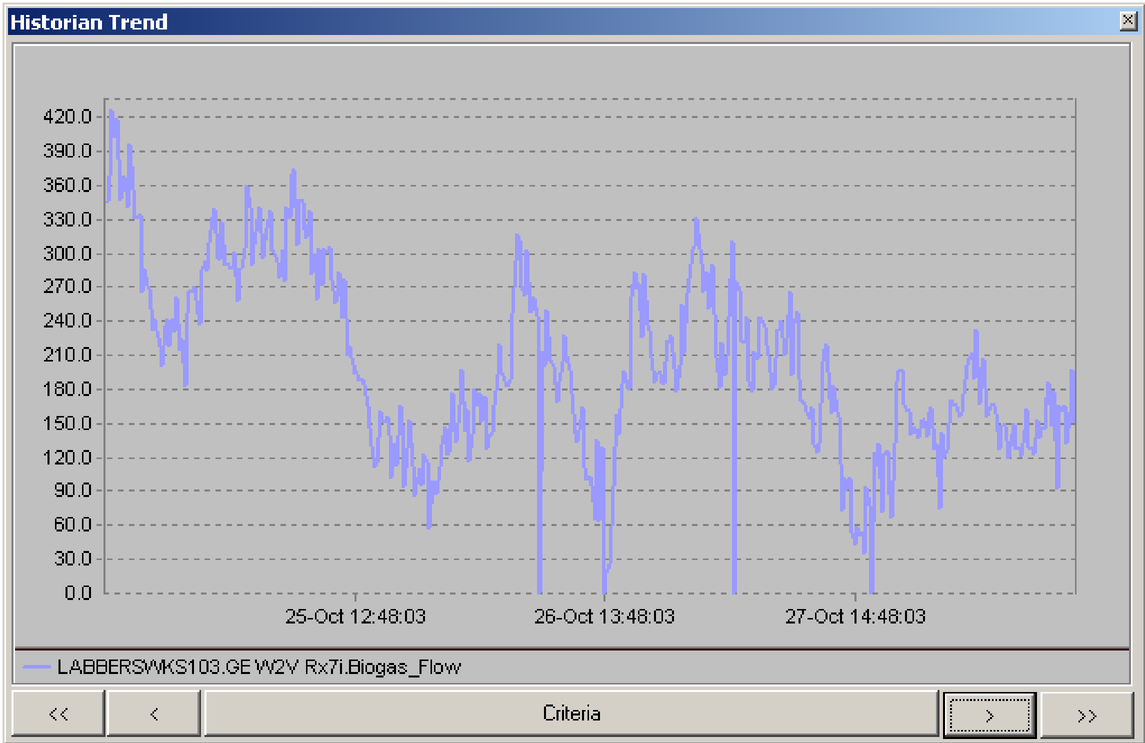

Figure 37 Biogas flow measurement for the first 3 days of test

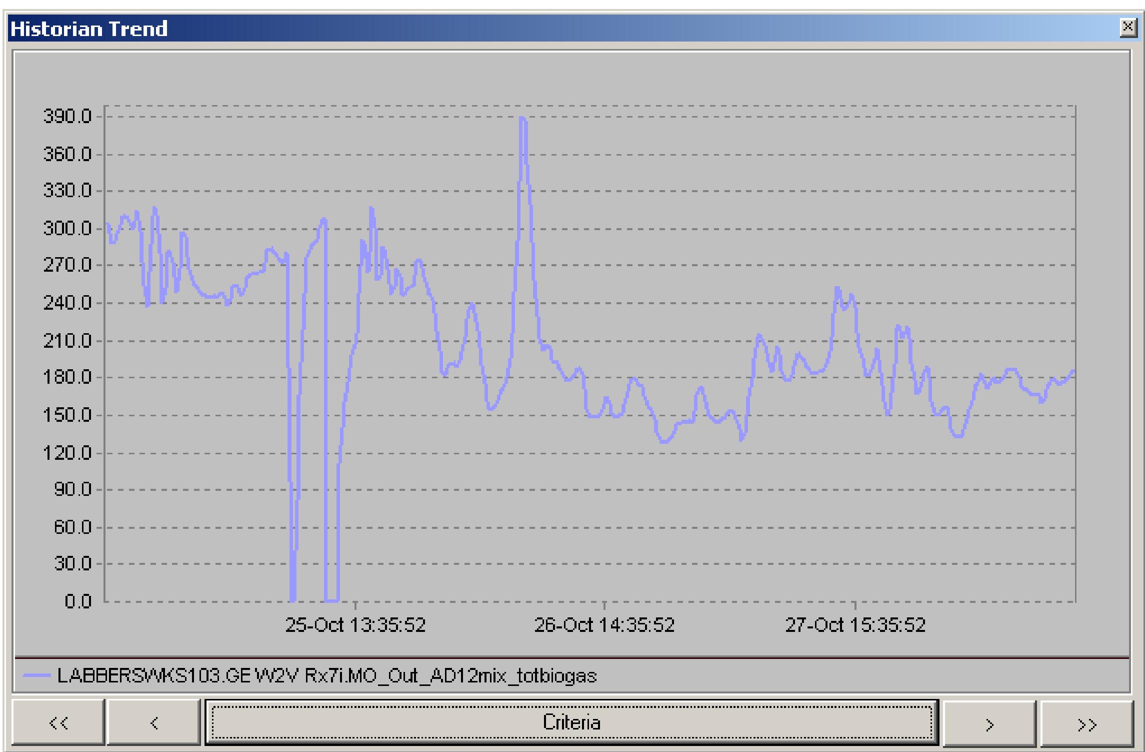

Figure 38 Biogas flow prediction from EKF for the first 3 days of test

4.6 Supervisory Control

In February 2013, the GE team did full analysis first to understand the details of the current control mechanism implemented in the plant as well as the challenges for process operation. More detail discussions and actions were undertaken regarding various aspects of the plant operation. Then the mechanisms to pass supervisory control suggestion to the operational PLC were discussed with ABI plant personnel.

The GE team discussed with the ABI personnel and passed the Online EKF Monitoring and Supervisory Control estimated process results and trend parameters from the GE PLC to the ABI PLC, which is the ultimate and convenient interface for ABI to receive the suggestions from the developed software and implement into the ABI BERS plant in addition to the already up-loaded TOC/TIC analyzer results and the Biogas analyzer measurements.

Based on the insights and information from the Online EKF monitoring test results, the GE team and ABI personnel had interactions around the process pH setting as well as the alkalinity level of the reactors over different operation conditions. At GE's suggestion, the plant operator has changed the EQ tank pH lower setting limit from 6.85 to 6.5 for better system performance without affection on system stability.

One supervisory control suggestion to ABI in Q2 2013 was the relaxation of EQ tank level control. The existing EQ tank level control is to maintain a tight control of the liquid level in the EQ tank, which brings the raw influent flow disturbances directly to the AD operation. The suggested idea was aimed at using the EQ tank to dampen the variations in the raw influent flow and maintain a relatively consistent effluent flow for the EQ-AD combined system for a more stable operation condition, especially for losing less the biomass in the AD reactors.

The GE team constructed a few ideas to coordinate the reactors in the process, such as the reactor feed rate control based on the estimated accumulated biomass inside a reactor from the field running EKF, and those ideas as well as other systematic supervisory control strategies were studied offline and suggested to ABI for further consideration. One test carried out in the summer 2013 to increase the biomass in R1 was to reduce the feed rate to R1, which had less accumulated biomass inside the reactor at the test time. However, after 3 months of plant test run, the results did not increase significantly as expected due to the design limit in the feed flow mixing in the bottom of the reactor.

Though the supervisory control suggestions were not fully implemented by the ABI plant site yet or has not shown the expected results due to the process limits, the value of the supervisory control based on the Online EKF estimations caused attentions in ABI plant. The suggested supervisory controls are expected to be realized in a future time period.

5 Program Phase II Summary

In the Phase II plant demonstration of the monitoring an supervisory control solution, the implementation and test runs shows the capability of the software in the WWTP plant and identify out the areas where continuous improvements are expected. During the process, the team has learned a lot from the real world application, and a summary will be beneficial for future effort in the area.

In general, currently, most WWPT's are still in a low level of process monitoring and control. Though some easy online measurements, such as flow and pH, are available in most plants, operation critical quality measurements, such as COD and BOD, are still measured offline manually at a much lower frequency, mostly once per day. This may be sufficient if the plant operates in a steady state for a long time. However, due to the huge unknown disturbances with the most industrial WWTP as this ABI plant, there is a definitely need for a better solution for the operator to monitor the influent quality trends, the performance of the biochemical reactors and the potential operational risks in the plant. Shifting from manual offline operation to online automatic intelligent control is a long term demand in the industry.

GE's EKF based monitoring and supervisory control solution shows its capability to catch the process underline disturbances and to release the trends in the process parameter space, such as biomass growth rate and biomass loss rate as shown in the plant test. These outputs from the software solution provide the base for operator to find out the root causes of disturbances, recognize the subtle changes in the process and make control decisions in a timely manner.

The reliability of the online instruments are important for the success of the monitoring and supervisory control solution, especially the key quality instruments. The TOC analyzer used in the program is not rugged enough yet for the long term online operation in the heavy solid loaded wastewater application. The results have been in feedback to the instrument manufacturer for a better design and hope the next generation of the instrument will be more mature for application in the industry.

In the project, it is realized that the quality of some measurements are very poor, and therefore good smart data pre-conditioning methods are in need for real world application. The program developed a useful measurement pre-condition functioning block for the particular application. More general and adaptive data pre-condition algorithm is still in demand for broad application of the solution in Food and Beverage industry or other industries.

Due to the unforeseen delays in a field test program, in the project planning phase, it would be better to plan a longer time span for the filed demonstration project. It is also realized that an early field test would be beneficial, so that more feedback is available in an earlier stage and more iterations can be implemented in the field test program.

There was a business advocacy to commercialize the results in the beginning of the project. However, due to changes in the business world, the advocacy is absent at the end of the program, and the program needs find other paths for commercial applications. There is a need to combine the technology development, the business commercialization mechanism and customer needs together for a long-term driving force to push the technology from lab development to real world broad applications.

Overall, in the Phase II ABI plant pilot test project, the team demonstrated the capability of the monitoring and supervisory control solution developed in Phase I of the program for the detection of the disturbances in the influent stream, the long-term trend in the biochemical reactions in the process and the process unmeasured parameters. Due to the reliability issue of TOC analyzer used in the plant site, the field test incurred heavy onsite maintenance and some data unavailability. Despite of this difficulty, the results of the field test provide the plant operator more detail information about the plant disturbances and operational trends for better system stability and process performance. The supervisory control provided suggestions to the operator to control the plant for better results.

The project team suggests for a long-term support for the field tested technology for broad application in the Food and Beverage industry when the next generation online instrument becomes more reliable in the high solid wastewater application. A long-term commercialization plan of this technology will benefit more industrial customers in the future.

Abbreviations

ABI	Anheuser-Busch InBev. Company
AD	anaerobic digester
BOD	biological oxygen demand
CHP	combined heat and power
COD	chemical oxygen demand
CSTR	continuously stirred tank reactor
DO	dissolved oxygen
EKF	extended Kalman filter
IC	internal circulation
KPI	key performance indicators
MBR	membrane bioreactor
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
PA	pre-acidification
PLC	Programmable Logic Controller
RO	reverse osmosis
TIC	total inorganic carbon
TOC	total organic carbon
TSS	total suspended solids
UASB	upflow anaerobic sludge blanket
VFA	volatile fatty acids
VSS	volatile suspended solids
WWTP	wastewater treatment plant

References

Flexible Distributed Energy & Water from Waste for Food and Beverage Industry, Phase I final technical report.

Flexible Distributed Energy & Water from Waste for Food and Beverage Industry, Quarterly progression report, Q4 2011 to Q4 2013.

ABI Website, www.anheuser-busch.com/s/index.php/our-responsibility/environment-our-earth-our-natural-resources/energy/

ABI BERS plant historical operation data

TOC analyzer User's manual, GE Analytical Instrument

Gascard II/ Gascard II Plus Infrared Gas Monitor User's Manual, V1.6, Edinburg Instrument Company

Proficy Machine Edition 6.0, GE Intelligent Platform

Proficy Historian 3.5, GE Intelligent Platform