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THESIS

INDUSTRIAL AUTOMATION OF SOLAR-POWERED HYDROGEN GENERATION PLANT

by

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June 2018

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13. ABSTRACT (maximum 200 words)

This study combined and modified designs of solar-powered hydrogen generation and compression facilities in order to allow for continuous autonomous operation of a 100-percent renewable hydrogen system. The hydrogen generation autonomous operating system was built and tested, including assembly, programming, and operation.

Utilizing a total system design approach in order to achieve long-term operation without human intervention was key. The design was based around an industrial-type programmable logic controller. It included limiting the number of sensors and controls to improve reliability. Commercial-off-the-shelf components were used due to their proven reliability, accuracy, and durability. Designed-in system safety features include smoke detectors, oxygen and hydrogen sensors, and emergency shutdown pushbuttons, which trigger emergency shutdown if an unsafe condition occurs.

The final generation system was operated continuously for nine days to prove design robustness and to provide data for system validation and improvement. Modifications to system programming and changes in sensors and controls will improve efficiencies. New developments in water distillation, dehumidification, and purification can be easily added to improve efficiency and provide the necessary water for continuous system operation. Implementation of the hydrogen compression automation system will be extremely useful in providing fuel for future projects such as a hydrogen-powered gas turbine.

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INDUSTRIAL AUTOMATION OF SOLAR-POWERED HYDROGEN GENERATION PLANT

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LIST OF ACRONYMS AND ABBREVIATIONS

ACRONYMS

AC	Alternating Current
AEMR	Annual Energy Management Report
ALU	Arithmetic Logic Unit
CPU	Central Processing Unit
COTS	Commercial-off-the-shelf
DC	Direct Current
DIN	Deutsches Institut fur Normung
DoD	Department of Defense
DOE	Department of Energy
ESTEP	Energy System Technology Evaluation Program
FY	Fiscal Year
H_2	Hydrogen Gas
I/O	Input/Output
LED	Light Emitting Diode
NPS	Naval Postgraduate School
NPT	National Pipe Thread
O_2	Oxygen Gas
PC	Personal Computer
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PV	Photovoltaic
ROM	Read Only Memory
RAM	Random Access Memory
SLPM	Standard Liters per Minute
SSR	Solid State Relay
USB	Universal Serial Bus

SYMBOLS

Symbol	Name	Units
A	Ampere	amps
in	Inch	inches
mA	Milliampere	milliamps
mm	Millimeters	millimeters
Pa	Pressure	Paschal
psi	Pressure	pounds per square inch
SLPM	Standard Liters Per Minute	standard liters per minute
V	Voltage	volts
VAC	Voltage Alternating Current	volts
VDC	Voltage Direct Current	volts
L	Volume	liters

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I. INTRODUCTION

A. MOTIVATION

The United States is the world's largest consumer of energy, much of which comes from other countries. To keep pace with an ever-changing and advancing world economy, Americans must continue developing new technologies to reduce energy usage and produce energy within U.S. borders. This thesis, an iteration in a series of theses, focuses on the automation of a hydrogen production facility previously developed by master's students at the Naval Postgraduate School (NPS).

The energy policy act of 2005 is one of the most recent laws aimed at curbing government energy expenditure [1]. Its main focus is energy and water usage, including setting goals for energy reduction. While this is the bill's main goal, it also encourages investment in new energy technologies and sets guidelines for renewable energy resource utilization. Hydrogen technology as a renewable resource is a possible solution to these goals since its only products are energy and water.

Title 8 of this bill specifically addresses hydrogen as a renewable energy source. It focuses on promoting hydrogen commercialization, encouraging energy research into the capture and usage of hydrogen, and specifically using hydrogen to diversify transportation fuels [1]. The desired end result is reduced dependency on foreign oil and a more supportive structure within the national energy economy [1]. Section 812 even encourages the use of solar and wind energy for production of hydrogen, which is the ultimate goal of this thesis series.

The U.S. Department of Defense (DoD) is required by national law to produce an energy strategy for the future [2]. Energy is an integral part of the United States' national infrastructure and economy; therefore, an assured supply of energy is also a very important consideration for government agencies, and a necessary part of the national security strategy [2]. The DoD energy strategy is specific to energy used for military operations, but an energy reduction on established military bases would be extremely valuable to the future of the U.S. military as a force.

In FY 2014, the DoD consumed 87.4 million barrels of fuel worldwide, representing not only a large cost burden for the product, but also a requirement for long supply chains which incur even greater cost [2]. While this is a 30 percent reduction from the peak year of 2007, it still represents a large vulnerability to U.S. operations around the world [2]. Having energy sources near to or at critical operational areas would significantly reduce supply chain vulnerabilities [2]. The goals of improving combat effectiveness and supportability and diversifying energy supplies directly align with of the goals of this thesis [2].

The FY16 DoD Operational Energy Report includes a section on energy needs of operational bases around the world. It specifically outlines the need for new technologies which could be used on expeditionary bases for power generation [3]. In addition, the U.S. military requires the development of sustainable microgrids for remote locations [3]. Both applications are ideal settings for a hydrogen generation and storage system like the one in this thesis. Exploring the possible elimination of the need for fuel for electrical generation in remote settings would be a valuable step in DoD energy development.

The FY15 DoD Annual Energy Management Report sets guidelines for future energy and water usage reductions. This project could provide a twofold benefit; the hydrogen process could produce electricity and also provide the byproduct of water. While this process would not reduce water or power usage, it would alleviate the need to have stringent reduction requirements. The goals of 25 percent increase in renewable energy electricity generation and 16 percent decrease in water consumption named in the aforementioned report could be tackled simultaneously [4].

B. OBJECTIVES

The goal of this thesis is to improve upon the current hydrogen plant design by creating a comprehensive system design, automating control of the system, and completing an extensive system validation test. The current system design is setup in an experimentation mode that demonstrated the feasibility of such a system [5], [6]. First, an overarching system control design was completed, including the generation and storage facilities. Second, due to the large scope of the entire design, the generation portion of the control design was implemented and validated.

The first step in the completion of this thesis was creating a comprehensive, current system drawing. Since the previous research was separated into generation [5] and compression [6] the two systems had to be combined. This was done through a combination of analyzing previous theses diagrams and retracing physical systems. Once the full system diagram was created and the hydrogen production flow understood, it was possible to focus on how to set the system up for automation.

The next step in the process was determining what components needed to be added to the system to allow successful integration between the two. A systems analysis approach was taken to both determine what sensors were likely to be needed to provide for data collection and system control and then minimize the number of controls needed [7]. The combination of sensors and controls which yielded the least number of components was desirable as it would lead to a more robust and efficient system.

Finally, a system validation test was completed. The system was run for nine days with minimal human intervention. Hydrogen flow data was collected to show actual system operational production. The multiple day test was completed to show that the system is capable and robust.

C. LITERATURE REVIEW

Current hydrogen mass production methods in the United States are traditional: using steam reforming of natural gas [8]. However, new methods such as the use of renewable energy or electrical grid power for electrolysis are becoming available [8]. Other, more advanced methods using biomass and microorganisms are the focus of some experiments [8]. The goals of this project and its continuation will help advance the possibilities of a hydrogen economy through incorporation of renewable technologies.

The use of hydrogen is growing within the private sector and should be embraced within the military to help reduce the demand for energy and water procurement [4]. The continued development of hydrogen technology by industry will allow for rapid deployment of hydrogen systems in the military setting. The use of renewable energy for hydrogen generation opens up many possibilities for remote locations and areas where other fuels are becoming increasingly expensive. Eventually, hydrogen production and usage could become more cost effective than all petroleum based fuels [8].

Foreign entities are devoting considerable resources to hydrogen production and storage technologies [9]. The issues of compression and storage are being actively pursued as the focal point for allowing hydrogen as a feasible power source [9]. Figure 1 shows the volumetric energy density of typical fuels. This figure illustrates the importance of high pressure storage solutions as they are the only means for transporting a volume of hydrogen with a high enough energy content. Storing hydrogen at pressures high enough to achieve the amounts necessary for transportation services is difficult and extremely energy intensive [9]. The hydrogen storage station developed in this thesis series has been used to test the fairly new technology of solid state hydrogen compression [9]. Solid state hydrogen technology presents a new possibility for efficient hydrogen compression [10].

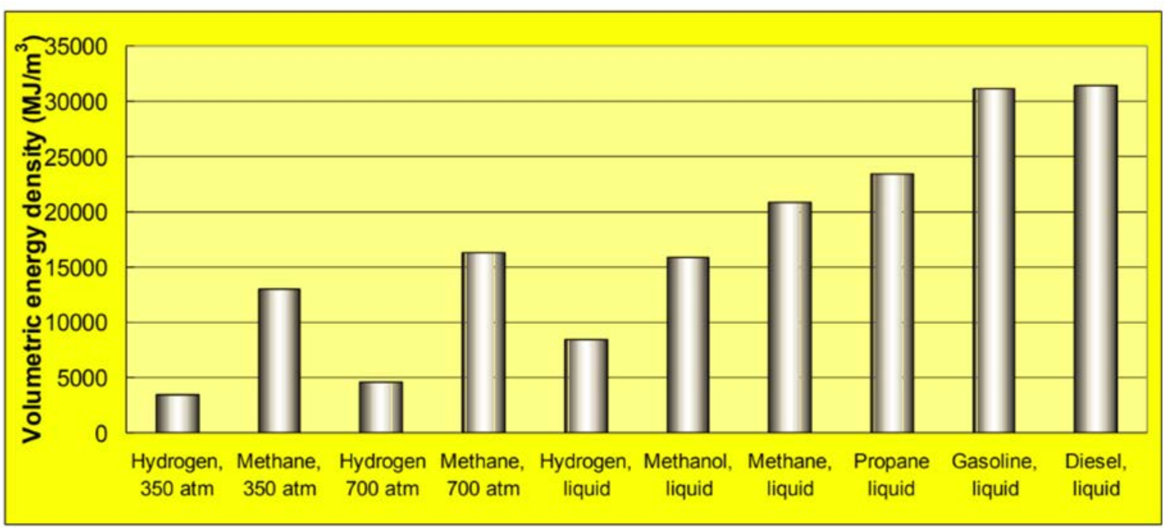

Figure 1. Volumetric energy density of typical types of fuel (LHV). Source: [9].

New hydrogen storage methods are just as crucial to the advancement of hydrogen usage as are compression techniques [9]. Gaseous and liquid storage methods are currently most widely available [9]. The storage of hydrogen in metal hydrides is possible also; through a chemical reaction hydrogen is stored in solid metal hydrogen compounds under pressure and heat is released [9]. When heat is reapplied and the pressure reduced then hydrogen is released from the metal hydrides [9]. Other storage methods are currently being developed and could prove to be more viable for this system in the future [9].

The uses of hydrogen in the electrical power sector have been discussed in the past [11]. Electrolysis for grid support can be utilized to help stabilize the grid during fluctuating electrical consumption [11]. Hydrogen conversion by fuel cell can provide a buffer during morning and evening periods when loads change considerably [11]. If a load is reduced, the generation can be ramped down slowly and excess energy can generate hydrogen [11]. If the load is increasing, then hydrogen can be consumed to avoid fast ramp up of critical machinery [11].

Because a large portion of renewable energy resources are located in the central United States, as shown in Figure 2, it is difficult to move their power to where it is needed [11]. Also, renewable sources are not constantly available; sometimes they overproduce, and sometimes they under produce, commonly called intermittency [11]. Hydrogen storage could solve both of these issues as excess power can be used to produce hydrogen which could then be sent by truck or pipeline across the country to needed locations. This transported hydrogen could be then converted back to grid electricity or used for other things such as fuel cell vehicles.

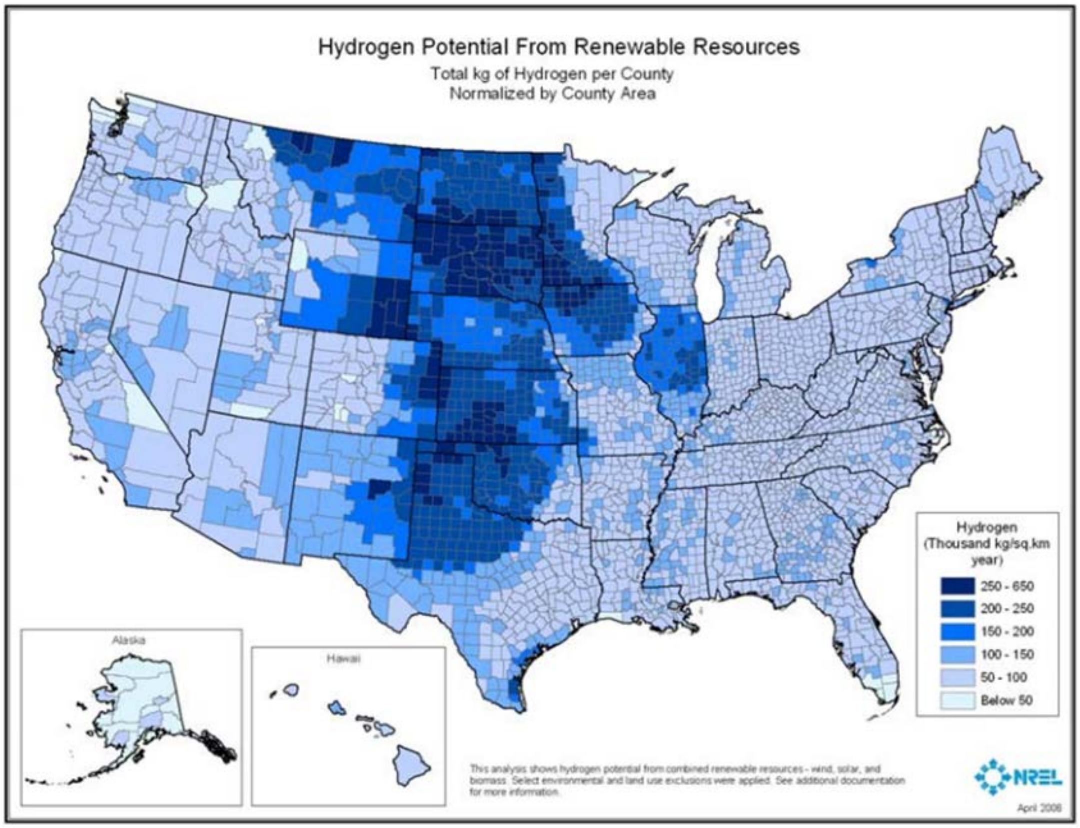

Figure 2. Hydrogen production potential from renewable resources, by county. Source: [12].

A novel type of storage system that could yield a large hydrogen storage potential is underground salt deposits [11]. Underground storage locations are created where airtight rock formations provide a closed container type of space [11]. Most of these are located in the central United States or around the Great Lakes [11]. These would be ideal since large amounts of renewable energy are located in these areas. This would provide a large buffer storage for hydrogen gas from renewables.

Hydrogen storage is an environmental imperative, and it also has certain economic benefits [13]. Assuming large scale hydrogen storage is achievable, the savings in not needing electricity generation systems to be sized to peak loads would be enormous [13]. Another benefit of hydrogen storage and pipeline transmission capability could be in the reduction of large scale transmission lines. [13]. Pipeline distribution of hydrogen for usage in fuel cells could dramatically reduce costs of power transmission over long distances. [13].

D. PREVIOUS SETUP

1. HYDROGEN GENERATION

The original work of this research was geared toward proving the concept of a solar powered hydrogen production facility [14]. Designing the system using commercial-off-the-shelf components (COTS) was a key goal [14]. Utilizing the hydrogen generated by the system to power a fuel cell it provided preliminary data on the feasibility of this idea [14]. This preliminary data, collected for a previous thesis, was used with a scalability factor to decide if large scale systems of this type could be cost effective in the future [14]. The following is a brief description of the components of the system and how they are utilized. Figure 3 shows the original concept design diagram [14].

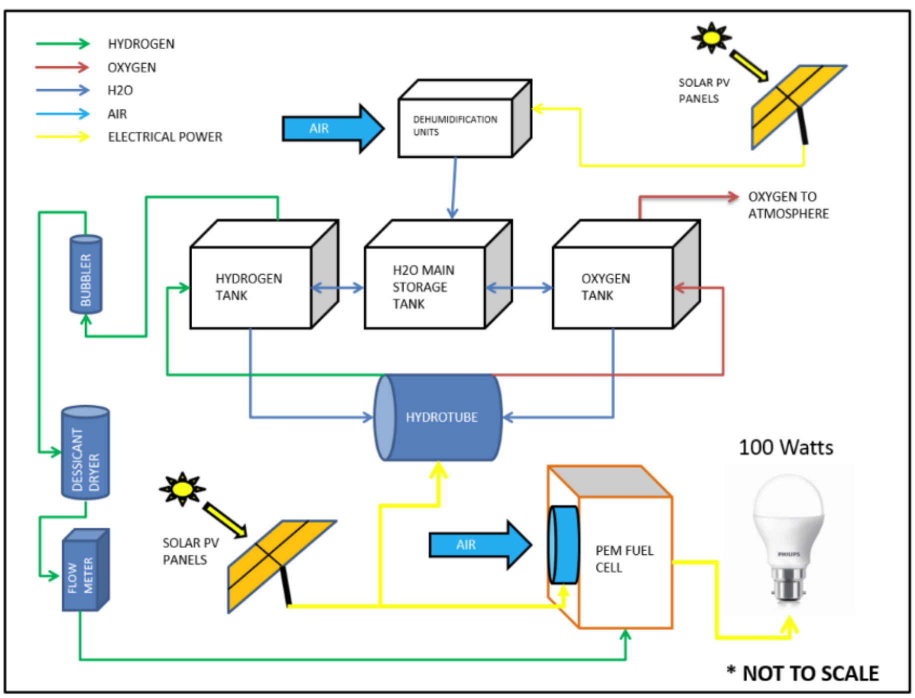

Figure 3. Original concept design diagram. Source: [14].

Distilled water generation was accomplished by the system with four dehumidification units [14]. These units had internal tanks which stored the distilled water [14]. Due to this setup it was necessary for the operator to manually shutdown the system to fill the hydrogen and oxygen process tanks [14].

The alkaline electrolyzer required that the operator prep the system before operation because the electrolyzer had to be supplied with a solution of potassium hydroxide [14]. The operator mixed the proper percentage of salt into the distilled water to initially fill the process tanks, electrolyzer, and associated tubing between the process tanks and the electrolyzer [14].

The bank of solar panels and charge controller provided the system with approximately 12-volt direct current [14]. The charge controller automatically started up when the solar panels were receiving enough power for startup. This feature allowed for easier control of the system but did not help regulate the power needs of the system [14].

The electrolyzer fed hydrogen and oxygen to the respective process tanks at approximately 3447 Pa (0.5 psi) above atmospheric [5]. When water is disassociated, it produces a larger gaseous volume of hydrogen than oxygen [5]. This difference in volume produced a pressure differential between the two process tanks, which was addressed by the operator manually adjusting a needle valve [5]. This would allow more of the oxygen gas to escape so the volume of hydrogen leaving the system would be the same as the volume of oxygen leaving the system [5].

At the outlet of each of the process tanks was a water bubbler [5]. The bubbler was especially necessary on the hydrogen side and had the effect of removing particulates and other gasses from the hydrogen stream [5]. It also served as a barrier to prevent backflow of air into the hydrogen process tank [5]. The bubbler on the oxygen side helped to smooth out the needle valve operation and allowed the operator to monitor the oxygen outflow more easily [5].

In each process tank outlet was a gas flow meter [5]. These were included in the system for experimentation and validation purposes and are not necessary for hydrogen production [5]. They are kept on the system in case changes are made to components in the future and additional testing is needed [5].

On the outlet of the hydrogen line after the bubbler was a desiccant dryer, shown in Figure 4 [5]. This ensured that moisture was removed from the hydrogen before going to the fuel cell [5].

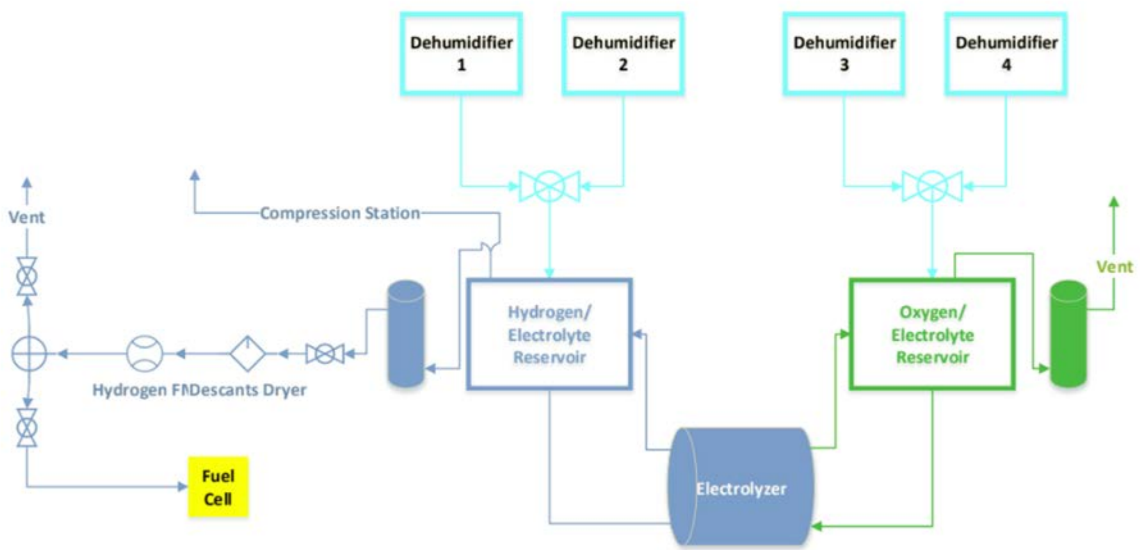

Figure 4. Second iteration concept design diagram. Source: [5].

2. HYDROGEN STORAGE

One of the more recent developments in this project was a hydrogen compression and storage facility which was fed hydrogen from the generation system [6]. The complexity of the hydrogen compression system prevents discussing every valve and gauge in the system but is shown in Appendix A [6].

The basis for the hydrogen compression system was the Xergy brand electrochemical compressor [6]. This compressor has no moving parts but instead uses direct current to transport hydrogen molecules through a proton exchange membrane to increase pressure [6]. These compressors have the potential for higher efficiencies and longer operational cycles between maintenance when compared with traditional mechanical compression methods [6].

The high pressures needed to achieve the desired storage capacity required the use of multiple safety devices [6]. Rupture disks and relief valves which vent to atmosphere were located throughout the system and protect from over compression [6]. Since this thesis only focused on compression facility design and not actual operation these safety devices are adequate for monitored testing purposes [6]. Future programming and automation can shut down the system before these devices are tripped in order to save already compressed hydrogen [6].

II. ENABLING TECHNOLOGY

A. PROGRAMMABLE LOGIC CONTROLLERS

To build a robust control system, a programmable logic controller (PLC) is used for system control. This chapter gives a brief overview of PLCs as described by Bolton in his book, *Programmable Logic Controllers* [15]. PLCs are designed to be used in industrial and manufacturing settings where high cycle reliability is needed. The ease and relative simplicity of programming helps to make PLCs available to engineers and allows for ease of troubleshooting by trained technicians [15].

A PLC is a digital computer which is simplified for a specific purpose. The origins of the PLC rest in the automotive industry, and were designed as a way for engineers to automate industrial processes. The logic based step-by-step system found in PLCs allows for simple programming without an extensive knowledge of computers or computer type programming. A simple, rugged design which can be used in almost any environmental conditions make PLCs ideal for the industrial setting [15].

PLCs are generally a combination of a central processing unit (CPU), power supply, programming device, memory storage unit, input/output (I/O) interfaces, and communication paths. The CPU carries out the program stored in the memory. It includes a clock based on the processing speed of the CPU. Due to the use of timer instructions, the clock is an integral part of a PLC. The CPU also contains an arithmetic and logic unit (ALU) which is responsible for most other instructions used in PLC programming [15].

Inside the PLC, the busses provide the communication paths within the unit. Information within the unit is transmitted in binary in groups of bits. The data bus takes data to and from the CPU for processing. The address bus tells the CPU where information is to be taken from or written to. The control bus is used by the CPU to instruct memory devices to receive or send data or perform some other auxiliary action. The system bus takes signals to and from I/O devices [15].

PLCs also contain a small amount of memory necessary for their operation. As opposed to a conventional computer, PLCs are not designed to store large amounts of data.

Read only memory (ROM) provides a permanent storage location for the PLC operating system. Random access memory (RAM) serves as the storage location for the users program and sensor data storage. I/O device information, values of timers and counters, and other important information necessary for program operation are stored in RAM as well [15].

The I/O unit provides an interface between the PLC and outside devices such as controls and sensors. Each I/O point has a unique address that can be referenced in the associated control program. The I/O modules provide isolation and signal conditioning when they interpret incoming signals into bits. There are multiple different types of signals that can be used such as 12/24 volt digital signals and 0–5 volt or 4–20 mA analog signals [15].

Programs are written for PLCs using various types of language. Originally ladder logic was developed which allowed the programmer to easily see the steps which the unit was taking as it moved through the program. PLCs now have options such as structured text programming, which is typically considered traditional computer programming. There is also the functional block diagram type of programming interface which allows for a more flexible type of ladder logic programming. These programs are usually written using a programming software specific to the PLC manufacturer chosen [15].

To provide information for the CPU to make decisions, input devices are necessary. Sensors and transducers satisfy this purpose by converting physical readings into electrical signals. Digital sensors provide a discrete, on/off signal. Analog sensors provide a signal which has many possible values which are proportional to the variable being measured. Later in this chapter are descriptions of the various types of I/O devices which will be used for this project [15].

Many performance characteristics can be applied to sensors but for this project only a few are important: error, accuracy, range, and reliability. Error is the relative difference between the measured value and the actual value. Accuracy of the sensors can be adjusted to produce the sensitivity necessary for the application. The range of a sensor can greatly affect the accuracy if measuring a large range is necessary. Reliability is also important since this system is designed to function reliably for a long period of time [15].

B. INPUT DEVICES

Various input devices are needed to provide external information into the system for the PLC program to act on. Mechanical switches generate an on or off signal depending on their position. When a switch is thrown or a button is depressed, a signal is sent to a digital input on the PLC. These switches are generally user operated but can be automatically pressed by some movement in the process design [15].

Temperature sensors come in various designs and can serve different purposes. In this project, thermocouples will be used. The current generated within the thermocouple produces an analog signal which can be fed into an analog input of the PLC. The benefits of thermocouples are that they are relatively rugged and can operate over large temperature ranges [15].

Pressure sensors are necessary to monitor pressures on the compression side of the hydrogen generation system. The pressure transducers in this system operate using a diaphragm and pressure cavity to create a variable capacitor [16]. As the diaphragm is deformed by a change in pressure, the capacitance changes [16]. This change can then be converted to an analog signal used by the PLC [16].

Liquid level indicators are used to monitor the level of substance in a tank. In this project, ultrasonic tank level sensors are used. They provide an analog output of the level of a tank by bouncing sound waves off the surface of the liquid [17]. This type of sensor is programmed before use and depends on the depth of the tank and the height of the sensor from the bottom of the tank [17].

Current transducers are utilized in this project for data collection and system operation. A current transducer consists of a metal coil encircling the wire that a current is flowing through [18]. The magnetic flux created by the current in the wire produces a proportional current in the coil using the Hall Effect [18]. This generated current, along with the associated electronic circuit, produces an analog signal which can be sent to the PLC [18].

A voltage transducer is different from a current transducer in that the circuitry provides a direct contact to the line being measured [19]. In this circuit, the voltage being measured is applied through a series of resistors and amplifiers to change the signal to the desired proportional analog signal [19]. An isolation amplifier is included in this circuit which isolates the voltage being read from the rest of the transducer circuitry in order to prevent damage to the rest of the system if a short or overload occurs [19].

C. OUTPUT DEVICES

A second group of devices are used by the PLC and its program to regulate system operation. Solid state relays (SSR) are similar to mechanical switches, but are specifically designed for controlling processes with digital outputs from the PLC. They do not have any moving parts but instead use semiconductor switching elements to open or close a switch. SSRs use an LED and photocoupler setup to open and close the associated circuit. As the digital signal is sent from the PLC to the SSR it lights up the LED which shines on the photocoupler which then closes (or opens) the desired circuit [15].

Control valves come in many different types. For this project, electric solenoid operated fluid valves are used to control water movement between tanks. When the PLC sends a signal to the SSR, it closes the solenoid circuit for the valve which then opens or closes the respective valve [15].

Proportional valves are similar to standard control valves but instead of an open or close setting they have multiple settings. A proportional valve is used to finely control the amount of fluid that can pass through it. The valve receives an analog signal from the PLC and opens or closes to a level proportional to that signal [15].

D. DATA COLLECTION

Data collection is accomplished using a separate PC running MATLAB software. MATLAB code, shown in appendix G, was written to pull data from the flow meter and store it for later analysis.

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III. DESIGN STRATEGY

A. OVERALL DESIGN

The numerous components within this system presented an automation design challenge. This section details the overall design strategy and how major design challenges inherent to the system were approached. Specific means for achieving these goals will be discussed in the sensors and controls sections as well as the programming section. The design was influenced by the following factors: process tank refilling during operation, sensitivity of electrolyzer to voltage variations, and process tank balancing. The overall system design is shown in Figure 5.

A two level tank design was utilized to allow for filling the process tanks while they are in operation. This prevents air from entering the system and eliminates the need for a purge cycle after each refill. While the dehumidifiers are operating, the water they produce drains directly into the storage tanks through a normally open valve. As the level of water in the respective process tank becomes low, the valve between the storage tank and the process tank opens and the valve between the storage tank and the dehumidifiers closes. The water inside the storage tank does not let air into the process tank as the water drains into it as long as the water in the storage tank is above a minimum level. This allows for continuous operation of the system.

Second, the electrolyzer operates over a very small voltage range. Equipment operation coupled with the variance of solar power necessitate a control scheme to ensure the electrolyzer is operating at an optimum power level. To do this, each individual piece of equipment must be capable of being turned on and off. If the electrolyzer voltage becomes too low, the system needs to turn off the dehumidifiers to ensure that the electrolyzer stays within its operating voltage range. The programming scheme that allows this to happen will be discussed in the programming section of this report.

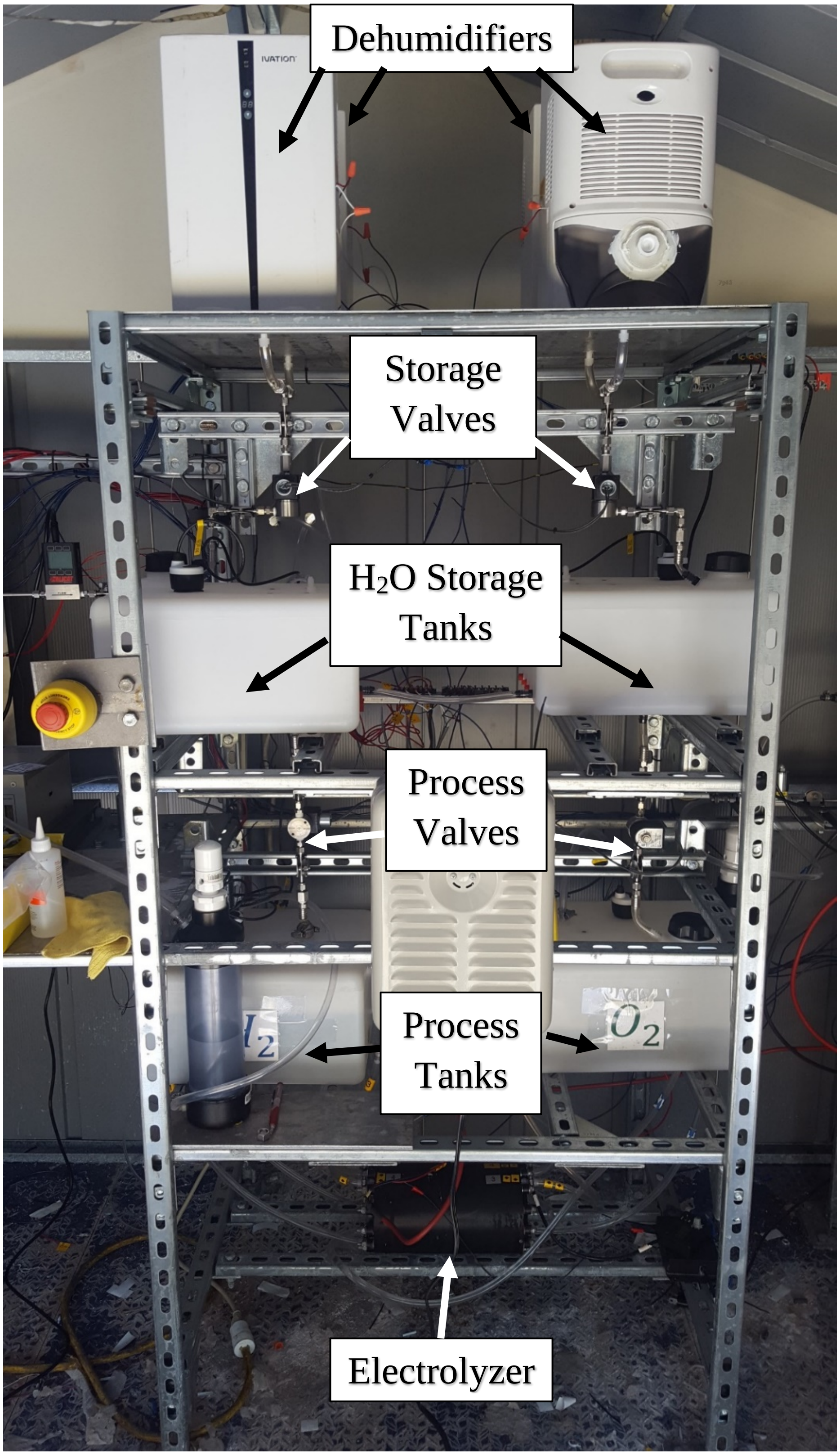

Figure 5. Overall mechanical system design.

Finally, the most challenging part of this system is balancing process tank levels. The levels in these tanks must be kept nearly equal to allow continuous operation of the system. Two factors make balancing difficult; fluctuations in gas production due to fluctuations in solar power, and gaseous hydrogen having a lower density than oxygen when the water is disassociated. As more water is split, the needle valve is closed slightly to account for the proportionally lower amount of oxygen being produced. To control this, a proportional valve is used. This allows the PLC to calculate an analog signal which will set the valve at the proper height. In addition to the proportional valve, a normally open backup valve is located in a secondary oxygen process tank outlet line. This is necessary because when the system is operating in an open configuration with no back pressure, the proportional valve will not allow enough oxygen out to balance the tanks. The programming scheme used to achieve this control will be discussed in the programming section of this report.

B. SENSORS

When considering sensor design, the system was broken down into six categories: flow meters, current and voltage transducers, pressure transducers, tank level indicators, thermocouples, and safety sensors. The following is a discussion on each of these categories and how they were approached.

An Alicat brand flow meter is located on the hydrogen process tank outlet for data collection. This flow meter is calibrated for hydrogen gas flow measurement and includes a 9 pin connector for data output. A laptop, running MATLAB, is used to pull data from the flow meter and record for later analysis.

Voltage transducers are installed on the charge controller and electrolyzer. These sensors are necessary when programming to tell certain pieces of equipment when to turn on and off, depending on solar power input and electrolyzer voltage.

Pressure sensors will be used on the compression side of the system. A pressure sensor will be utilized before and after the compressor to obtain data on the solid state compressor performance. Another pressure sensor will be used in line before the fuel cell to provide a measurement for data on fuel cell hydrogen consumption. It may also be necessary in the future to vary the pressure into the fuel cell, especially as the system is upgraded and expanded. A pressure transducer in concert with a controllable regulator will allow for varying pressures into the fuel cell. The last pressure transducer will be on the storage tank bank and it will provide a signal to be used by the PLC to ensure the pressure in the tank bank does not get too high. A pressure sensor will be located on a nitrogen tank bank for system purging and valve control on the compression side of the system. Another pressure sensor will be located on a spare hydrogen tank used in the purging process.

Tank level indicators are used in multiple locations throughout the system. Distilled water storage tanks serve two purposes; adding water to the process tanks to keep the system running at optimal efficiency, and providing a collection area for the dehumidified water. Process tanks store the potassium hydroxide solution necessary for the electrolyzer to function properly. Process tank level measurements are used by the PLC for two main decisions; to ensure that process tank levels are within limits, and to regulate the proportional valve to maintain tank level equality.

C. SAFETY

As this system is developed toward the goal of a feasible, commercialized system, safety will become increasingly important. Due to the explosive nature of hydrogen gas, there will be multiple safety features built into the system.

Emergency shutdown buttons are located in easy-to-reach locations, built into the design of the two buildings. The emergency shutdown buttons feed a digital signal into the PLC and trigger total system shutdown if pressed.

Smoke detection units are built into each building which feed a digital signal into the PLC and trigger total system shutdown if tripped.

Hydrogen sensors will be installed in the rafters of each building and will function in a similar manner as the smoke detectors. Due to the highly flammable and explosive nature of hydrogen, the hydrogen concentration in the air must be kept below 4 percent. These hydrogen sensors will send a digital signal to the PLC if a 3 percent hydrogen in air concentration is detected.

Due to the potential fire and explosion hazards of the system, oxygen sensors will be used in key locations. One oxygen sensor will be placed in the outlet line of the process tank to ensure there is no oxygen leaking into the system or through the electrolyzer. Another oxygen sensor will be placed in the outlet line of the compressor to ensure that no oxygen has leaked into the system before the hydrogen goes into the storage tanks. These oxygen sensors will also help to analyze the electrolyzer, compressor, and piping capability to keep outside gasses from leaking into the system.

D. CONTROLS

Once the PLC receives inputs from the sensors, it can use its program to make decisions on how to operate the controls in the system. The focus in control design is to allow the system to operate autonomously while using the minimal number of controls. To do this, the types of controls were broken down into the following sections: switches, gas valves, and liquid valves.

Different types of switches can be used for autonomous control. For this project, solid state relays (SSRs) are the best option for multiple reasons. The benefit of using SSRs in this project is that they have no potential for sparking when the switch is opened or closed because the switching is done internally to the relay with no moving parts. An electromechanical relay, on the other hand, has actual metal contacts that are moved to close a circuit. This could cause a spark, which would be very dangerous if there was a hydrogen leak in the system.

SSRs are located throughout the system. Any place where an electrically operated piece of equipment is located, an SSR is used to turn it on and off. The dehumidifiers, electrolyzer, tank valves, hydrogen compressor, and fuel cells all have their own SSRs.

Gas valves are included in the system design and will be installed in a future iteration of this project. One valve will be located on the outlet of the generation side of the system. This allows the system to stop running and remain primed. Another valve is located on the hydrogen buffer tank. Due to the large amount of hydrogen that will eventually be stored here, it is a good safety measure to have a controllable vent valve in case of emergency. Another controllable gas valve will be located on the outlet of the hydrogen storage tank, to allow the system to save the already produced hydrogen if either the generation or compression sides of the system need to be shut down.

After the compressor is a critical junction in the system. A controllable valve will be required on all three legs of this junction: the leg coming from the compressor, the leg going to the fuel cell, and the leg going to the storage tanks. These valves are needed because the compressor is not “airtight” and will leak hydrogen if it is under pressure and not operating. If the fuel cell is in use, the valve to it must be opened and the valve to the compressor must be closed if hydrogen is not being produced at that time. The valve at the inlet/outlet of the storage tanks will help store compressed hydrogen and will be opened if compression is in progress or if the fuel cell is being used.

IV. PRODUCT SELECTION

A. CONTROLLER

A wide range of PLC companies provide products that suit the needs of this thesis, but the choice of PLC for this project was not difficult. In previous theses done for the Energy Systems Technology Evaluation Program, (ESTEP) Allen Bradley PLCs were used in conjunction with Rockwell Automation's Connected Components Workbench (CCW) software. The ease of use of this brand of PLCs and the CCW software made those the ideal choice for this project.

Allen Bradley controllers are used for a wide variety of industrial automation processes. The Micro850 range of controllers was chosen for this project because they have been successfully incorporated in previous theses. The Micro850 range of controllers come in a base model utilizing 24-point or 48-point input output controller modules [20]. Due to the number of sensors and controls needed for this project and the housing of the project in two separate buildings, the 24-point controller was chosen. This allows for two 24-point controllers, one for each building, to be incorporated into the system; in the future, these controllers could be linked together over an Ethernet connection. The Micro850 24-point controller chosen includes 14 12/24 volt inputs and 10 24 volt source outputs [20]. The ports included on the controller are digital input output ports [20].

The Micro850 line of controllers also support multiple plug in modules and expansion blocks, which allowed for customization of the controller for the needs of this project. In order to read multiple analog input signals, two 2080-IF4 plug in modules were added. Each of these modules has 4 analog input ports which convert analog input signals into digital unsigned integers [21]. These signals feed into the PLC program and are refreshed every time the program cycles inside the PLC [21].

The other plug in module used was the 2080-OF2. This is an analog output module which supports two analog outputs [21]. These outputs can be used to control devices which have a continuously varying range of settings. This module is used for controlling the proportional valve signal as well as the on/off signal for that valve.

Two expansion modules were also added to the controller. The OF4 analog output module was added in case more analog outputs are needed later, and the OB16 module was added to provide 16 more digital output ports to the controller. This module was necessary to control the secondary oxygen outlet valve to make it possible for the system to balance tank levels. Figure 6 shows the Micro850 controller as wired with all attached plug in and expansion modules [22].

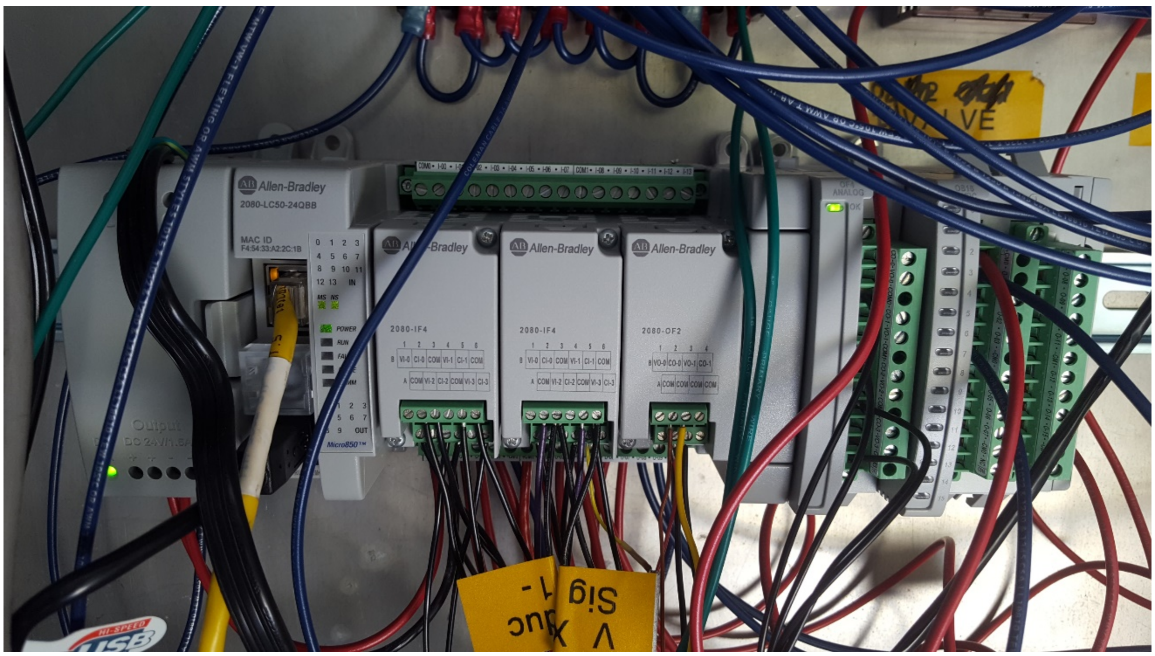

Figure 6. Allen Bradley Micro850 controller with plug in and expansion modules.

B. SENSORS

This system contains extra monitoring equipment because it is still in a relatively experimental phase. The addition of this equipment may be used for controlling the system in the future. It will be useful in keeping track of efficiencies within the system and could also provide an indication of equipment failure or malfunction.

Two different models of Eaton Cutler-Hammer DC current sensors were chosen for this project. The model EDC2420SP can support 50, 75, or 100 amp current [18]. The model EDC1420SC can support 5, 10, or 20 amp current [18]. The selectability of current range ensures that the highest fidelity in measurement can be achieved. These sensors are also useful because they can be repurposed in the future if new equipment is added. Both current sensors includes a 4–20 mA analog output which can be sent to the PLC [18].

Alicat flow meters were already located throughout the system, but only one is needed for this thesis. The model M-5SLPM-D/5M flow meter is used in this application. It reads volumetric flow rates up to 5 Standard Liters per Minute (SLPM) [23]. The data from the flow meter is output to a combiner box which has a USB output. This USB output is used by MATLAB to record the flow meter data. Figure 7 shows the Alicat flow meter as installed in the system.

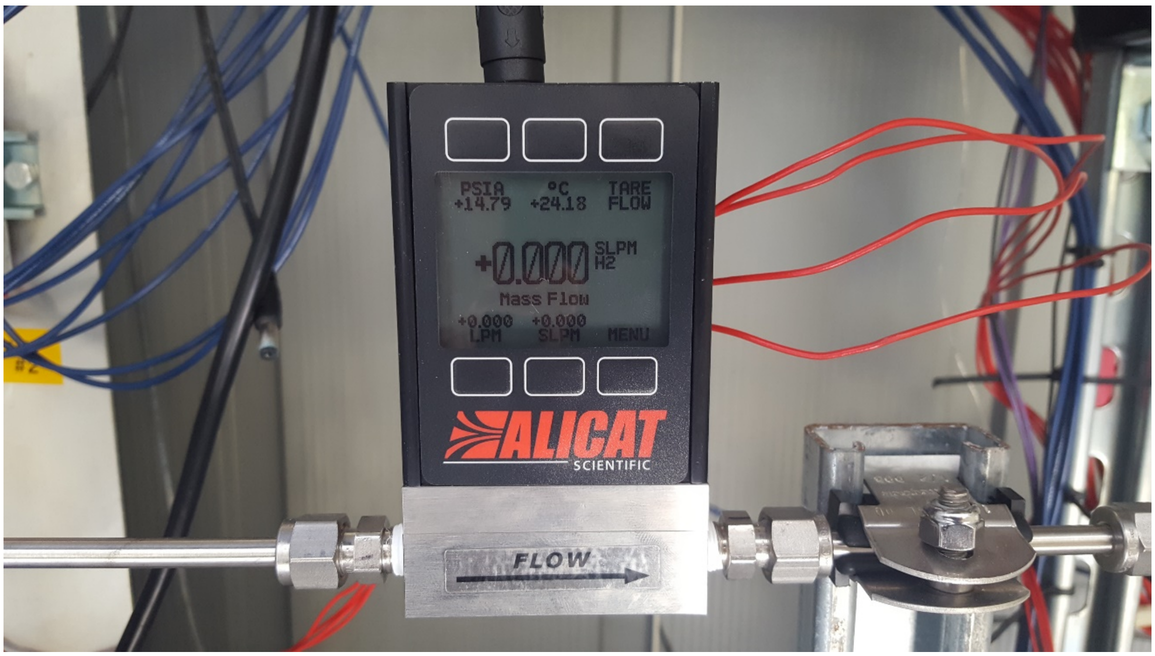

Figure 7. Alicat hydrogen flow meter.

The next group of sensors is the Phoenix Contact DC voltage transducer model MACX MCR-VDC. This sensor can support various voltage ranges from 0 to 660 DC volts, and the main voltage ranges used for this project are the 0 to 24 volt range and the 0 to 120 volt range [19]. Like the current sensors, the voltage sensors can be used with different equipment if necessary and offers a high fidelity in measurement due to the selectability. It includes a 4–20 mA analog output which can be sent to the PLC [19]. Figure 8 shows the voltage transducers which are located below the junction box on the right side of the system.

Figure 8. Phoenix Contact voltage transducers.

The tank level indicators are an integral part of this system as they provide the signal used by the Proportional Integral Derivative (PID) portion of the control program to maintain tank level. The Omega Engineering LVCN414-I, an ultrasonic non-contact tank level sensor, was chosen for this project. It is a programmable sensor adaptable to a range of tank sizes [24]. The adaptability is good for system upgrade purposes because future system development may require larger process tanks as the electrolyzer size increases. The sensor bounces a signal off the top of the water and calculates how long it takes the sound wave to travel to that surface and back to the sensor [24]. Then, using the programmed range, it sends out a 4–20 mA signal proportional to the tank level [25]. One of the tank level sensors inserted into the process tanks is shown in Figure 9.

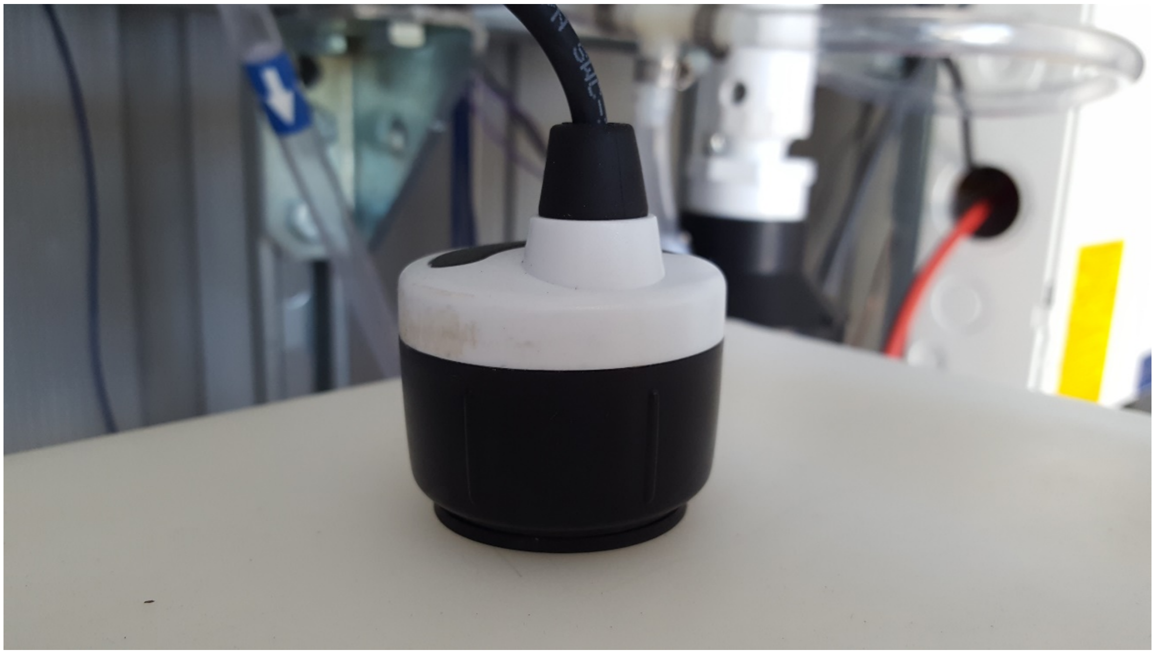

Figure 9. Omega ultrasonic tank level indicator.

Another challenge was created when this type of sensor was chosen. Since this sensor operates by bouncing sound waves off the level of the fluid in the tank, the gas in the rest of the tank affects the speed at which those waves travel. The speed of sound through hydrogen gas is 1270 m/s and the speed of sound through oxygen is only 326 m/s, and so the sensor readings needed to be adjusted while in the system. Since these sensors are calibrated for use in air this posed a problem. The solution was to take the signal input to the PLC and subtract a number which caused the PLC to see the correct tank height. This was done by operating the system until the tanks were filled with the respective gasses. The subtracted signal was then changed until the tank level reading was correct within the PLC program.

Safety measures must be built into the system design due to the potential of flame or explosion due to hydrogen leaks. Banner Engineering SSA-EB1P-02ECQ4 emergency shutdown buttons are located in each building, as shown in Figure 10. The pushbutton is supplied with power from the 24 volt PLC buss which feeds through to the PLC digital input port [26]. When the button is pressed this connection is broken which triggers a total system shutdown.

Figure 10. Emergency stop pushbutton.

Any flame or spark could cause flame propagation or explosion if a hydrogen and oxygen mixture is present in sufficient quantities. The ideal system will have good leak integrity and contain all H2 created, however, other components in the system could catch fire and damage the system, increasing the risk of H2 leakage. To mitigate this risk, smoke detectors have been added to the system which, if activated, trigger total system shutdown. The smoke detector chosen is the Edwards Signaling 711U, a simple three wire module, which provides a signal to the PLC if the smoke alarm is triggered [27]. Figure 11 shows the location of the smoke detector within the building, located in the rafters for maximum sensor coverage [27].

Figure 11. Smoke detector.

C. CONTROLS

This system is still in the experimental stage and is not equipped with battery or capacitor storage. The lack of reliable power for automation controls led to the selection of controls which operate off 120-volt outlet power or 24 volt DC power from the PLC power supply.

SSR selection for this system involved the consideration of several factors. SSRs used within this system were chosen to be compatible with known equipment voltage and current ranges. Due to the continuously evolving nature of the system, most of the components are oversized to account for future upgrades. The chosen PLC requires that the SSRs be able to be controlled with a 24V digital output.

The Crydom DC100D100C was the SSR chosen for control of the electrolyzer circuit. This relay can be used for voltage up to 100 VDC and amperage up to 100 A [28]. Although the max current of the electrolyzer in the system is only 45 A, this will allow for future upgrade to a larger electrolyzer for increased hydrogen production. In this system an external heat sink is used with the SSR since it has a high level of power flowing through it [28]. Figure 12 shows the location of the SSRs mounted on the heat sink. Two SSRs are used for the electrolyzer because current flows through the electrolyzer from the positive and negative terminals.

Figure 12. Crydom solid state relays used for electrolyzer control.

The Magnecraft 861SSR115-DD was the SSR chosen for control of each dehumidifier circuit. Since each dehumidifier is controlled independently for system programming purposes, a smaller SSR can be used. The dehumidifiers operate at about 6 A and 12 VDC. This SSR has a max current rating of 10 A and max voltage rating of 32 VDC [29]. This SSR contains an internal heat sink which provides adequate heat dissipation for the unit, provided the separation distance from nearby SSRs is adequate [29]. Figure 13 shows the location of the SSRs as mounted on the main control panel.

Figure 13. Magnecraft relays for control of dehumidifier power.

The OMRON G3NA-225B is the SSR used for all valves except the proportional valve. This SSR can operate with a load voltage up to 240 VAC and amperage up to 25 A, which is necessary since the valve solenoids operate on AC power and at steady state will be in the range of 12 A at 120 V [30]. These SSRs are mounted to a metal panel, which provides adequate heat dissipation without requiring an external heat sink [30]. In addition, the valves controlled by these SSRs operate intermittently and for only a few seconds during tank top-off. Figure 14 shows the mounting of the SSR used to control the backup oxygen tank outlet valve.

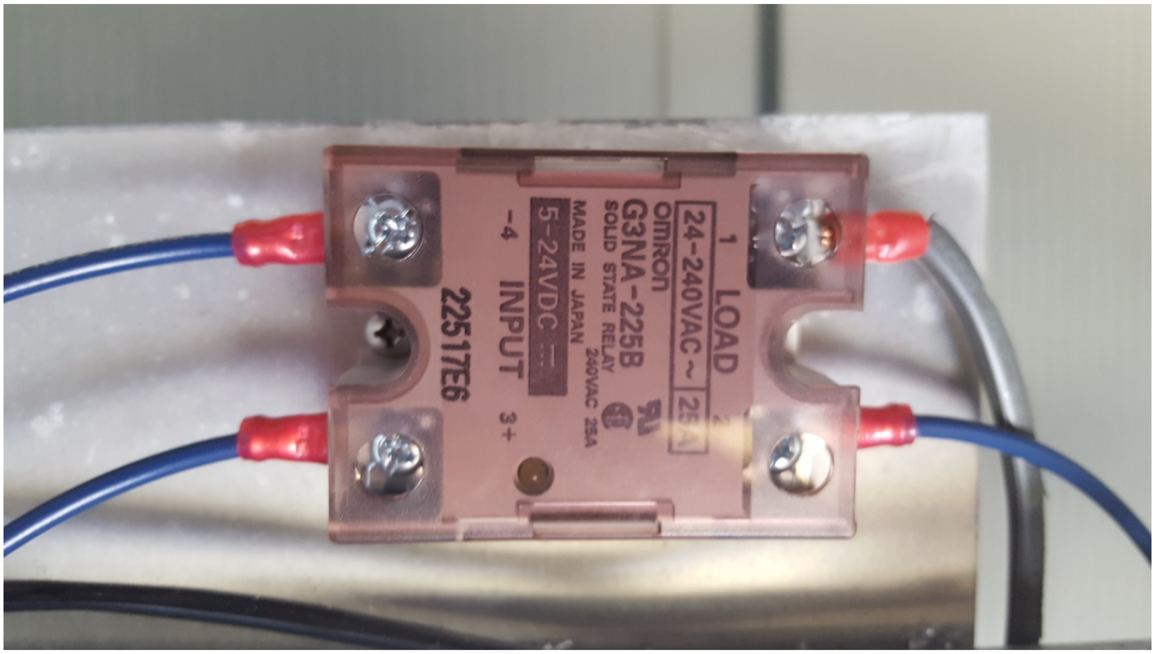

Figure 14. OMRON relay used for valve control.

With the new setup of the system the flow in and out of the storage and process tanks must be controlled. Solenoid operated valves are best suited for this purpose because they are controllable and will experience only a light duty cycle. The valves controlling the flow between the dehumidifiers and the process tanks need to be normally open valves so that, during normal operation, the water produced by the dehumidifiers will empty directly into the storage tanks. The valves between the storage tanks and the process tanks need to be normally closed valves so that the hydrogen produced can be fed to the compression side of the system.

The Omega SV133 valve was chosen for the connection between the dehumidifiers and water storage tanks. This is a normally open, direct acting solenoid valve in a coil, plunger, and sleeve configuration [31]. The plunger spring holds the valve open allowing flow through [31]. When the proper voltage and current are applied, the electromagnet causes the stop to attract the magnetic plunger [31]. This causes the plunger to contact the orifice to prevent flow through while compressing the spring [31]. When the power is turned off, the spring pushes the plunger back up and opens the valve again [31]. Figure 15 shows the location and piping around this normally open valve between the dehumidifiers and the oxygen H2O storage tank. This valve was chosen because it is designed for liquids or gasses, it has a large ambient temperature operating range, and has a standard power supply [31]. The power supply utilizes standard 120 V power so it can be connected directly to wall outlet. It also has a ¼ inch National Pipe Thread (NPT) fitting which works well for the system configuration [31].

Figure 15. Omega SV133 normally open fluid control valve.

The Omega SV127 was chosen for the connection between the water storage tanks and the system process tanks. This valve has similar characteristics to the SV133 except that it is a normally closed valve [32]. In this valve, the plunger is held against the orifice by the spring [32]. When power is sent to the valve the magnet acts to pull the plunger away from the orifice, letting liquid flow through [32]. All other specifications are the same as the SV133. Figure 16 shows the location of the valve between the oxygen water storage tank and oxygen process tank.

Figure 16. Omega SV127 normally closed fluid control valve.

The proportional valve controls the flow of oxygen out of the oxygen process tank. Based on the analog signal received from the PLC, the proportional valve opens and closes to let the necessary amount of oxygen out of the system, balancing the liquid levels in the hydrogen and oxygen process tanks. For this task, the FSV13 was chosen. The FSV series of valves have fast response times, large temperature ranges, 4 to 20 mA control signals, and good leak integrity [33]. The FSV 13 was chosen specifically for its 21,500 mL/min max fluid transfer rate [33]. Figure 17 shows the FSV13 valve on the left and its signal control box on the right.

Figure 17. Omega FSV13 proportional control valve and corresponding control box.

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V. PROGRAMMING

A. CONVERSION FROM ANALOG TO DIGITAL

As discussed earlier, this project uses multiple analog devices for both measurement and control through the PLC. The signals from these devices must be converted from a continuous analog signal to a digital variable for use in this system. This is done through the analog plug-in module of the PLC. This module takes the continuous 0–20 mA or 0–10 V signal it receives and turns it into an unsigned integer variable that can be used inside the PLC programming. Since this PLC uses 16 bit unsigned integers, the value shown will be a number from 0 to 65,535. This conversion is done using formulas 1 and 2, depending on input type [15].

$$\text{unsigned integer value} = \text{current in} \times \frac{65,535}{20} \tag{1}$$

$$\text{unsigned integer value} = \text{voltage in} \times \frac{65,535}{10} \tag{2}$$

Analog values can be converted to real numbers to aid in understanding system performance and programming adjustment. For example, it may be beneficial to know the tank level in millimeters (inches) so that the program can take the appropriate action if the level is too high or low. First, the unsigned integer is converted to a real number which has the same value as the unsigned integer but the program now recognizes it as a real variable type. Then, Equation 3 is used to turn the analog value into the real-world variable value desired.

$$\frac{x_I - x_B}{x_H - x_L} \times \left(y_H - y_L\right) + y_L \tag{3}$$

In this equation, variables are defined as such: x_I is the analog input value; x_H is the analog high value 65,535; x_L is the analog low value 0; x_B is the analog baseline level of the sensor, or the reading at its lowest level. The real-world variables in this equation refer to the lowest and highest possible values; y_H is the real-world high value, and y_L is the real-world low value. Using the tank example, the lowest possible value of the tank level is 0 mm (0 in) and the highest possible value is 139.7 mm (5.5 in).

B. PROGRAMMING BLOCK DESCRIPTIONS

The CCW software gives the programmer the option of using structured text, ladder diagram, or function block diagram programming. The step-by-step, visual nature of the function block diagram programming type made it ideal for this project. A function block is the basic unit of this style and is what makes calculations or decisions within the program. Function blocks are organized into three main categories discussed below; standard function blocks, user defined function blocks, and ladder diagram type blocks. Standard function blocks are numerous and common to a variety of PLC programs. The standard blocks used in this thesis are described in detail in Appendix D.

1. User Defined Function Block Descriptions

The user defined function block allows the programmer to create a unique block that can be reused throughout the programs without the need to rebuild for each calculation. The user defined function block is embedded in each main program and visually acts like any other single function block. These blocks are used in this program to calculate tank levels and voltage readings.

a. Tank Level Measurement

Since information about tank levels was needed in multiple programs, a tank level measurement block was created for each tank. Each tank needed its own measurement block for calibration purposes. While the tank level indicators were all programmed in the same way, their readouts are not exactly the same. These small deviations and adjusting for the difference in sound speed through hydrogen and oxygen gasses meant that a baseline value had to be subtracted from the sensor readout. The baseline value is adjusted after the system reaches a steady state operation.

Figure 18 shows the construction and flow of the analog value through a user defined function block. Prior to the analog value entering the function block, it is converted from an unsigned integer variable to a real variable using an ANY_TO_REAL block. The variable then has the baseline value subtracted from it. This baseline value is determined by experimentation and is different for each tank. This value is then divided by the analog high signal (65,535) and multiplied by the reference point high signal which is the maximum value the sensor can read. Since all of the tanks are the same size, this value is 139.7 mm (5.5 in). The resulting variable output is the current level of the tank in millimeters (inches).

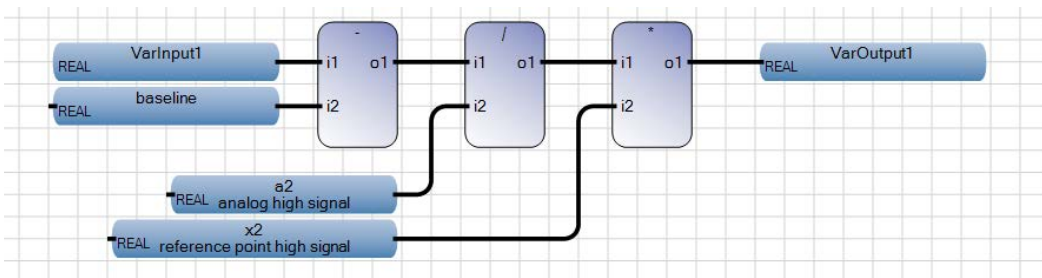

Figure 18. Tank level measurement conversion in user defined function block.

b. Voltage Measurements

Voltage measurements are taken on the cable from the photovoltaic (PV) panels to the charge controller and on the cable from the charge controller to the electrolyzer. The user defined function blocks for voltage measurement are of the same style as the tank level measurement blocks. The baseline values are adjusted for calibration purposes; because the PV voltage block reference point high signal is 120 volts and the electrolyzer voltage block reference point high signal is 24 volts.

2. Ladder Diagram Type Blocks

Within the function block diagram program bits and pieces of ladder diagram programming are used. Ladder rungs usually include a power rail and contact on the left and a coil and power rail on the right. The benefit of using ladder diagram programming is the ease of use when turning equipment on and off. In Figure 19, the left power rail continuously feeds a true signal to the contact, which would be some variable defined elsewhere in the program. When the contact variable becomes true the signal passes on to the coil and causes it to become true. The coil is another variable which is usually associated with some output signal.

Figure 19. Ladder diagram rung inside function block diagram program.

The coil is used when turning equipment on or off. Coils are located on the right side of a rung and can be thought of as a lightbulb. If using a direct coil and preceding item in the rung is true, then the coil reads true and turns the associated equipment on. If the preceding item is false, then the coil value is also false and the equipment is turned off. The reverse coil is the opposite. If the preceding item in the rung is true then the coil reading is false. If the preceding item is false then the coil value is true.

Contacts are located on the left side of a rung and can be thought of as a switch. If a direct contact is made true, then the true signal flows to the right towards the coil. If it is false, the signal does not flow through. A reverse coil is the opposite. If a reverse coil value is true, then the signal does not pass through and if it is false, then the signal passes through.

C. PROGRAMS AND PROGRAM FLOW

A two program approach was used to ensure safe operation of the system: a normal operation program and a total shutdown program. The normal operation program controls startup, shutdown, and normal system operation. The total shutdown program is utilized if an emergency condition is detected by an operator or installed safety devices and results in an immediate system shutdown.

Before programming began a logic flow diagram was created to help define the tasks the program needed to accomplish. Figure 20 shows these tasks organized in a startup configuration. In reality the PLC is cycling more than once every second so the operations within the program are occurring nearly simultaneously.

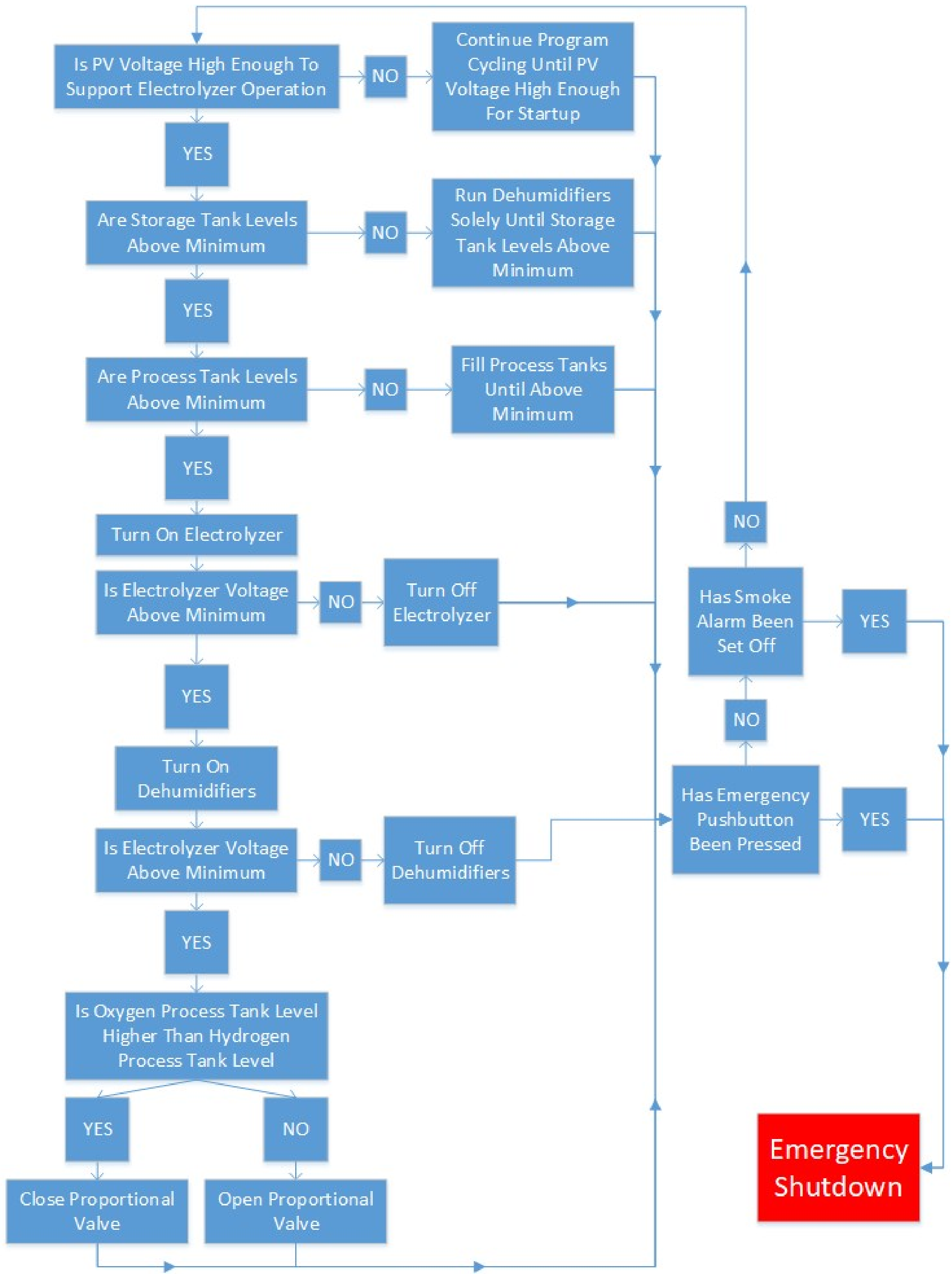

Figure 20. Ideal logic flow diagram for programming design.

The normal operation program is the backbone of the system. The following is a breakdown of the normal operation program and how each line works within the program. The line numbers referenced below are shown in the actual code and can be viewed in appendix F for more detail. Appendix E includes a list of variables used in the order they appear in the code.

In line 1, the program converts the charge controller voltage transducer input to an actual voltage value. This is done by inputting the analog signal from the voltage transducer and converting that signal from an unsigned integer variable type to a real variable type. The corresponding user defined function block then converts the analog input value into an actual voltage value.

Line 2 checks to see if the solar panel voltage is above the minimum voltage needed for system startup. This voltage was determined by trial and error to find when the solar panels were producing enough power to run the electrolyzer. The startup voltage is set low enough to account for power spikes during electrolyzer startup. The output of this line is a Boolean variable which can be used to turn equipment on and off later.

The next step to system startup is to check if the storage tank levels are above a minimum value of 12.7 mm (0.5 in). Line 3 takes the analog signal from the tank level indicator for the respective storage tank and converts it from an unsigned integer to a real variable type. Then the user defined function block converts this analog input value into an actual tank level in millimeters (inches). After this level is obtained, it is checked against the storage tank minimum variable. If either of the storage tanks are low, the storage tank low variable becomes true, and is used later to turn on the dehumidifiers and to turn off the electrolyzer. This variable is key in determining how the system will operate. If the tanks are too low, the electrolyzer will not come on and the program will continue to just produce water until there is enough for electrolyzer operation.

The group 4 lines are used to turn on and off the four dehumidifiers. Each of the dehumidifiers needs its own line of programming for power management purposes. These lines have multiple contacts on the left side of the line. The operation of the top group of lines is detailed here and the other lines follow the same pattern. Line 4.1 has a contact for the “dehumid_H2_1_on” variable and the “turn_on_electrolyzer” variable as well as a reverse contact for the “dehumids_off” variable. If the contact variable values are true and the reverse contact variables are false, then the true signal passes through. In description, the system wants to turn on the dehumidifier, it knows there is enough voltage to run the system, and it does not want to turn the dehumidifiers off due to low electrolyzer voltage.

Line 4.2 has a direct contact for the “start_dehumid_H2” variable and the “turn_on_electrolyzer” variable as well as a reverse contact for the “dehumids_off” variable. If either line 4.1 or 4.2 are true, the signal passes through the OR gate and on to the timer. The timers for the dehumidifiers are set in five second intervals. This ensures that the dehumidifiers do not all turn on at the same time which can cause a large power drain and in turn cause the charge controller to fault. The “dehumid_H2_1_on” and “start_dehumid_H2” variables differ in that the first one becomes true if the storage tank is low and the second one is true if the storage tank is not at a maximum.

Once the coding is in place for the dehumidifiers, the operation relative to the process tanks is configured. Line 5 determines if the process tanks can be filled and if they need to be filled. The analog signal from the process tank TLI is converted to a tank level in millimeters (inches) using the user defined function block for that tank. Since the O2 process tank is connected to the H2 process tank through the electrolyzer the two tank levels are added together. This variable is compared to the “process_tank_sum_min” variable to ensure the total solution level is above 101.6 mm (4 in). If the process tanks are too low and the storage tank levels are high enough then the “fill_process_tanks” variable becomes true. This variable is used to open and close the necessary valves to fill the process tanks. The group 6 lines are used to open and close the necessary valves to fill the process tanks. To fill the process tanks, the normally open valve between the dehumidifier and the storage tank is closed while the normally closed valve between the storage tank and process tank is opened. This prevents air from entering the process tanks as the extra water in the storage tank acts as a bubbler.

Once the process and storage tanks are at an acceptable level, the electrolyzer can be turned on. Line 7 controls the power to the electrolyzer. The electrolyzer is turned on if the “electrolyzer_on_master” variable is true and the “storage_tank_low” and “fill_process_tanks” variables are false. These contacts ensure the electrolyzer will not run if the storage tank levels are low or if the process tanks are being filled.

After the electrolyzer is turned on, its voltage must be monitored. Line 8 converts the analog signal from the electrolyzer voltage transducer into an actual voltage value using the appropriate user defined function block. The “electrolyzer_actual_voltage” variable can then be used to compare with design parameter values to determine if equipment needs to be on or off. Line 9 checks to see if the electrolyzer voltage is greater than the minimum voltage allowed. If it is not, then the “electrolyzer_low_voltage” variable becomes true, and is used to turn off the dehumidifiers.

In line 10, the “electrolyzer_low_voltage” variable triggers the pulse timer to start. The pulse timer makes the “dehumid_off” variable true for thirty minutes. This is the best way to ensure that the electrolyzer is on long enough for the power to be stable. The “electrolyzer_low_voltage” variable is used in conjunction with the pulse timer and is fed into an OR gate. This ensures that, if the electrolyzer is fluctuating in voltage as it does during sunrise or sunset, the dehumidifiers will stay off during the fluctuations.

To utilize all available power from the solar panels, the system should run the dehumidifiers alongside the electrolyzer whenever possible. Group 11 lines check the storage tank levels to see if they are at maximum. If they are not, then the corresponding variables become true to turn the dehumidifiers on. This is different from checking that there is a minimum. If the tank levels are below the minimum then the electrolyzer will not run to prevent draining the system. These lines tell the dehumidifiers to run at the same time the electrolyzer is running which utilizes as much power as possible from the solar panels.

Line 12 is the PID control portion of the program and is used to control the H2 and O2 process tank levels. The goal is to keep the tank levels the same, and is accomplished through the use of a proportional valve on the oxygen gas outlet. The pressure in the H2 process tank will always be higher than the O2 process tank due to the greater volume of H2 produced as H2O is split. This causes tank level imbalance.

The set point for control of the tanks is 0, the desired difference between the levels of the H2 and O2 process tanks. The PID control function block opens or closes the proportional valve to maintain this set point using the associated gains. The gain type variable block inputs the necessary proportional, integral, and derivative gains to the PID function block. A simple feedback loop is used because no conversion or limiting factor needs to be in the loop.

Line 13 controls the secondary oxygen outlet. This outlet is needed when the hydrogen side has a very low back pressure. If this is the case this valve will remain open and allow all the oxygen out of the system. If the level of the hydrogen tank gets lower than the oxygen tank, the valve will close creating additional back pressure on the oxygen tank to help the proportional valve balance tank levels.

Line 14 is critical for the proper operation of the proportional valve. The proportional valve is controlled by its own electronics package. Even if the analog signal from the PLC is 0 the electronics will feed a small signal to the proportional valve which can keep it from closing completely. This line is used to send a 5 VDC signal to a separate pin on the proportional valve control box to trigger the total shutoff feature which completely removes all power from the proportional valve.

Lines 15 and 16 are used to trigger a total shutdown condition. If the process tanks are below the desired level and the associated storage tank is too low, then there is too little water in the system. This could lead to running dry which would severely damage the electrolyzer. In order to prevent this, the system will fault and shutdown the controller. This turns off all equipment and returns all valves to normal position.

Line 17 controls emergency shutdown caused by the emergency pushbutton. The emergency pushbutton continuously sends a signal through itself to the PLC. This signal prevents an operator from disconnecting the pushbutton while the system is running. For this reason this rung of code uses a reverse contact, if the button is pressed or totally disconnected, the variable becomes false which passes the true signal through the contact and triggers the total shutdown coil.

The lines labeled 18 are related to the smoke detector operation. Line 18.1 is for smoke detection triggering and causes emergency shutdown by sending a signal to the PLC. Line 18.2 is the smoke detector continuity rung which will cause emergency shutdown of the system if the smoke detector is disconnected. Again, this is done to prevent an operator from attempting to bypass or tamper with the detector.

The emergency shutdown portion of the program is shown in appendix G. This program causes the system to shut down by creating a fault in the controller. PLCs have internal settings which prevent them from looping inside a single program. This is to prevent the PLC from incurring errors due to accidental loops. This program utilizes that function to its advantage by causing a PLC fault if an emergency condition occurs and immediately shuts down the program.

D. FLOW METER DATA RECORDING

The Alicat flow meter was used to obtain hydrogen gas flow data to show system performance and reliability. To pull the measurements from the flow meter, MATLAB was used in conjunction with the flow meter combiner terminal. The combiner terminal can read up to nine flow meters and then output the data to a personal computer (PC) via a universal serial bus (USB) cable. The MATLAB code used is shown in Appendix H.

VI. RESULTS

The hydrogen production system was run continuously for nine days with minor adjustments made to its program less than once per day. These adjustments were made to achieve optimal system operation throughout the operating period. Additionally, minor changes were made to the program after the initial nine-day period to add safety features. Figure 21 shows the hydrogen production over the operating period.

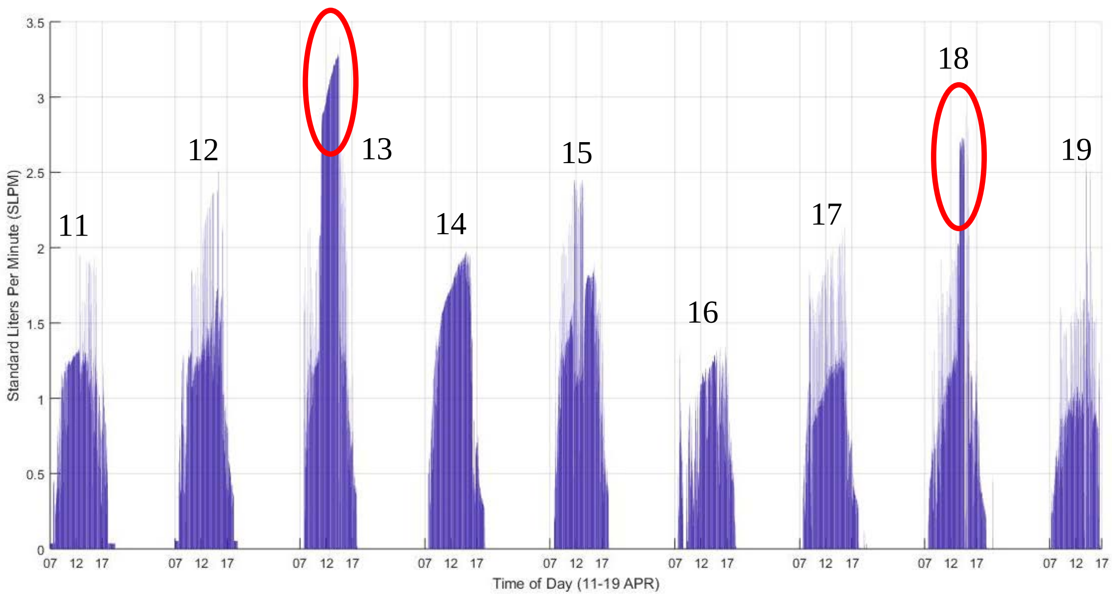

Figure 21. Hydrogen flow meter data, 11 to 19 April.

The overall hydrogen production of the system varied considerably over the operating period based mainly on weather. Peaks and valleys visible in the graph are due to power fluctuations caused by the dehumidifiers turning on and off. These power fluctuations usually result from weather, but can also be caused by momentary solar activity fluctuations or solar panel temperature fluctuations.

The two circled areas in the figure indicate invalid data due to TLI sensor malfunctions. When the sensor malfunctions, the tank levels are not balanced. If the imbalance occurs with the oxygen tank low, then oxygen is being pushed through the electrolyzer to the hydrogen process tank and eventually through the flow meter. Since the flow meter does not sense particular gasses, only total mass through, it causes a higher than normal flow rate reading. With the invalid data removed, the system produced 6063 liters of hydrogen over the operating period, an average of 673.7 liters per operating day.

April 14 had the highest hydrogen production of the operating period and is shown in Figure 22. The peaks and valleys visible in the plot are due to dehumidifier startup and shutdown, but these fluctuations are less frequent and have a smaller effect on system operation. This plot shows a gradual ramp up in hydrogen production in the morning and a fairly quick drop off in the evening. The sharp evening drop off occurs because the solar panels are shaded by a tall portion of the building in the evening.

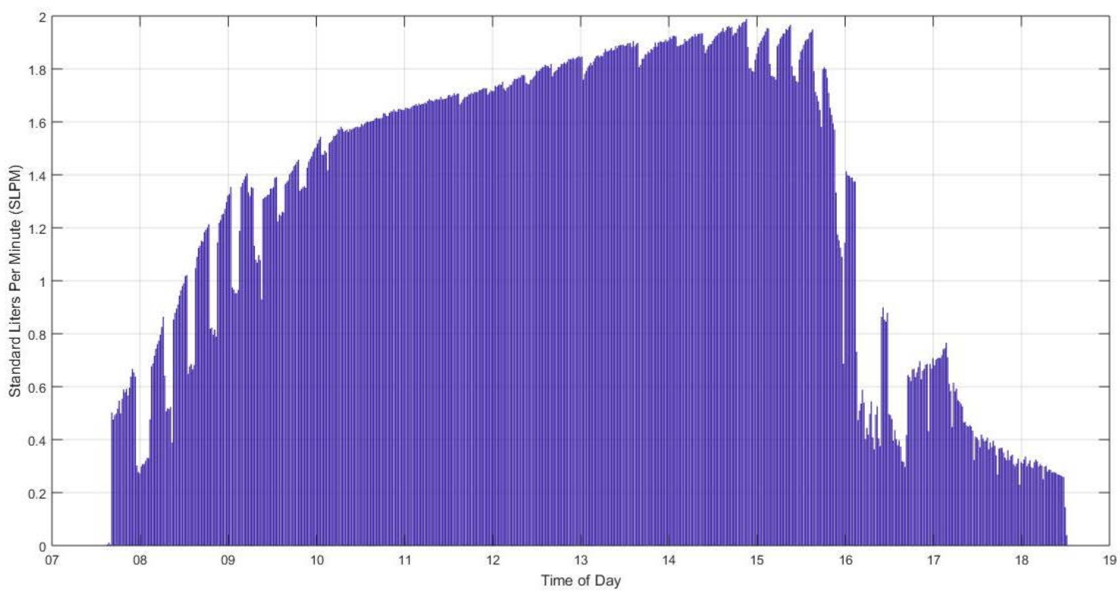

Figure 22. April 14 hydrogen flow meter data.

A low hydrogen production day, April 12, is shown in Figure 23. This data shows a very slow ramp up in the morning and gradual drop off in the evening. Hydrogen production fluctuations caused by dehumidifier start up and shutdown have a more dramatic effect on the system. This plot shows the large power fluctuations caused by electrolyzer start up when the system restarted after a low voltage condition. The lower amount of solar energy available throughout the day causes a more inefficient system overall.

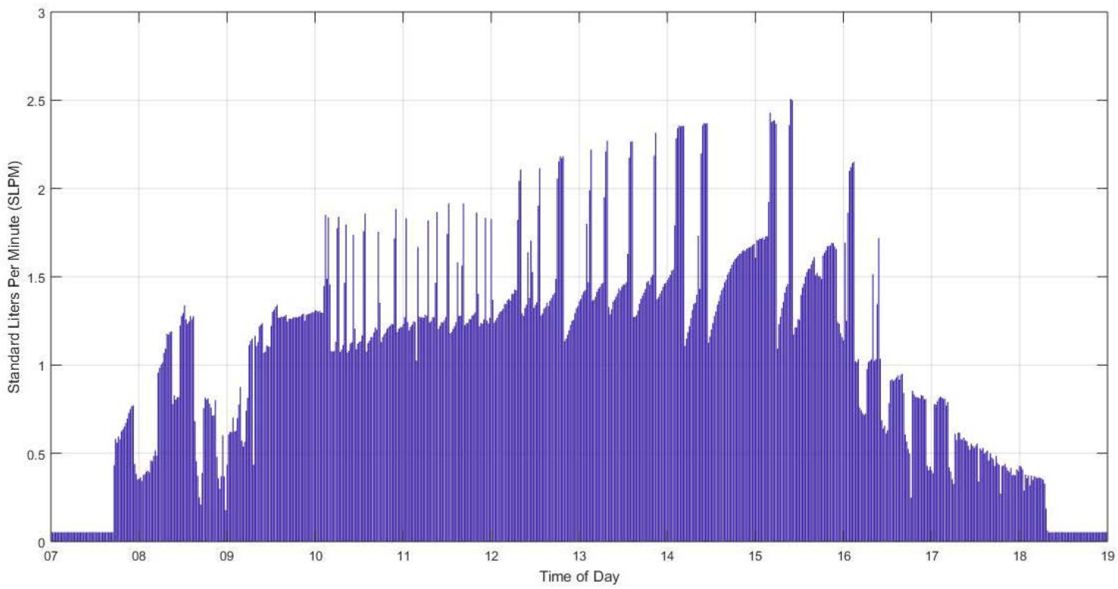

Figure 23. April 12 Hydrogen flow meter data.

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VII. CONCLUSION

Overall the system performed very well and required only minor adjustments throughout the operating period. The mechanical design of the system is effective and the two-level tank design provides an optimal set-up for storing water and filling process tanks without air intrusion. The system program is sound and would only require minor changes to provide more efficient operation. Two issues with sensor design and operation arose during system automation and are discussed below.

The first issue was with the TLIs. This is due to the following system and sensor flaws. The speed of sound difference between hydrogen and oxygen caused inaccurate readings, even with in-system calibration of the sensor. As the system is operating during the day the readings are fairly consistent because a constant internal pressure is created and hydrogen always fills the tank. The sensor is always projecting its ultrasonic waves through nearly pure hydrogen gas.

At night, however, the lack of airtight integrity in the system becomes a problem due to the nature of the fittings. When the system shuts down during the night, it is likely that the hydrogen diffuses out of the tanks through minuscule leaks in the tank and hose fittings. This allows air to enter the tanks by the same method. When air enters the tank, the tank level indicator, pre-calibrated to measure pure hydrogen in the hydrogen process tank, reads much lower than it actually is.

This problem was not usually an issue if the tank levels were already high enough because the hydrogen pressure builds quickly as the system starts up and the tank level indicator reads the correct level again. The problem was noticed when the tank levels seemed to be too low at night, causing the system to allow more water from the storage tanks into the process tanks. This not only caused the levels of the process tanks to be higher than desired, but also diluted the process tank solution, reducing the production of hydrogen.

The second problem with the TLIs was simply incorrect readings. The TLIs had a tendency to get “stuck” on a high or low reading. This occurred in both process tank TLIs and is what caused the invalid readings on two days of the operating period, the red circled periods in Figure 20. When the TLI for the oxygen process tank continuously output a signal that was higher than the hydrogen process tank signal, the valves on the oxygen outlet remained closed. This caused pressure to build up in the oxygen process tank and eventually forced oxygen back through the electrolyzer and out the hydrogen process tank outlet causing an abnormally high reading on the flow meter. Potential solutions to the TLI issue will be discussed in the recommendations section.

The second issue was that the current dehumidifiers do not produce enough water for continuous electrolyzer operation, partially due to intermittent operation of the dehumidifiers. Although it is known from the previous thesis that the dehumidifiers are incapable of producing enough water this could be mitigated somewhat by better programming. Devising a scheme to run one or two dehumidifiers constantly would produce more water than trying to run all dehumidifiers simultaneously and then having startup and shutdown throughout the day.

These two issues aside, the system produced a considerable amount of hydrogen over the nine-day period. This hydrogen could be used for a variety of processes and tasks such as electricity generation or fuel cell vehicle operation. The current system design could be scaled up to meet any requirements necessary. This system provides a test bed for new technology integration and can provide hydrogen for ancillary projects as needed.

A good example of hydrogen usage that would be especially valuable in a military setting is a hydrogen fuel cell powered drone. Current commercial drones of this type advertise a flight time of 150 minutes with an onboard storage tank of 9 liters of hydrogen gas [34]. This current hydrogen production system, even with its small scale, has produced enough hydrogen in nine days to operate this drone for 673 sorties, amounting to 1682 hours of UAV flight time.

VIII. RECOMMENDATIONS

A. WATER PRODUCTION

Although the system produced hydrogen effectively, many improvements can be made. Water production is one of the main issues with the system. Without enough water production the system will be required to go through intermittent cycles of water production and hydrogen generation. Developing a system that can operate both of these processes continuously would be ideal. While increased water production could be accomplished with an increase in the number of dehumidifiers, this would require a larger solar panel area. Dehumidification is therefore not the best choice for the distilled water production necessary for continual operation.

One possible solution is a solar distillation facility. Solar distillation is accomplished with a simple water basin covered with a clear material. As the water evaporates from the basin, it condenses on the cover material. This material is angled so that the distilled water runs off into a collection basin. Water distilled in this manner could then be used in the hydrogen generation system. The only issues with this approach is that another large area is needed for the distillation plant, and an environmental water source must be readily available. This would not be a large issue near bodies of water or where groundwater is abundant, but could not be operated efficiently in arid environments. If water sources are available, this could be a low-cost alternative to dehumidification.

A new dehumidification type technology for water production in arid regions has been developed which can pull as much as 0.25 liters of water per kilogram of material from air with a relative humidity as low as 10–40 percent using only thermal energy [35]. While this is only experimental, the materials and construction are feasible and could conceivably be accomplished after more development.

B. SENSOR IMPROVEMENTS

One of the major improvements necessary for the system is the TLIs. Due to the differences in sound speed through hydrogen and oxygen ultrasonic sensors are not the best choice. If these sensors were to be used they would be more effective if mounted in a stand pipe. Each stand pipe could have air in it since it would never come in contact with the process tank gas. This would make the sensors much more accurate. If this approach were taken it would be more effective in a larger tank configuration.

A float sensor could be used in this application fairly easily. Float sensors exist on the market which can be used in this solution and would work well since there is very little disturbance of the liquid. A non-invasive load cell system could be used for tank measurement as well. If the tanks were placed on a scale it would be very easy to calculate the amount of fluid in each tank and compare.

If simplicity is the future goal a combination of float switches could be used. Since the tank levels do not need to be equal to function effectively, it would not matter how high or low the liquid in the tank is as long as it is above the tank outlet line. Having a sensor at the high and low level of each tank combined with the correct programming would make this approach relatively simple.

A combination of tank level sensors may be an option as well. If two sensors are available and are constantly checked against each other, it would be possible via programming to determine if one of the sensors was malfunctioning. Larger process tanks will also make system operation easier as small changes in tank level will be less noticeable.

C. PROGRAMMING CHANGES

The operation of the dehumidifiers could be optimized by programming for greater efficiency. This would allow more continuous operation of the system overall, and would also lead to more water production. Addition of current sensors on equipment combined with programming changes would also help with system power management.

Future programming of the system could also incorporate an auto-tune feature. This could be used on the electrolyzer along with the proportional valve to help regulate power and gas flow. If the power usage of the electrolyzer were adjustable, it would operate continuously throughout the day and thus provide a larger amount of hydrogen over time.

D. EXCESS ENERGY STORAGE

Currently, the system does not have any outside energy storage such as batteries or capacitors. The addition of these would smooth out the operation of the system providing an avenue for capturing excess power produced by the PV array. This stored energy could then be used to smooth out system operation during periods of intermittent clouds and reduce the number of system restarts during the day. Storage capability will be necessary for total off grid operation of the system and all associated control devices.

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APPENDIX A. HYDROGEN COMPRESSION SYSTEM DIAGRAM (ED)

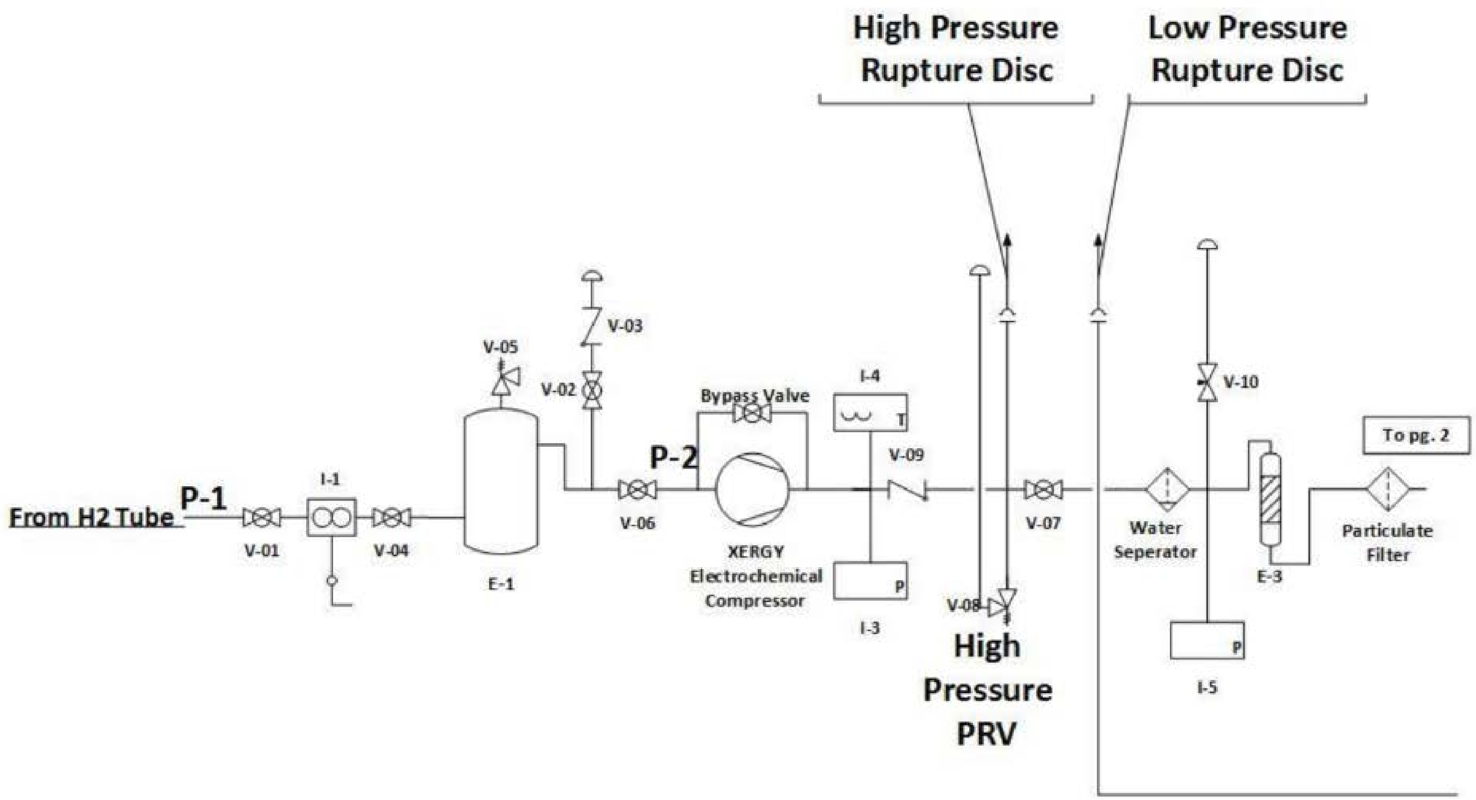
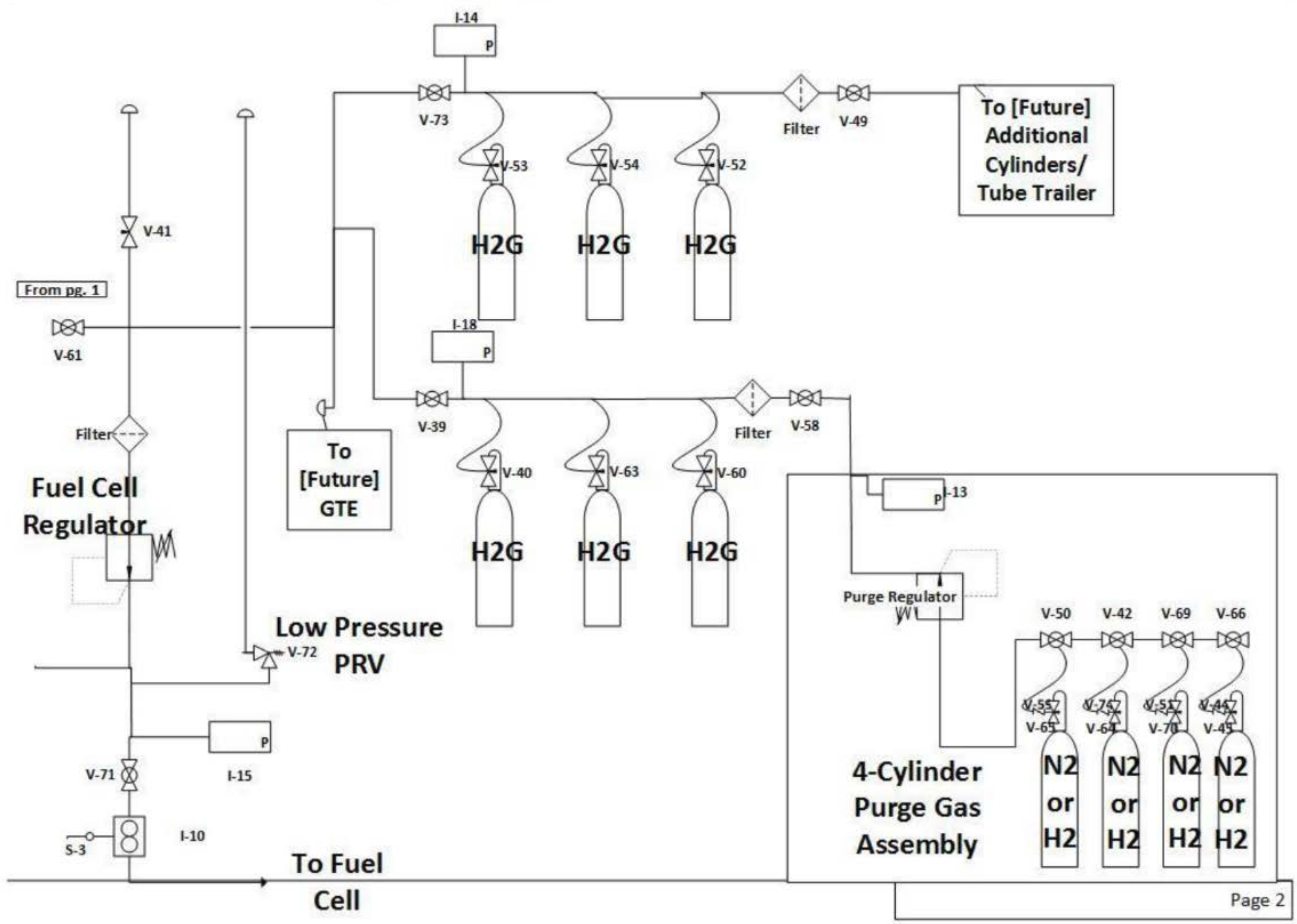


Figure 24. Hydrogen compression system diagram. Source: [6].


I-14
P
V-73
V-53
V-54
V-52
Filter
V-49
To [Future] Additional Cylinders/ Tube Trailer
H2G
H2G
H2G
V-41
From pg. 1
V-61
I-18
P
V-39
Filter
V-58
V-40
V-63
V-60
H2G
H2G
H2G
Filter
Fuel Cell Regulator
To [Future] GTE
P
I-13
Purge Regulator
V-50
V-42
V-69
V-66
V-65
V-64
V-70
V-45
Low Pressure PRV
V-72
P
I-15
V-71
S-3
I-10
4-Cylinder Purge Gas Assembly
N2 or H2
N2 or H2
N2 or H2
N2 or H2
To Fuel Cell
Page 2

Valve List					
Displayed Text	**Description**	**Line Size**	**Valve Class**	**Manufacturer**	**Model**
V-01	PFA Tubing Ball Valve				
V-02	PFA Tubing Ball Valve				
V-03	Poppet Check Valve				
V-04	PFA Tubing Ball Valve				
V-05	Relief Valve				
V-06	316 SS Ball Valve	1/4" T	40G Series	Swagelok	SS-43GS4
V-07	316 SS Ball Valve	1/4" T	40G Series	Swagelok	SS-43GS4
V-08	300psi 316L SS Relief Valve	1/4" T	PRV Series	Swagelok	PRV2-N2F-02-0-VV
V-09	316 SS Poppet Check Valve	1/4" T	CP Series	Swagelok	SS-4CP4-1/3
V-10	316 SS Needle Valve	1/4" T	1 Series	Swagelok	SS-1RS4
V-11	316 SS Ball Valve	1/4" T	40G Series	Swagelok	SS-43GS4
V-12	316 SS Needle Valve	1/4" T	1 Series	Swagelok	SS-1RS4
V-13	50 psi 316 SS Relief Valve	1/4" T	R Series	Swagelok	SS-RL3S4
V-14	316 SS Ball Valve	1/4" T	40G Series	Swagelok	SS-43GS4
V-15	316 SS Ball Valve	1/2" T	40G Series	Swagelok	SS-43GS8
V-16	316 SS Ball Valve	1/2" T	40G Series	Swagelok	SS-43GS8
V-17	316 SS Ball Valve	1/2" T	40G Series	Swagelok	SS-43GS8
V-18	316 SS Ball Valve	1/2" T	40G Series	Swagelok	SS-43GS8
V-19	316 SS Ball Valve	1/2" P	54 Series Manifold	Matheson Gas	54-48V
V-20	316 SS Ball Valve	1/2" P	54 Series Manifold	Matheson Gas	54-48V
V-21	316 SS Ball Valve	1/2" P	54 Series Manifold	Matheson Gas	54-48V
V-22	316 SS Ball Valve	1/2" P	54 Series Manifold	Matheson Gas	54-48V
V-23	Brass Cylinder Valve	13/16"	CGA350	Norris Cylinder	Model 8BC250
V-24	Brass Cylinder Valve	13/16"	CGA350	Norris Cylinder	Model 8BC250
V-25	Brass Cylinder Valve	13/16"	CGA350	Norris Cylinder	Model 8BC250
V-26	Brass Cylinder Valve	13/16"	CGA350	Norris Cylinder	Model 8BC250
V-27	Brass Cylinder Valve	13/16"	CGA350	Norris Cylinder	Model 8BC250
V-28	Brass Cylinder Valve	13/16"	CGA350	Norris Cylinder	Model 8BC250
V-29	Integrated Pigtail Check Valve	13/16"	CGA350	Matheson Gas	54-48V
V-30	Integrated Pigtail Check Valve	13/16"	CGA350	Matheson Gas	54-48V
V-31	Integrated Pigtail Check Valve	13/16"	CGA350	Matheson Gas	54-48V
V-32	Integrated Pigtail Check Valve	13/16"	CGA350	Matheson Gas	54-48V
V-33	Brass Cylinder Valve	13/16"	CGA350	TBD	TBD
V-34	Brass Cylinder Valve	13/16"	CGA350	TBD	TBD
V-35	Brass Cylinder Valve	13/16"	CGA350	TBD	TBD
V-36	Brass Cylinder Valve	13/16"	CGA350	TBD	TBD
V-37	316 SS Ball Valve	1/4" T	40G Series	Swagelok	SS-43GS4
V-38	316 SS Needle Valve	1/4" T	1 Series	Swagelok	SS-1RS4

Instrument List

Description	Connection Size	Service	Manufacturer	Model
Flowmeter	1/4" NPT M	Normal	Alicat	
Flowmeter	1/4" NPT M	Normal	Alicat	
Pressure Gage	1/4" NPT M	Normal	McDaniel Controls Inc.	2.5" SS Model KN 0-3000 PSI
Themometer	1/2" NPT M	Normal	Swagelok	T48L-040-DS-08-G-8-NTSS
Pressure Gage	1/4" NPT M	Normal	McDaniel Controls Inc.	2.5" SS Model KN 0-3000 PSI
Pressure Gage	1/4" NPT M	Normal	McDaniel Controls Inc.	2.5" SS Model KN 0-3000 PSI
Pressure Gage	1/2" NPT M	Normal	NoShok	4" SS Model 40-500-3000-psi-CC
Pressure Gage	1/2" NPT M	Normal	NoShok	4" SS Model 40-500-3000-psi-CC
Pressure Gage	1/2" NPT M	Normal	NoShok	4" SS Model 40-500-3000-psi-CC

Pipeline List

Displayed Text	Description	Line Size	Schedule	Design Pressure [psig]	Design Temperature [F]	Quantity
P-1	PFA Tubing	1/4OD x 0.062"	Hose	275	400	1
P-2	316 SS Seamless Tubing	1/4OD x .049"	Tube	4 800	100	5
P-3	316 SS Seamless Tubing	1/2OD x .049"	Tube	4 800	100	5
P-4	316 SS Tubing	1/2OD	Tube	3 000	100	1
P-5	PFA Tubing	1/4OD x 0.062"	Hose	275	400	2
						59

Equipment List

Displayed Text	Description	Manufacturer	Material	Model
E-1	Water Bubler		PVC	
XERGY Electrochemical Compressor	Electrochemical Compressor	Xergy		X-CELL
Water Seperator	High Pressure Service Water Seperator With Drain	Parker	316 SS	SJN2L-100WSY
E-3	Activated Charcoal Filter With Drain	Parker	316 SS	SJN2L-AWCY
Particulate Filter	High Pressure Service Particulate Filter With	Parker	316 SS	SJN2S-4CWCY
Filter	40 Micron, 7 Micorn, 2	Swagelok	316 SS	SS-4TF-SS-8TF-
Purge Regulator	0-500 PSI	Matheson	316 SS	3510A
Fuel Cell Regulator	0-50 PSI	TESCOM	316 SS	44-2260-241-1532

APPENDIX B. ELECTRICAL SYSTEM DIAGRAM

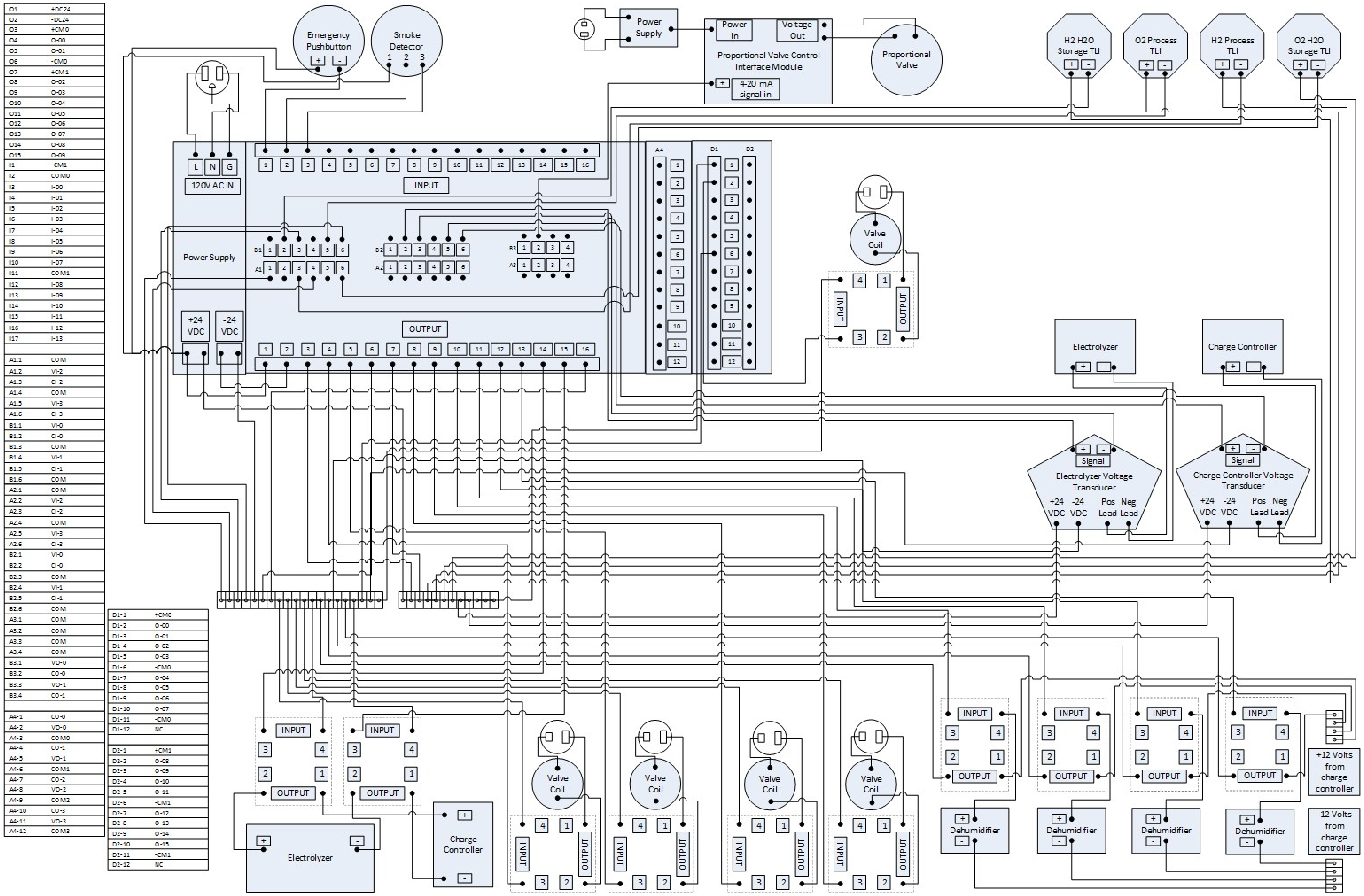


Figure 25. Hydrogen production facility automation electrical diagram.

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APPENDIX C. MECHANICAL SYSTEM DIAGRAM

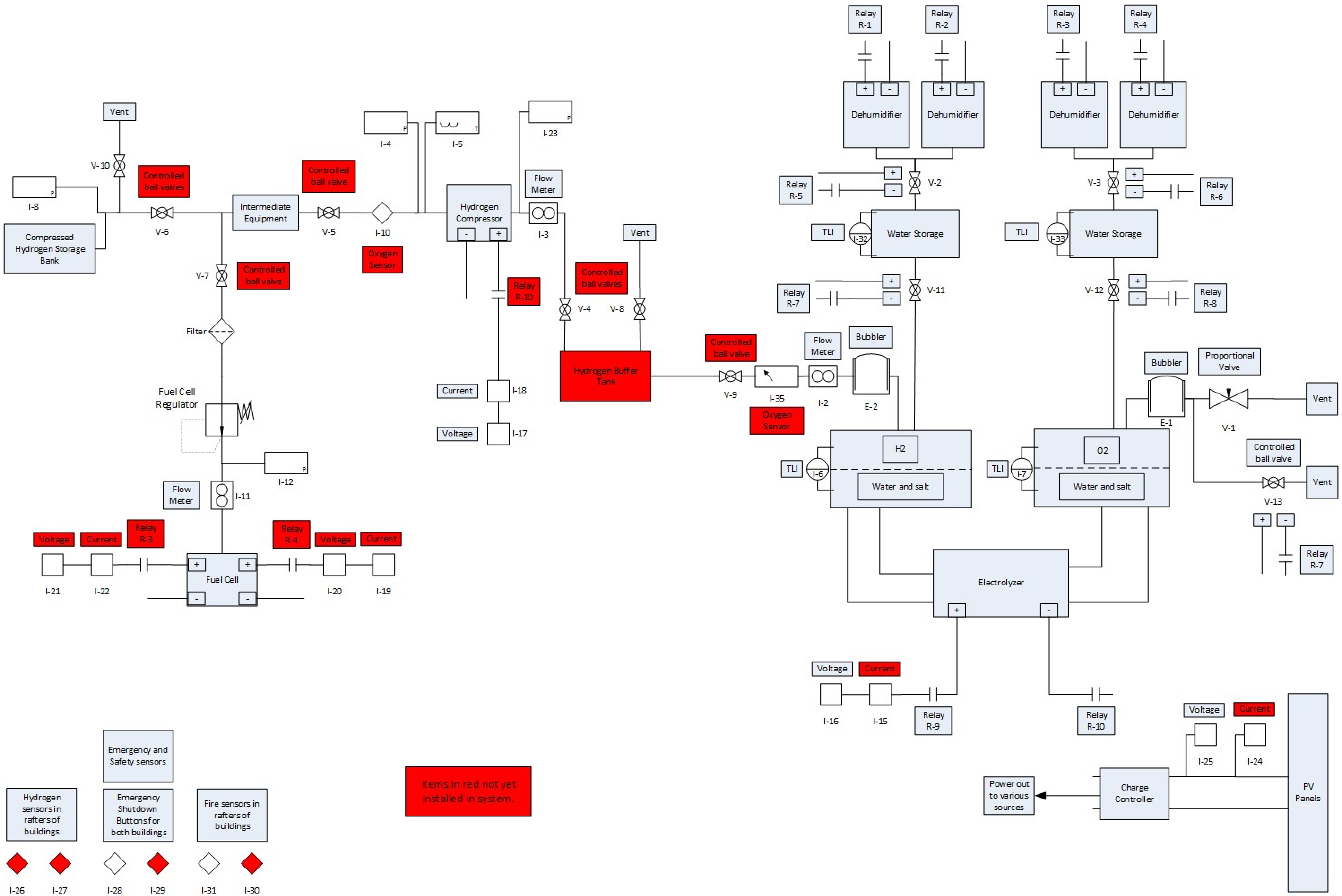

Figure 26. Hydrogen production and compression facilities mechanical system diagram.

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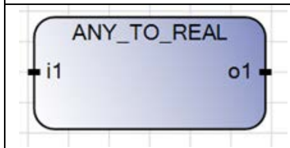
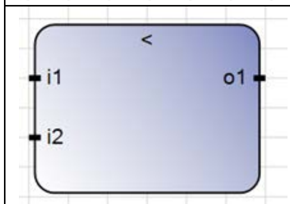
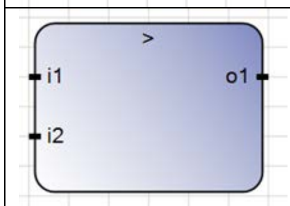
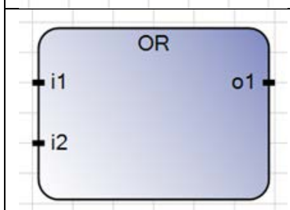
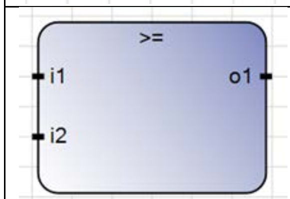
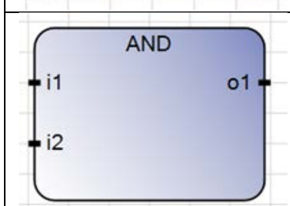
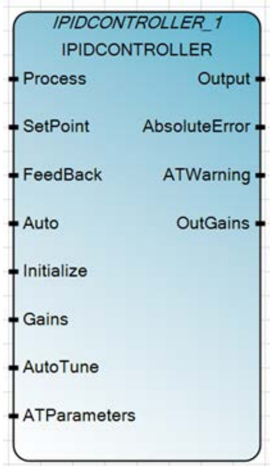
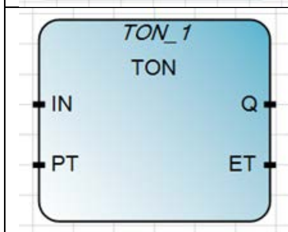
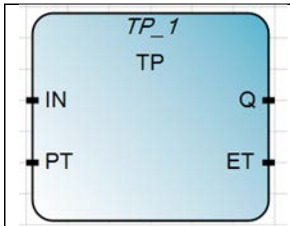
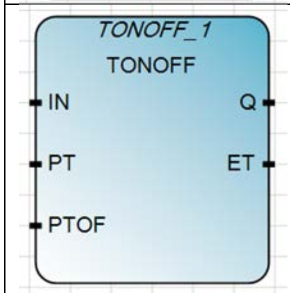
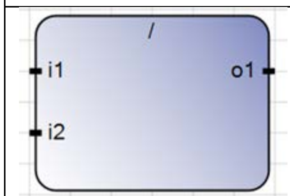
APPENDIX D. FUNCTION BLOCK DESCRIPTIONS

	A variable block allows for utilization of any variable within the program. This could be a user defined variable or some input/output source variable.
	The any-to-real function block takes an input variable and turns it into a real variable. This instruction is mainly used to turn an unsigned integer variable, which is an analog input signal, into a real variable. The reason for needing the real variable form will be discussed in depth in the user defined function block section.
	The less than function block simply checks to see if one variable is less than another variable. If it is then the output is true, if not then it is false.
	The greater than function block simply checks to see if one variable is greater than another variable. If it is then the output is true, if not then it is false.
	The OR function block checks to see if either of the two inputs are true. If either one is true then the output is true. If neither input is true then the output is false.

	The jump block tells the program to move from that location in the program to another location which is defined by a label.
	The label is used in conjunction with a jump block and it is the location in the code that the jump block sends the program to.
	The addition block adds two variable values together and outputs the sum of those variables. Within the program these can be any type of variable, but for this thesis they are usually used with real variables.
	This block takes in two variables and tests to see if the top variable is greater than or equal to the bottom variable. If it is then the output is true, if it is not greater than or equal to then the output is false.
	This block takes in two variables and tests to see if the top variable is less than or equal to the bottom variable. If it is then the output is true, if not the output is false.
	The AND block is used for Boolean logic. It tests to see if the two input variables are true, if so then the output is true. If either or both of the input variables are false then the output is false.

	This block provides the function of subtracting the bottom input variable from the top input variable. The output is of the same form as the input variables.
	This block is used to implement a PID controller in the PLC. The PID controller allows the user to maintain a setpoint by adjusting the PLC controller outputs. The PID function block includes all necessary logic and programming to implement this control system.
	The Timer On Delay (TON) function block is used to turn on an output after a certain amount of time has elapsed. The IN spot on the TON block is a Boolean input. When the input becomes true the timer is started. The block's internal timer is set by the PT spot which is a time variable input. Once the time has elapsed the Q spot, which is the output of the TON block, becomes true. If the input to the TON block becomes false while the timer is running then the timer is reset. The output of this block is always false if the input is false. This block is generally used to turn on a piece of equipment or output after a certain amount of time has elapsed.

	The pulse timing function block is used to turn on an output for a set duration. The IN spot on the TP block is a boolean input. When the input becomes true the timer is started and the output spot Q becomes true. Once the timer has elapsed the output becomes false. If the input becomes false while the timer is counting this does not affect the output which will stay true until the timer has elapsed. This block is generally used to turn on a piece of equipment or output for a set amount of time.
	The time delay on/off block is used to delay the output of the block from true to false and from false to true. The IN spot on this block is a boolean input. The PT spot on this block is the on-delay time setting. The PTOF spot on this block is the off-delay time setting. When the input to this block becomes true the on-delay timer is started. When this timer is elapsed the output of this block becomes true. If the input to this block changes from true to false during on-delay timer counting then the timer is reset and the block does nothing. If the on-delay timer has elapsed and the output has become true then it will stay true until the input to this block becomes false and the off-delay timer has elapsed. Once the off-delay timer has elapsed and the output is false again the block is essentially reset and the process repeats.
	This block divides the top input by the bottom input.
	This block multiplies two outputs together.

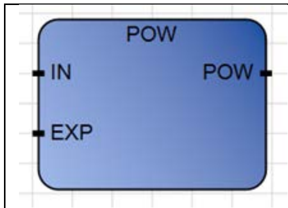
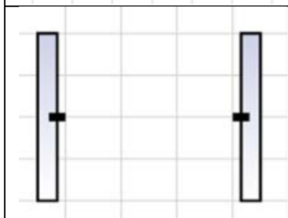
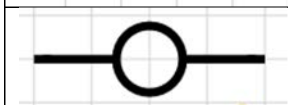
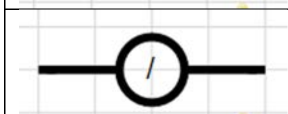
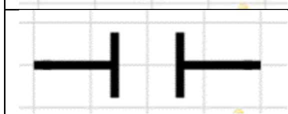
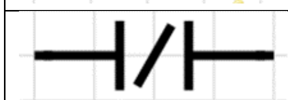
	The raise power block takes the input and raises it to the power specified on the EXP spot on this block.
	Power rails are used when programming in ladder style and are the beginning and end of a rung.
	If the signal preceding a direct coil is true then the value of the direct coil variable is true. If the preceding signal is false then the direct coil variable is false.
	If the signal preceding a reverse coil is true then the value of the reverse coil variable is false. If the signal preceding is false then the reverse coil variable is true.
	If the value of the variable on a direct contact is true then the true signal passes through the direct contact and on to the next item on the rung. If the value is false then the signal does not pass through.
	If the value of the variable on a reverse contact is true then the true signal does not pass through the contact. If the value is false then the true signal passes through the contact and down the line.

Table 1. Function block descriptions. Adapted from [36].

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APPENDIX E. LIST OF VARIABLES

Name	Alias	Type	Value	Function
_IO_P2_AI_01	Charge Controller Volt	UINT		Analog input from charge controller voltage transducer.
PV_voltage		REAL		Actual voltage of PV panels going to charge controller.
PV_min_voltage		REAL	92	Used to determine if PV voltage is high enough to start up the system.
time_delay_electr_on		TIME	10 sec	Delays electrolyzer on signal to eliminate power fluctuation on/off cycling
turn_on_electrolyzer		BOOL		Used to turn on equipment. True if PV voltage is high enough.
electrolyzer_on_master		BOOL		Used to turn on equipment. True if PV voltage is high enough.
_IO_P1_AI_01	H2 TLI Store	UINT		Analog input from H2 H2O storage tank TLI.
_IO_P1_AI_02	O2 Store TLI	UINT		Analog input from O2 H2O storage tank TLI.
H2storageH2O		REAL		Tank level of H2 H2O storage tank in inches.
storage_tank_min		REAL	0.5	Minimum storage tank level in inches.
O2storageH2O		REAL		Tank level of O2 H2O storage tank in inches.
start_dehumid_H2		BOOL		Becomes true if H2 H2O storage tank level is below the minimum allowable level.
start_dehumid_O2		BOOL		Becomes true if O2 H2O storage tank level is below the minimum allowable level.
storage_tank_low		BOOL		Becomes true if either H2 H2O storage tank level or O2 H2O storage tank level is low.
dehumid_H2_1_on		BOOL		Used to turn on/off H2 dehumidifier 1 if storage tank levels not at maximum.
dehumids_off		BOOL		Used to turn on/off dehumidifiers depending on electrolyzer voltage.
time_delay1		TIME	5 sec	Time delay for H2 Dehum 1 to turn on.
_IO_EM_DO_04	H2 Dehum 1	BOOL		Digital output port used to turn on/off H2 dehumidifier 1

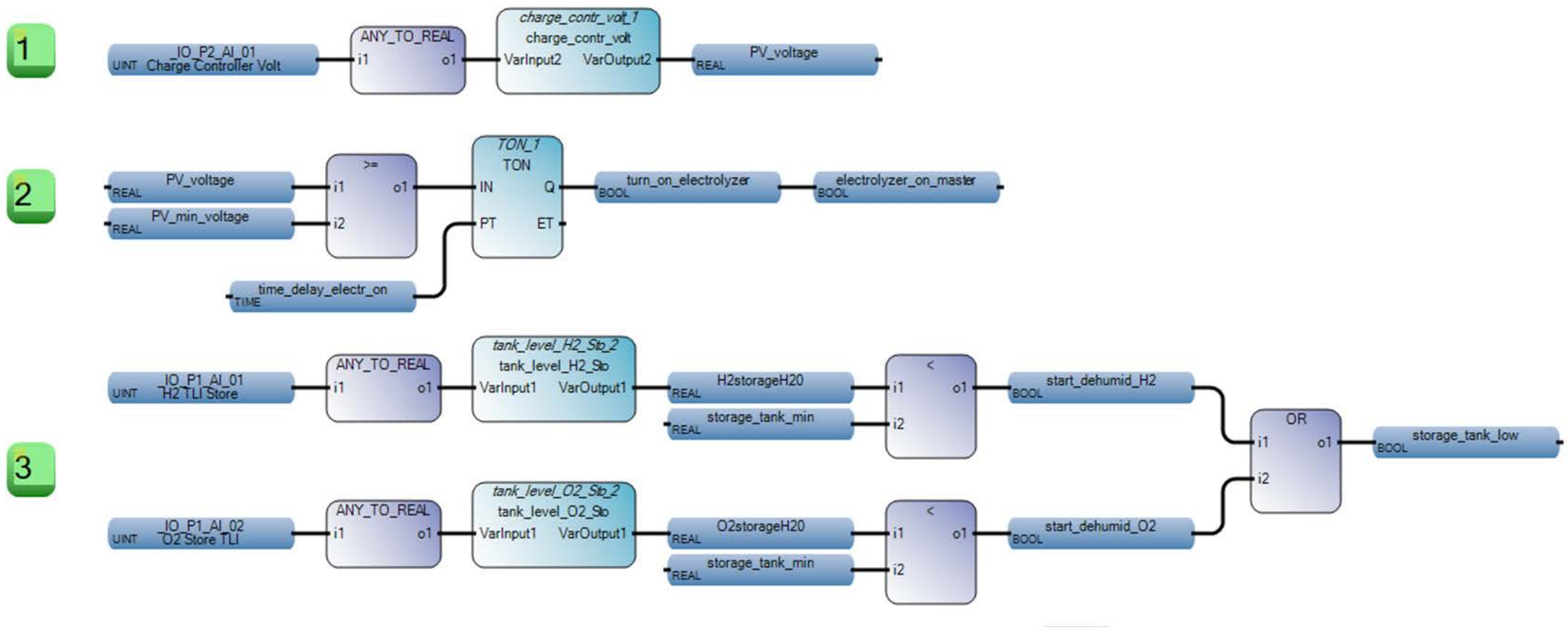
dehumid_H2_2_on		BOOL		Used to turn on/off H2 dehumidifier 2 if storage tank levels not at maximum.
time_delay3		TIME	15 sec	Time delay for H2 Dehum 2 to turn on.
_IO_EM_DO_05	H2 Dehum 2	BOOL		Digital output port used to turn on/off H2 dehumidifier 2
dehumid_O2_1_on				Used to turn on/off O2 dehumidifier 1 if storage tank levels not at maximum.
time_delay2		TIME	10 sec	Time delay for O2 Dehum 1 to turn on.
_IO_EM_DO_06	O2 Dehum 1	BOOL		Digital output port used to turn on/off O2 dehumidifier 1
dehumid_O2_2_on				Used to turn on/off O2 dehumidifier 2 if storage tank levels not at maximum.
time_delay4		TIME	20 sec	Time delay for O2 Dehum 2 to turn on.
_IO_EM_DO_07	O2 Dehum 2	BOOL		Digital output port used to turn on/off O2 dehumidifier 2
_IO_P1_AI_00	H2 TLI Process	UINT		Analog input from H2 process tank TLI
H2process_level		REAL		Tank level of H2 process tank in inches
_IO_P1_AI_03	O2 Process TLI	UINT		Analog input from O2 process tank TLI
O2process_level		REAL		Tank level of O2 process tank in inches
process_tank_sum_min		REAL	4	Used to determine if the sum of the process tank levels are high enough for operation
fill_process_tanks		BOOL		Used to open/close valves that let water from storage tanks to process tanks
_IO_EM_DO_00	O2 Valve In	BOOL		Digital output port used to close/open valve from dehumidifiers to O2 H2O storage tank
_IO_EM_DO_01	H2 In Valve	BOOL		Digital output port used to close/open valve from dehumidifiers to H2 H2O storage tank
_IO_EM_DO_03	O2 Out Valve	BOOL		Digital output port used to open/close valve from O2 H2O storage tank to O2 H2O process tank
_IO_EM_DO_02	H2 Valve Out	BOOL		Digital output port used to open/close valve from H2 H2O storage tank to H2 H2O process tank
_IO_EM_DO_09	Electrolyzer Black	BOOL		Digital output port used to close electrolyzer negative lead circuit
_IO_EM_DO_08	Electrolyzer Red	BOOL		Digital output port used to close electrolyzer positive lead circuit

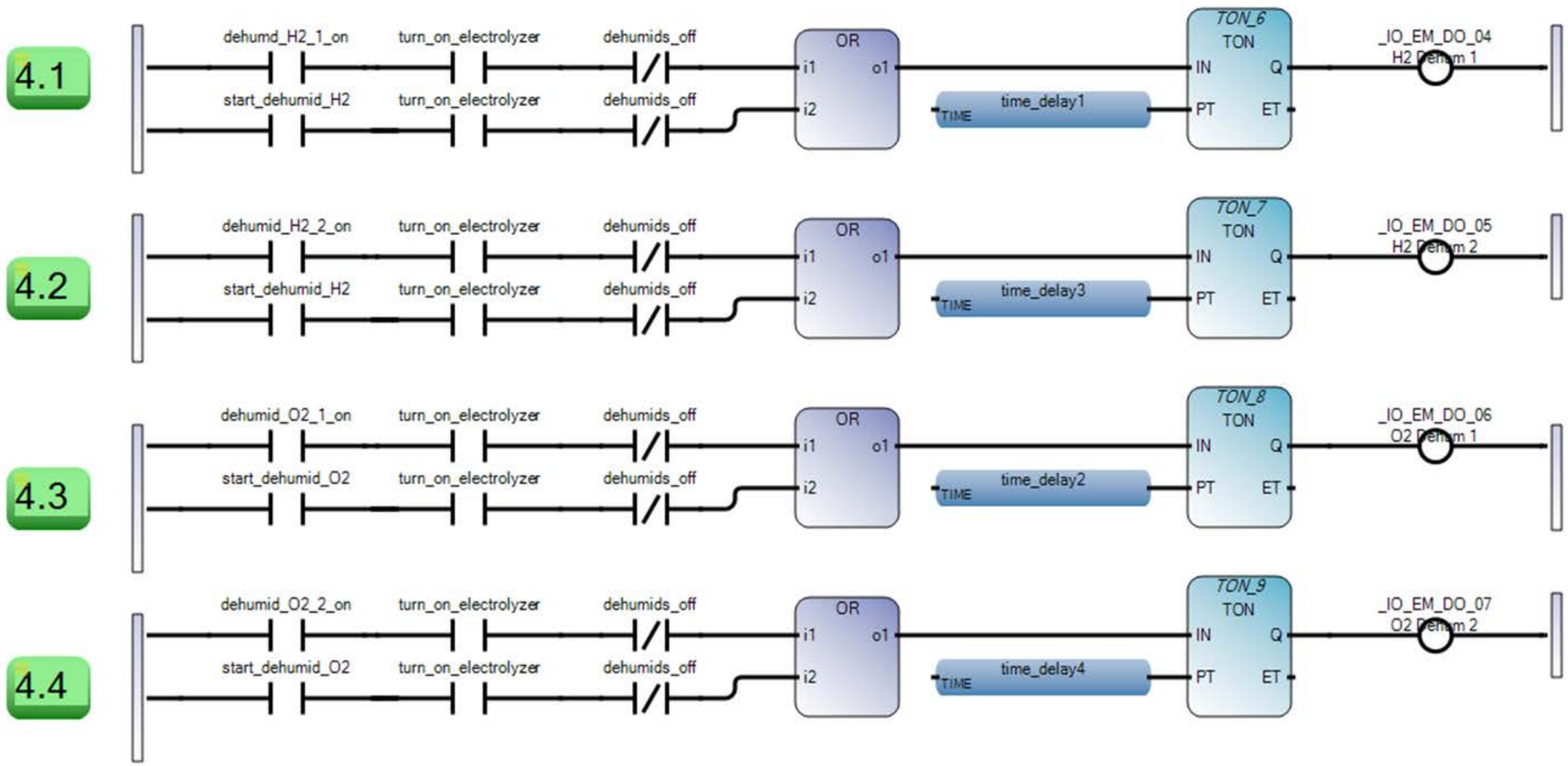
_IO_P2_AI_00	Electrolyzer Voltage	UINT		Analog input from electrolyzer voltage transducer.
electrolyzer_actual_voltage		REAL		Actual voltage across electrolyzer
electrolyzer_min_voltage		REAL	10	Used to determine if electrolyzer voltage is high enough to turn on dehumidifiers
electrolyzer_low_voltage		REAL		Used to turn off dehumidifiers if voltage on electrolyzer is too low
dehumid_on_delay		TIME	3 min	Time delay to turn dehumidifiers on once electrolyzer voltage is high enough
off_timer		TIME	1 min	Time delay to shutdown system if electrolyzer voltage is low and dehumidifiers are already off
SHUTDOWN		BOOL		Variable used to turn the entire system off
storagedesiredlevel		REAL		Used to determine if the storage tanks are below the max level
setpoint		REAL		Used to tell the PID controller what the ideal tank level sum should be
input_auto		BOOL	TRUE	Tells the PID controller to operate in normal mode
input_initialize		BOOL	TRUE	Tells the PID controller to operate in normal mode
my_gains		GAIN_PID		Gain input variable style for PID controller
	Direct.Acting	BOOL	TRUE	Tells the PID controller to open the valve when the output is positive and close the valve when the output is negative
	ProportionalGain	REAL	100	Proportional gain value
	TimeIntegral	REAL	0.01	Integral gain value
	TimeDerivative	REAL	0	Not used
	DerivativeGain	REAL	0.1	Derivative gain value
error		REAL		Error of PID controller
PID_valve_control		REAL		Output of PID controller
_IO_P3_AO_00		UINT		Analog ouput port used to control proportional valve on oxygen outlet
process_delay		TIME	2 min	Time used to close/open secondary oxygen outlet valve
process_elapsed		TIME		Shows time elapsed from process delay TONOFF
_IO_X2_DO_00	on_off_pro_valve	BOOL		Digital output used to close/open secondary oxygen outlet valve
prop_dummy_min		UINT	2	Used to create boolean variable if process value is less than it
one		REAL	1	Creates variable with real value of one

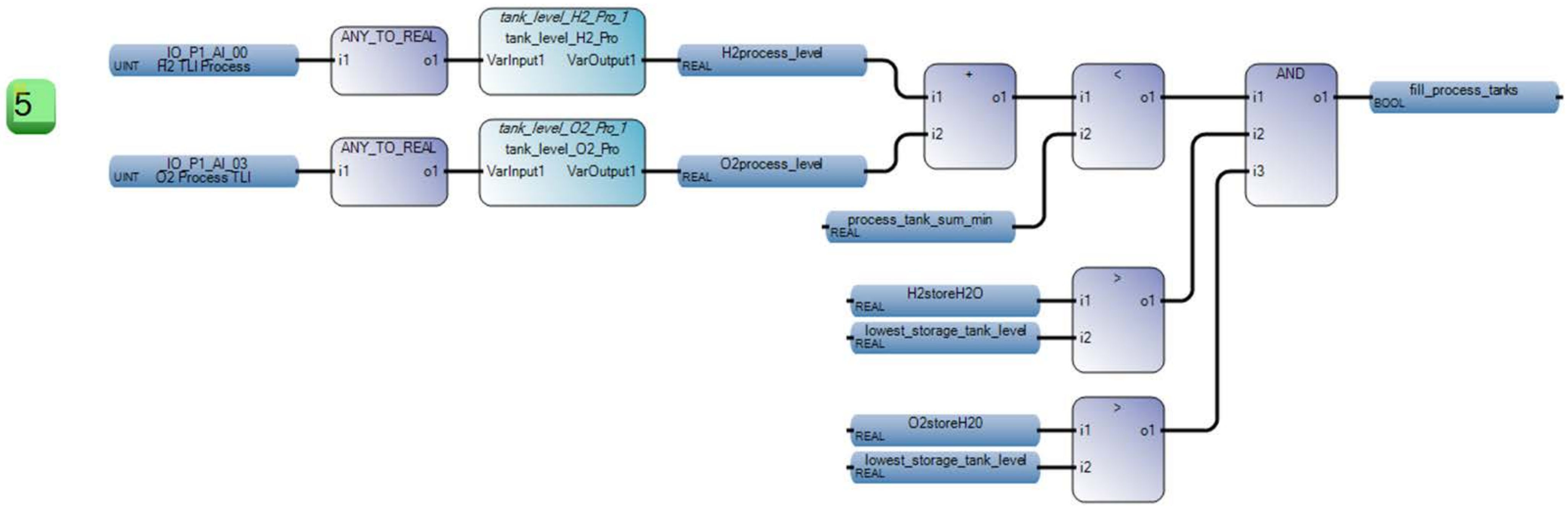
prop_dummy_power		REAL	15	Used as power to raise input to
_IO_P3_AO_01	TTL_process_set	UINT		Used to totally turn on or off proportional valve
processdesiredlevel		REAL	1	Lowest process tank level allowed
lowest_storage_tank_level		REAL	0.5	Lowest storage tank level allowed
_IO_EM_DI_00	Emergency Stop Press	BOOL		Triggers emergency shutdown if emergency pushbutton is pressed or disconnected.
_IO_EM_DI_02	Smoke Detector Setoff	BOOL		Triggers emergency shutdown in smoke is detected.
_IO_EM_DI_01	Smoke Detector Contin	BOOL		Triggers emergency shutdown if smoke detector is disconnected.

Table 2. List of variables used in system program in order of use.

APPENDIX F. COMPRESSION SYSTEM OPERATION PROGRAM



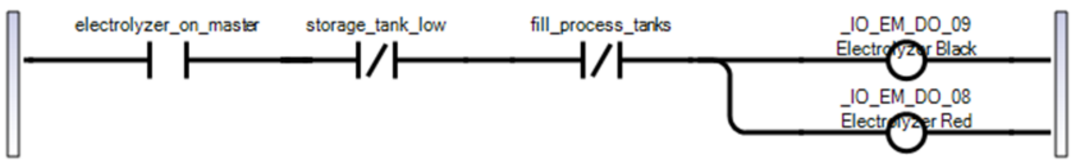

4.1
dehumd_H2_1_on
turn_on_electrolyzer
dehumids_off
start_dehumid_H2
turn_on_electrolyzer
dehumids_off
OR
i1
o1
i2
time_delay1
TIME
TON_6
TON
IN
Q
PT
ET
_IO_EM_DO_04
4.2
dehumid_H2_2_on
turn_on_electrolyzer
dehumids_off
start_dehumid_H2
turn_on_electrolyzer
dehumids_off
OR
i1
o1
i2
time_delay3
TIME
TON_7
TON
IN
Q
PT
ET
_IO_EM_DO_05
4.3
dehumid_O2_1_on
turn_on_electrolyzer
dehumids_off
start_dehumid_O2
turn_on_electrolyzer
dehumids_off
OR
i1
o1
i2
time_delay2
TIME
TON_8
TON
IN
Q
PT
ET
_IO_EM_DO_06
4.4
dehumid_O2_2_on
turn_on_electrolyzer
dehumids_off
start_dehumid_O2
turn_on_electrolyzer
dehumids_off
OR
i1
o1
i2
time_delay4
TIME
TON_9
TON
IN
Q
PT
ET
_IO_EM_DO_07

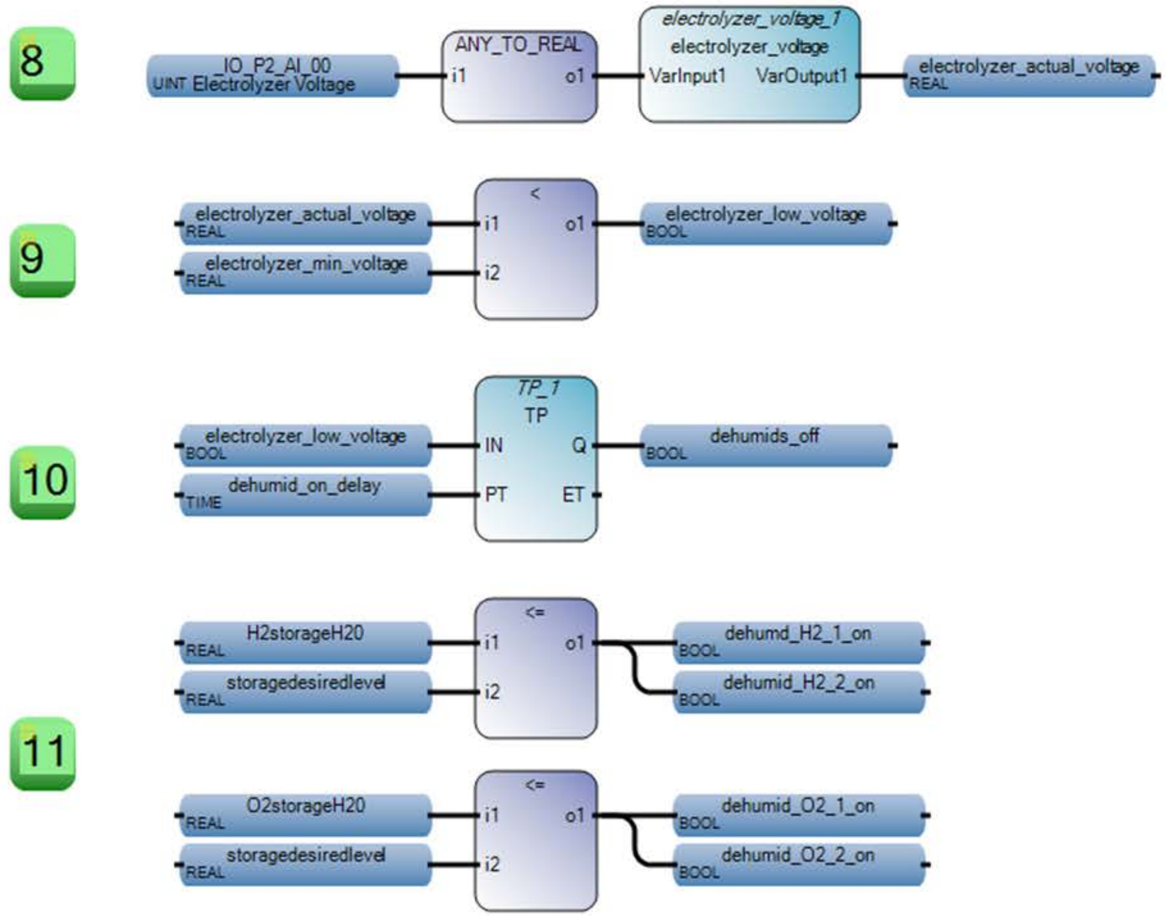

5
UINT IO_P1_AI_00 H2 TLI Process
ANY_TO_REAL
i1
o1
tank_level_H2_Pro_1
tank_level_H2_Pro
VarInput1
VarOutput1
REAL H2process_level
UINT IO_P1_AI_03 O2 Process TLI
ANY_TO_REAL
tank_level_O2_Pro_1
tank_level_O2_Pro
REAL O2process_level
+
<
AND
i2
i3
BOOL fill_process_tanks
REAL process_tank_sum_min
>
REAL H2storeH2O
REAL lowest_storage_tank_level
REAL O2storeH20

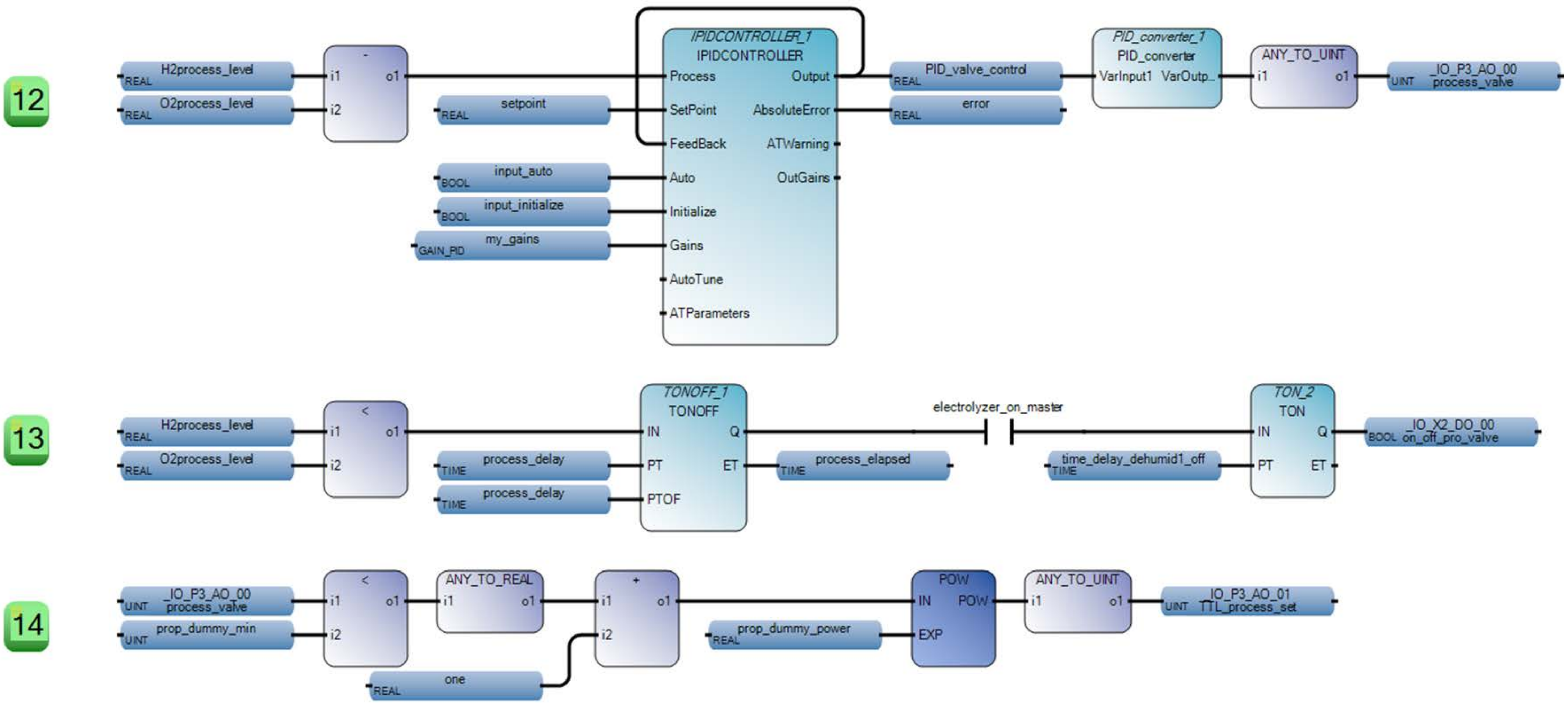
6


fill_process_tanks
_IO_EM_DO_00
O2 Valve In
fill_process_tanks
_IO_EM_DO_01
H2 In Valve
fill_process_tanks
_IO_EM_DO_02
H2 Valve Out
fill_process_tanks
_IO_EM_DO_03
O2 Out Valve

7


electrolyzer_on_master
storage_tank_low
fill_process_tanks
_IO_EM_DO_09
Electrolyzer Black
_IO_EM_DO_08
Electrolyzer Red


8
_IO_P2_AI_00
UINT Electrolyzer Voltage
ANY_TO_REAL
i1
o1
electrolyzer_voltage_1
electrolyzer_voltage
VarInput1
VarOutput1
electrolyzer_actual_voltage
REAL
9
electrolyzer_actual_voltage
REAL
electrolyzer_min_voltage
REAL
<
i1
i2
o1
electrolyzer_low_voltage
BOOL
10
electrolyzer_low_voltage
BOOL
dehumid_on_delay
TIME
TP_1
TP
IN
PT
Q
ET
dehumids_off
BOOL
11
H2storageH20
REAL
storagedesiredlevel
REAL
<=
i1
i2
o1
dehumd_H2_1_on
BOOL
dehumid_H2_2_on
BOOL
O2storageH20
REAL
storagedesiredlevel
REAL
<=
i1
i2
o1
dehumid_O2_1_on
BOOL
dehumid_O2_2_on
BOOL


12
H2process_level
O2process_level
REAL
-
i1
i2
o1
IPIDCONTROLLER_1
IPIDCONTROLLER
Process
SetPoint
FeedBack
Auto
Initialize
Gains
AutoTune
ATParameters
Output
AbsoluteError
ATWarning
OutGains
setpoint
input_auto
input_initialize
my_gains
BOOL
GAIN_PID
PID_valve_control
error
PID_converter_1
PID_converter
VarInput1
VarOutp...
ANY_TO_UINT
_IO_P3_AO_00
process_valve
UINT
13
<
TONOFF_1
TONOFF
IN
PT
PTOF
Q
ET
process_delay
TIME
process_elapsed
electrolyzer_on_master
TON_2
TON
time_delay_dehumid1_off
_IO_X2_DO_00
on_off_pro_valve
14
prop_dummy_min
one
ANY_TO_REAL
+
prop_dummy_power
POW
EXP
_IO_P3_AO_01
TTL_process_set

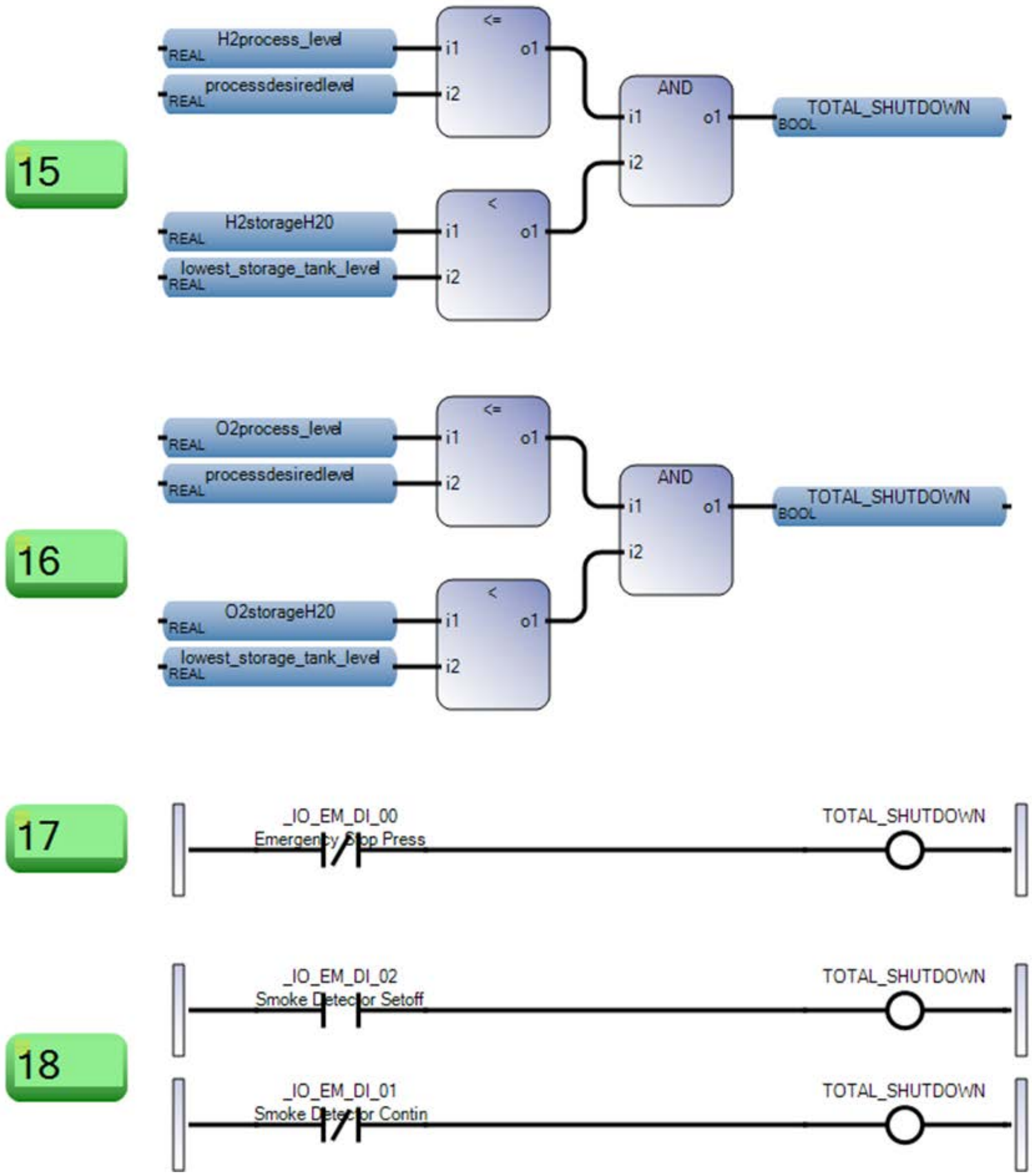


Figure 27. Normal operation system program image from CCW software.

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APPENDIX G. EMERGENCY SHUTDOWN PROGRAM

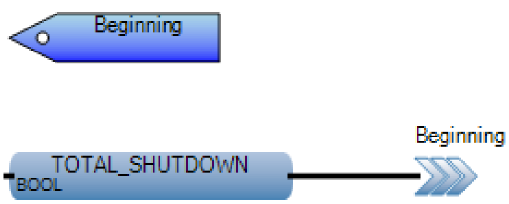

Figure 28. Emergency shutdown system program image from CCW software

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APPENDIX H. FLOW METER DATA COLLECTION MATLAB CODE

```
% Set filename based on days of test"
filename='19APR'
%Establish Communications with Alicat Flow Meter
flowMeter=serial('COM3','Timeout',2,'BaudRate',19200,'Terminator','CR');
fopen(flowMeter)
%Preallocate Data Arrays
runtime = 1380; %minutes
time = zeros(1,runtime);
timerecord = zeros(1,runtime);
inletflowrate = zeros(1,runtime);
inletpressure = zeros(1,runtime);
inlettemp = zeros(1,runtime);

for i=1:runtime % # of samples to collect
    tic
    time(i)= now;
    fprintf(flowMeter,'A');
    IN = fscanf(flowMeter);
    [OUT.ID,OUT.pressure,OUT.temp,OUT.LPM,OUT.SLPM,OUT.gas] =
 strread(IN,'%s%f%f%f%f%s','delimiter',' ');
    inletflowrate(i) = OUT.SLPM;
    inletpressure(i) = OUT.pressure;
    inlettemp(i) = OUT.temp;
    toc
    pause(60-toc)
end
datestr(time)

fclose(flowMeter);
delete(flowMeter);
clear flowMeter;
```

Figure 29. MATLAB code for data collection from flow meter. Adapted from [6].

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APPENDIX I. MATLAB CODE FOR FLOW METER DATA ANALYSIS

```
% Import data from spreadsheet
%% Import data for 11 April
data11 =
xlsread('C:\Users\LAPTOP2\Documents\MATLAB\Birkemeier\11APR.1.xls','She
et1');
data11(:,2)=data11(:,2)+.0360;

%% Import data for 12 April
data12 =
xlsread('C:\Users\LAPTOP2\Documents\MATLAB\Birkemeier\12APR.1.xls','She
et1');
data12(:,2)=data12(:,2)+.0530;

%% Import data for 13 April
data13 =
xlsread('C:\Users\LAPTOP2\Documents\MATLAB\Birkemeier\13APR.1.xls','She
et1');

%% Import data for 14 April
data14 =
xlsread('C:\Users\LAPTOP2\Documents\MATLAB\Birkemeier\14APR.1.xls','She
et1');

%% Import data for 15 April
data15 =
xlsread('C:\Users\LAPTOP2\Documents\MATLAB\Birkemeier\15APR.1.xls','She
et1');

%% Import data for 16 April
data16 =
xlsread('C:\Users\LAPTOP2\Documents\MATLAB\Birkemeier\16APR.1.xls','She
et1');

%% Import data for 17 April
data17 =
xlsread('C:\Users\LAPTOP2\Documents\MATLAB\Birkemeier\17APR.1.xls','She
et1');

%% Import data for 18 April
data18 =
xlsread('C:\Users\LAPTOP2\Documents\MATLAB\Birkemeier\18APR.1.xls','She
et1');

%% Import data for 19 April
data19 =
xlsread('C:\Users\LAPTOP2\Documents\MATLAB\Birkemeier\19APR.1.xls','She
et1');
```

```
% Plot flow meter data for all days
figure(1)
hold on
bar(abs(data11(:,1)),abs(data11(:,2)))
bar(abs(data12(:,1)),abs(data12(:,2)))
bar(abs(data13(:,1)),abs(data13(:,2)))
bar(abs(data14(:,1)),abs(data14(:,2)))
bar(abs(data15(:,1)),abs(data15(:,2)))
bar(abs(data16(:,1)),abs(data16(:,2)))
bar(abs(data17(:,1)),abs(data17(:,2)))
bar(abs(data18(:,1)),abs(data18(:,2)))
bar(abs(data19(:,1)),abs(data19(:,2)))

% Set data labels vector for 0700, 1200, and 1700 each day
datelabels = [datenum(2018,04,11,07,0,0) datenum(2018,04,11,12,0,0)
datenum(2018,04,11,17,0,0) ...
    datenum(2018,04,12,07,0,0) datenum(2018,04,12,12,0,0)
datenum(2018,04,12,17,0,0) ...
    datenum(2018,04,13,07,0,0) datenum(2018,04,13,12,0,0)
datenum(2018,04,13,17,0,0) ...
    datenum(2018,04,14,07,0,0) datenum(2018,04,14,12,0,0)
datenum(2018,04,14,17,0,0) ...
    datenum(2018,04,15,07,0,0) datenum(2018,04,15,12,0,0)
datenum(2018,04,15,17,0,0) ...
    datenum(2018,04,16,07,0,0) datenum(2018,04,16,12,0,0)
datenum(2018,04,16,17,0,0) ...
    datenum(2018,04,17,07,0,0) datenum(2018,04,17,12,0,0)
datenum(2018,04,17,17,0,0) ...
    datenum(2018,04,18,07,0,0) datenum(2018,04,18,12,0,0)
datenum(2018,04,18,17,0,0) ...
    datenum(2018,04,19,07,0,0) datenum(2018,04,19,12,0,0)
datenum(2018,04,19,17,0,0)];

% Add data labels to Figure 1
axis on
grid on
xticks(datelabels)
datetick('x','HH','keepticks')
xlabel('Time of Day (11-19 APR)')
ylabel('Standard Liters Per Minute (SLPM)')

% Plot data for April 14th
figure(2)
bar(data14(:,1),data14(:,2))

% Create data labels for every hour on April 14th
datelabels2 = [datenum(2018,04,14,07,0,0) datenum(2018,04,14,08,0,0)
datenum(2018,04,14,09,0,0) ...
    datenum(2018,04,14,10,0,0) datenum(2018,04,14,11,0,0)
datenum(2018,04,14,12,0,0) ...
    datenum(2018,04,14,13,0,0) datenum(2018,04,14,14,0,0)
datenum(2018,04,14,15,0,0) ...
    datenum(2018,04,14,16,0,0) datenum(2018,04,14,17,0,0)
datenum(2018,04,14,18,0,0) ...
    datenum(2018,04,14,19,0,0)];
```

```
% Add data labels for April 14th to Figure 2
axis on
grid on
xticks(datelabels2)
datetick('x','HH','keepticks')
xlabel('Time of Day')
ylabel('Standard Liters Per Minute (SLPM)')

% Plot flow meter data for April 12th
figure(3)
bar(data12(:,1),data12(:,2))

% Create data labels for each hour on April 12th
datelabels2 = [datenum(2018,04,12,07,0,0) datenum(2018,04,12,08,0,0)
datenum(2018,04,12,09,0,0) ...
    datenum(2018,04,12,10,0,0) datenum(2018,04,12,11,0,0)
datenum(2018,04,12,12,0,0) ...
    datenum(2018,04,12,13,0,0) datenum(2018,04,12,14,0,0)
datenum(2018,04,12,15,0,0) ...
    datenum(2018,04,12,16,0,0) datenum(2018,04,12,17,0,0)
datenum(2018,04,12,18,0,0) ...
    datenum(2018,04,12,19,0,0)];

% Add data labels for April 12th to Figure 3
axis on
grid on
xticks(datelabels2)
datetick('x','HH','keepticks')
xlabel('Time of Day')
ylabel('Standard Liters Per Minute (SLPM)')
```

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LIST OF REFERENCES

[1] *Energy Policy Act of 2005*, Pub. L. No. 109–58, [Online]. Available: https://www.gpo.gov/fdsys/pkg/PLAW-109publ58/pdf/PLAW-109publ58.pdf

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