The Importance of Standard SCADA Protocols to the Reliable Operation of Distributed Farm-Scale Anaerobic Digesters

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Abstract— **The Clarkson University portable anaerobic digester was operated for a period of three months utilizing only local control and data acquisition. Operational and failure data from that experimental run is discussed and a method of how standard SCADA protocols can be employed to improve system uptime is presented.**

Index Terms— **Distributed Control, Energy Management, Renewable Energy, SCADA systems.**

I. INTRODUCTION

THERE can be no doubt as to the growth potential of renewable energy. With a continuing focus on renewable generation as a solution to concerns of energy independence and global climate change, the requirements of control and maintenance are frequently overlooked. Anaerobic manure digesters offer the potential for 359 MW of environmentally friendly base-load power generation across the US [4]. Most of these units would be less than 100 kW, and would be primarily installed for reasons other than electrical generation, most notably farm waste management and odor control [5].

With this thinking in mind, numerous anaerobic digesters were developed and installed in the 1970’s, but much of that equipment broke down or failed at least partly due to operator inexperience, lack of technical support, and maintenance issues[1].

Even as late as 1998, the failure rate for continuously mixed and plug flow digesters approached 70% [2]. Furthermore, digesters are perceived as being very expensive [3]. This is a valid concern, and when combined with their high failure rates, suggests that farmers are understandably uneasy about installing them. Many of these failures could have been prevented with a reliable and robust communications connection to remotely monitor and address situations before they could balloon into major system problems.

When in the 1970’s the equipment was first installed, the Internet and computerized, low cost industrial control equipment were not available. With the availability of low cost industrial control hardware and nearly ubiquitous home Internet links, an effective real time System Control and Data Acquisition (SCADA) system to control large numbers of small (<100kW) distributed generators is possible.

This paper presents results from the summer operating season of the Clarkson anaerobic digester and how a distributed controller could have helped. First, the Clarkson anaerobic digester and its local control and monitoring will be discussed. Next, several failure and digester maintenance events will be presented, followed by a discussion of how real time SCADA would have helped prevent or address those concerns. Finally, a method and means for reliable distributed digester control is presented, which is currently being developed for the Clarkson digester.

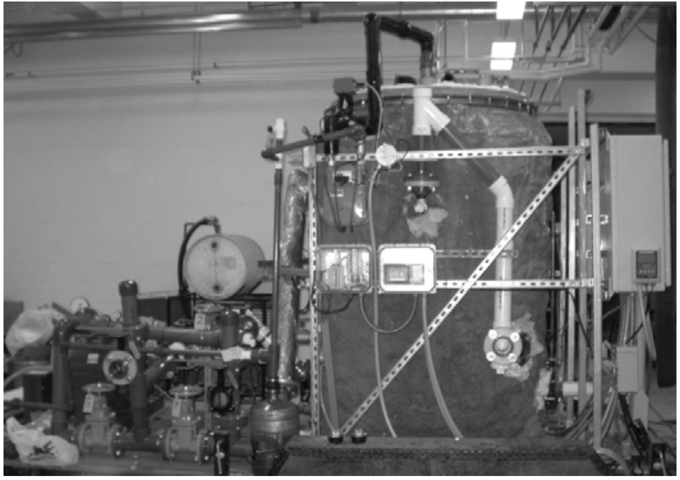

Fig. 1. The Clarkson Anaerobic Digester, taken before the equipment was installed on site. At left is the manure mixing system, at right are the control enclosures, and directly at the center is the gas system and HMI panel.

II. THE CLARKSON ANAEROBIC DIGESTER

Clarkson University operates a pilot-size Anaerobic Digester, illustrated in Fig. 1. The system consists of a 500 gallon stainless steel tank, manure mixing and feeding systems, tank heater system, gas monitoring, and control cabinets. There is no generator on the unit, but the gas monitoring system measures flow, methane concentration, and gas temperature.

The entire apparatus is mounted on a trailer capable of being towed by a standard pickup truck. The digester’s primary purpose was for the analysis of manure digestion in sand-bedded dairy farms common to northern New York State. The system was designed to monitor numerous data channels pursuant to this research, but only locally. No remote communications link or industrial-grade SCADA connection to external monitoring software was initially deployed.

The digester’s controller is an off-the-shelf Programmable

Logic Controller (PLC) with RS-485 based input modules to interface with the system's sensors. Data acquisition is performed as a function built into the PLC, taking time stamped samples every 10 minutes of 21 temperature channels, methane flow, methane concentration, and tank pressure. The front panel of the control enclosures has pushbuttons which tell the PLC to feed the system or mix the tank under operator supervision. The front panel is also equipped with manual hard-overrides, to supersede PLC operation if required. The PLC is programmed with an automatic control algorithm for tank mixing and heating. Also incorporated into the control programming is an electrical load management algorithm to ensure that the digester's electrical load stays within the available service.

The interface to configure the digester and check its parameters locally is through an RS-232 connected Human Machine Interface (HMI) panel, which has a menu structure and data displays as shown in Fig. 2. This panel was very useful for local system debugging, and for easy configuration of the system parameters. The HMI features a color-coded touch screen, where red screens indicate changing parameters essential to operation (mixing times, heater set points), and green screens are purely informational.

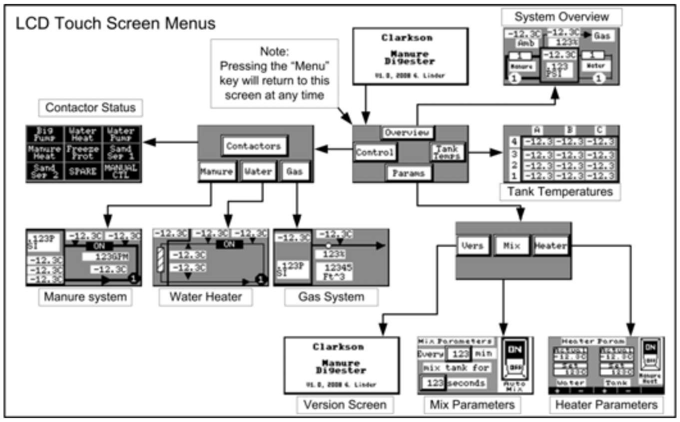

Fig. 2. The digester's menu screens show general configuration options. There are 13 screens total, allowing all local data channels to be observed in real time by the attendant operators. Wherever possible the data and flows are shown graphically, within the limits of the HMI screen's limited resolution.

The local HMI and DAQ system stored and allowed local monitoring of all parameters. However, there was no way to remotely observe the data or change set points. The data presented in this paper was downloaded every few weeks into a laptop as a CSV file. This means that the time between a failure and adjusting the digester could have been as long as several weeks.

Notably absent from this monitoring and control system was an integrated power monitoring system. An external data logger was added midway through the operational period. A power meter integrated into the local controller will be added for the next deployment.

III. DATA AND ANALYSIS OF FAILURE MODES

The digester operated for a period of three months in the summer of 2008. During this time, numerous experiments relating to sand studies were performed. However, also during this period, numerous failures occurred, due chiefly to random events and equipment vandalism. The lack of a remote data connection and real time monitoring seriously affected operation of the digester. When a minor problem developed or a system failed, no one was immediately notified and no repair action could take place until the next feeding crew was able to manually check the status.

With the current digester controller, and indeed many other renewable energy control systems, data is gathered once a day or less frequently to diagnose long term problems. What follows are five examples of real-world summer situations where a more immediate data connection would have been very useful, where systems operated sub-optimally and required outside intervention.

A) Manure feed inlet rate control and pressure monitoring.
B) Unwarned power outages causing damage to gas system.
C) Untrustworthy gas measurements due to temperature fluctuations.
D) Moisture condensation prevention via temperature monitoring.
E) Electrical load monitoring and temperature dependence.

The importance of the event is discussed, as well as the reasoning behind the needs to be able to see the events in real time. For the purposes of "real time" in this analysis, it means getting system operation data continuously with an update rate of less than 10 minutes.

A. *Flow Adjustment via Real Time Data*

Fig. 3 illustrates the tank pressure and methane flow rate versus time. The methane flow rate associated with this scale of digester is very small, but none the less indicative of a larger system. The digester at its peak produced more than 80 cubic feet per day.

The bottom line of the figure shows gas production in cubic feet per day. Of particular interest in this section is the peak of gas production at around 450 hours of operation. Knowledge of the flow rate on a tighter time schedule would have allowed the system operators to make more informed decisions about the feeding rate for the tank, allowing for continuously sustained gas output.

Monitoring gas output in real time is essential to efficient operation of anaerobic digesters with generator plants, as the gas output is used to power the generator itself. Knowledge of a fall in gas output or change in methane content could signal that the generator may not be able to operate at peak capacity.

Of further interest in Fig. 3 is the tank pressure. The top line shows tank pressure as a function of time. Notice the steady upward trend in this line and the large dips. Each large dip corresponds to a loss of pressure in the tank which would be an emergency situation. Such a large drop would be caused by a rapid release of biogas or a tank seam failure.

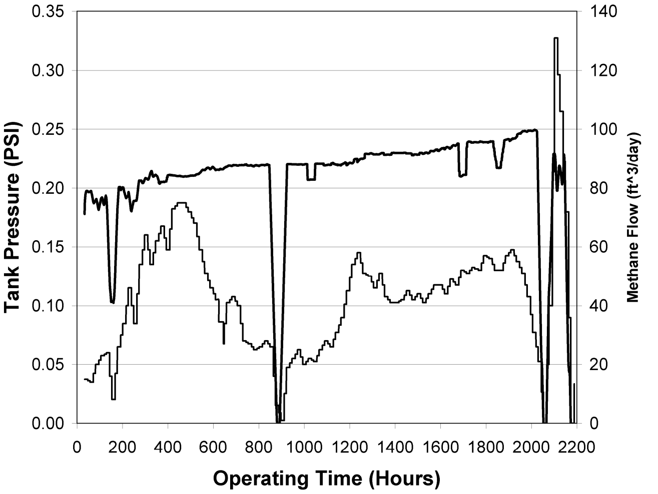

Fig. 3. The tank pressure in PSI is the upper curve and the methane flow rate in cubic feet per day is the lower curve and the right-hand axis. With a real time data acquisition system, the flow rate could have been adjusted at around 450 hours at maintain peak methane production.

B. Unwarned power outages causing damage to gas system

The methane sense system needs to operate on dry gas. Biogas contains hydrogen sulfide, which can combine with water vapor on the sensor to cause dramatic changes to the sensor's accuracy. In order to prevent damage to the sensor, and ensure measurement accuracy, the entire gas monitoring system was wrapped in heater taping and insulated.

Fig. 4. The top curve and right hand axis are methane concentration. The jagged saw-tooth like curve is cumulative methane volume in cubic feet. Each time there was a power outage, the gas volume counter resets to zero. Of particular interest is the circled area, which shows the methane volume counter reset and a rapid drop in methane concentration.

Fig. 4 illustrates an example of when having a poll/response type of data link would be very valuable. The jagged saw-tooth line is the cumulative methane counter. By design, each time there is a power outage or system reset, the methane volume counter resets to zero. The top line is the methane concentration, as measured by an in-line continuous methane sensor.

Unfortunately, at the time indicated by the circle in Fig. 4, the power failed and the gas sense heater shut down. This allowed a rapid drop in gas sense temperature. In this particular case, the power outage lasted nearly 10 hours, which was long enough to allow the gas system to cool to ambient temperature, condensing the water vapor and allowing it to combine with hydrogen sulfide gas and turn into sulfuric acid in the gas sensing system. This required rework of the gas sensor, and required extensive extra calibration data to prepare the gas data. The plotted data here has not been adjusted for the sensor damage.

There are many different manners of gathering data from remote nodes. Standard System Control and Data Acquisition (SCADA) protocols can be used in a variety of ways, and one of them allows for polling/response of a remote device. Employing this kind of protocol allows for real time monitoring of the data link channel.

Having a poll and response communications protocol would have immediately indicated a loss of communications, which in all cases could have allowed rapid response to figure out why. Had the power outage been noticed within an hour, the system could have been powered up and re-heated, which would have saved the methane sensor and a great deal of work in adjusting the methane sensor's output.

C. Untrustworthy gas measurements due to temperature fluctuations

Temperatures can change rapidly in gasses associated with a digester system, at least when compared to the time constants of large volumes of manure. Fig. 5 shows a different view of the same event as Fig. 4. The top line in Fig. 5 shows the raw gas measurement system temperature and the methane concentration. Notice the rapid temperature drop, and the ensuing plummet in methane sensor reading. Such a situation could have occurred if the gas system heater failed, for example.

It should be noted that all anaerobic digesters utilizing internal combustion engines for power generation require some kind of gas treatment, due to the hydrogen sulfide content of digester gas. There are numerous scrubbers, coolers, compressors, and heaters which can be used to "scrub" the damaging chemicals from biogas. A failure in one of these systems could lead to changes in engine operation or emissions associated with the prime mover.

Therefore, if the gas cleansing system on a digester fails, a rapid response can be employed to repair it. In the case of only having the temperature fall, assuming communications are still available, the response would have involved reading other data channels from the digester to figure out what had failed. This real time interaction requires a reasonable data update rate.

In a poll-response type SCADA system, the rapid temperature drop would have been discovered, and the system could have been examined to find out why the methane concentration dropped. In this case, it would have shown that the power had failed. However, there could be other situations would could lead to a drop in methane output, all of which would benefit from having real time information.

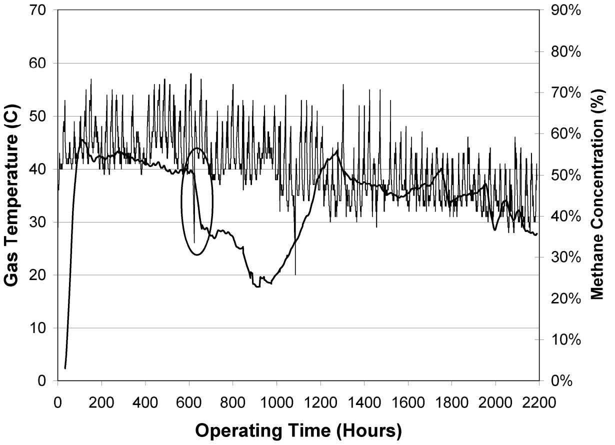

Fig. 5. The top noisy line and the left hand axis are the temperature of the gas in the gas characterization system. The right hand axis and bottom curve is methane concentration. Once again, particular attention is paid to the circled area around 600 hours into the operation. That particular dip in gas temperature corresponded to the loss of power situation, which caused the gas temperature to drop below its dew point.

D. Moisture condensation prevention via temperature monitoring

Fig. 6 represents several different temperatures. The top line is the gas characterization system, the middle dotted line the approximate dew point of the gas, the next line the digester's internal temperature, and the bottom line is the outside ambient air temperature.

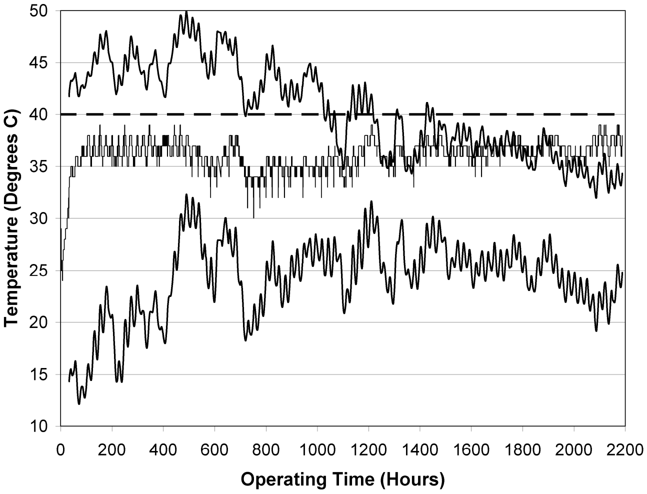

Fig. 6. All temperatures have been noise-filtered via running average. The top line is the temperature in the gas characterization system. The dotted line represents the approximate dew point of the biogas. The middle line represents the digester tank average temperature, and the bottom line represents the ambient outdoors temperature.

Even beyond standard single point failures, real time data gathering and analysis is required to ascertain the general health and maintenance requirements of the system. If data on the digester were gathered and tracked in real time, it would have been noticed the gradual sinking of the methane sensor temperature.

The data of Fig. 6 have been filtered with a moving average, so the asymptotic 10 hour failure of Fig. 5 is not visible. However, it can be seen that the gas characterization system temperature is gradually falling, even as the average ambient outdoor temperature remains constant. The result being that the methane heater system becomes ineffective at preventing condensation in the gas sensor after around 1100 hours of operation, as this is when the temperature falls below the dew point of the mixture.

This is the kind of symptomatic failure that could be addressed remotely. Why is the temperature falling? Knowledge of this event, if available in real time, could have sent someone on site to investigate the heater system insulation, heater tape, or control circuits to effect repairs. Data also would have provided information on the success of the repairs.

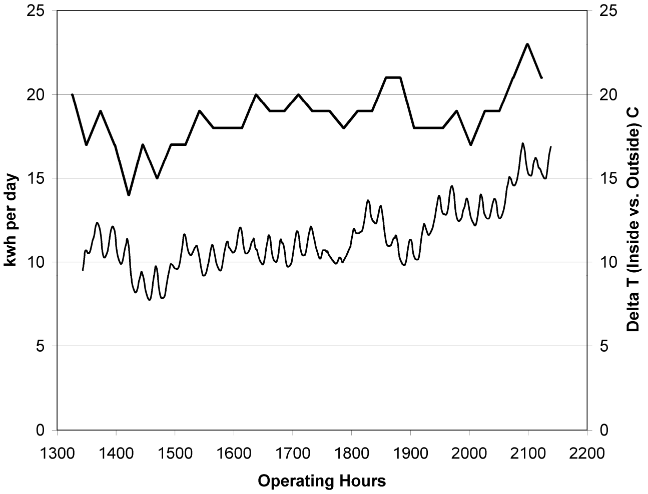

Fig. 7. Top line is noise filtered digester load in kwh per day. Lower line represents outside temperature. The trend here is that the daily load follows the outside temperature. Real time knowledge of this information would be important in heater system forecasting and potential repairs to pipe or tank insulation.

E. Average tank-environment temperature difference for electrical load prediction

Fig. 7 illustrates the digester load in kwh per day on the top and the temperature difference between the ambient environment and that average tank fluid temperature. The curves follow each other closely, offering evidence that the heater load is dependent on the outside temperature.

Given that the current version of the pilot scale plant is equipped with no generator due to its very low gas output, this graph still offers insight into the system's operation. The digester is equipped with a large 3 HP pump, which draws almost 5 kw when operated. The heater loop is 3 kw. The total electrical service available is approximately 6.2 kw. Monitoring load in such a way gives information about potentially damaging loads before they become a problem.

A higher level of communications and more real time data, for example, could be used to determine a locked rotor condition in the motor. Indeed, the thermal overload on the pump would trip first, but by comparing load information to the information from tripped thermal overloads could allow easy remote diagnosis and over-the phone advice to a farmer as to the severity of the problem.

IV. IMPLEMENTING REAL TIME MONITORING AND CONTROL ON FARM-SCALE ANAEROBIC DIGESTERS

Real time data gathering is standard in large-scale generating stations, where full time staffs monitor all operational equipment to assure healthy operation of the machinery. It is only now being introduced into small scale generators and renewable energy systems as the cost associated with such data gathering equipment has dropped. Commercially available low cost Programmable Logic Controllers (PLC) now come equipped with reliable control protocols. Additionally, proprietary network hardware can be replaced with standard WiFi Ethernet or low cost cellular data modems.

The problem is how to get large-scale monitoring into a machine where, even if deployed commercially, will produce less than 100 kW of electrical power. This is a common problem in the world of renewable energy, as most renewable generation units are much less than one MW, where the costs and technical requirements of traditional utility control and interfacing hardware cannot be economically employed.

The solution being implemented in the Clarkson Anaerobic Digester is to give it an interface to allow many of them to pool their resources to appear as a single generator to remote system operators. The digester is having its controller re-programmed to present a Distributed Network Protocol, Version 3 (DNP3) interface to the outside world. The DNP3 protocol will communicate over a low speed and inexpensive network link to a master station, which will then present only the values required for electrical operation to the next level, via HTTP.

This will allow the Clarkson Digester to present all relevant digester data in real time to the master station, but only those data relevant to its users or operators via the HTTP link. The system will consist of four different levels:

A) The local control system, implemented via MODBUS.
B) The digester to master station link, implemented via poll/response DNP3 over standard TCP/IP networks.
C) The user interface level, offered via a web page running on the master station and carried over TCP/IP to standard browsers.
D) A local link, if required, to allow the owner direct access to the digester if requested.

A. Local control system

The local control system, including the on-board HMI, offers the lowest-level interface to the digester systems, short of operating the circuit breakers. This will be the equipment used when field service staff is on site and needs to have absolute local control over the system. Changes to parameters and set points here will immediately effect the system’s operation, and could potentially damage equipment if used or adjusted carelessly. Such an HMI panel is implemented in the current Clarkson anaerobic digester to allow local control. All gathered data channels are available for real time checking to allow for easy repair and testing of thermocouples, gas sensors, or other on site equipment.

MODBUS is a standard for industrial control used in many industrial applications due to its simplicity and ease of implementation [6]. The choice to use MODBUS here opens up digester designers to take advantage of any vendor’s standards compliant sensors and input/output modules.

The PLC is programmed to allow the digester to operate safely if the loss of any communications links occurs. All real time control and monitoring functions are handled at the controller level, and the communications links are only for maintenance, monitoring, and programming.

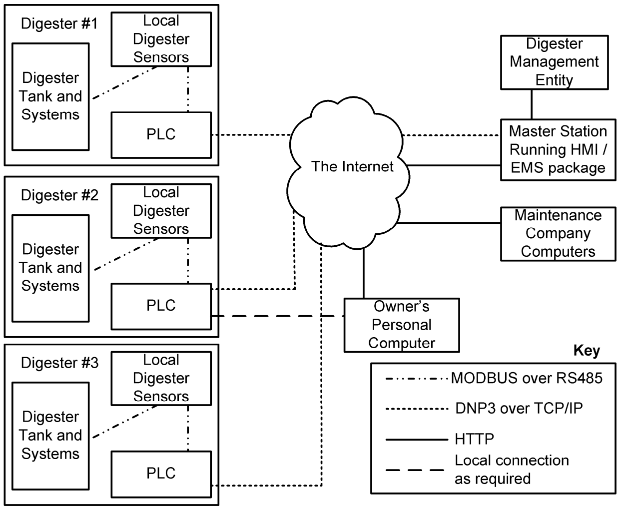

Fig. 8. Block diagram of proposed digester control system. For the demonstration case, there will only be one digester, but the number of digesters can be scaled easily, so long as they all use DNP3 and well document their chosen data points.

B. Digester to master station link

The data from the PLC will be transported via the DNP3 protocol tunneled through TCP/IP and the Internet. DNP3 allows for internet tunneling, and can be made secure via Secure Shell (SSH) or Virtual Private Network (VPN) systems. DNP3 offers polling, guaranteed time stamping, and facilities to recover backlogged data if a communications link goes down. It is also a widely supported standard.

In this design, the PLC also functions as a Remote Terminal Unit (RTU), acting as an interface between the DNP3 master station link and the MODBUS local RS-485 network. In practice this means that not all points used locally in the digester would be transported back via the DNP3 link, and further that the digester would be addressable by one number in the DNP3 network, instead of as a number of points associated with each of its onboard MODBUS devices. For example, the tags used for displaying data on the HMI would not be directly accessible over the DNP3 connection, as they are only useful locally to move data between the PLC and the HMI.

The PLC on the digester was chosen partially because of its built-in DNP3 interface on board, and code development is proceeding to implement these functions.

The master station in this case will be a standard high grade computer, running HMI or Energy Management System (EMS) software from a commercial vendor. There are many software packages available for substation automation or power grid monitoring. Using DNP3 as the intermediate levels allows the use of these standard and full featured systems, which often include easy to use tools to define new devices to the users. Negotiations are moving forward with various software vendors to find a package that enables the functionality required.

C. The user interface link

Another significant benefit of using off the shelf software is that they offer easy access to their internal databases, via the World Wide Web (WWW) over Hypertext Transport Protocol (HTTP). This allows users to log into the master station and see the same information as the user sitting at the digester control panel.

The user interface link would also be available to allow companies associated with the maintenance and repair of the equipment to download and see data without needing to go on site or install custom expensive software. Ideally, there will be a website set up that allows users to log in and make changes at different levels, based on their user parameters.

D. Local communications link

The owner of the equipment may want closer control or faster response times than this topology affords. If this is the case, a local on-site link could be installed. This could take the form of local software that speaks DNP3 on the system owner's computer, or else even a simple web page operated from the PLC itself which could mirror the on board control panel.

V. CONCLUSION

First, the Clarkson anaerobic digester and its local control and monitoring were discussed. Next, five key events of digester operation was discussed, and their importance related to remote monitoring and control explored. Finally, a method and means for reliable distributed digester control was presented.

At the present time, the digester has been powered off and cleaned for the season. Work will continue on the control software and telemetry equipment to deploy a demonstration version of the control topology outlined in this paper. When the digester re-deploys in the spring, it will be speaking DNP3 and be web-accessible via standard software running on a remote machine, allowing users around the world to view real time digester performance, and those who need access to change set points and system control parameters.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

Greg Linder (BSEE University of Illinois, 2005. MSEE Candidate, Clarkson University, 2009) grew up in the suburbs of Chicago and has been a developer, programmer, and tinkerer all his life. His experience includes work in controlling photovoltaic systems, solar car design, and battery charge balancing systems. Additionally, he has worked on RF systems at Fermi National Laboratory and X-ray diffraction equipment with the University of Illinois.

His current research involves enabling renewable energy communications by making many small, distributed generators appear as one central control entity to utility operators. More details are available at his personal website, http://www.linderlabs.com/glinder/ .