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Development and Implementation of a Data Acquisition System for a Grid Connected Photovoltaic Array

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Abstract

The project undertaken at the Building 190 facility seeks to upgrade an existing data acquisition system to allow for monitoring of the power being produced, and the power being delivered to the utility grid by the photovoltaic (PV) array located on the roof of the building. The PV array consists of 60 PV modules, resulting in a 4.5kWp (kW peak) array. These modules are able to be aligned into a large variety of array configurations via a Patch Panel. The PV array is connected to the utility grid via an SMA Sunnyboy 5000TL transformerless inverter. There is also a range of environmental sensors connected to the data acquisition system to allow for current environmental conditions to be monitored.

The original data acquisition program that was used for this project lacked the capabilities to record the power being delivered to the utility grid, and thus the main aim of this project was to upgrade the system to include this feature. The project also included the restoration of any and all equipment needed to allow for the data acquisition system to function properly. Restoration included the replacement of faulty environmental sensors, namely the anemometer and the wind vane. The newly installed anemometer also required installation of a FP-CTR-502 counter module.

A key aspect of the project was re-establishing data communication between the Allen-Bradley PLC and the PC host to the data acquisition system. Methods taken to restore communications included replacement of the PLC battery, removal of unnecessary serial connections and the alteration of the data transfer rate on the host PC to match that of the PLC. This successfully restored data communications between the PLC and host PC.

Overall, the data acquisition system that was developed is fully operational. The user of the system is able to record the power produced by the PV array and the current environmental conditions, both at one second intervals. This enables reliable data recording during times of inconsistent sun exposure. The user can also record the power being delivered to the grid, however, only at an extended sample rate of 36 seconds due to the sluggish behaviour of the PLC program.

Acknowledgements

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Most profound thanks to Mr. Simon Glenister whose knowledge, expertise and supervision has been invaluable in restoring the PV Array Patch Panel and the environmental sensors.

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List of Symbols

Symbol	Description
V_{sup}	Supply voltage
$V_{typicalThreshold}$	Difference of supply voltage and actual typical threshold voltage
$V_{maximumThreshold}$	Difference of supply voltage and actual maximum threshold voltage
$V_{minimumThreshold}$	Difference of supply voltage and actual minimum threshold voltage
$typicalV_{actualThreshold}$	Typical threshold voltage
$maximumV_{actualThreshold}$	Maximum threshold voltage
$minimumV_{actualThreshold}$	Minimum threshold voltage

Glossary

Abbreviation	Meaning
A	Amps
AC	Alternating Current
ACRE	Australian Cooperative Research Centre for Renewable Energy
CPU	Central Processing Unit
DAQ	Data Acquisition
DC	Direct Current
FP-1001	FieldPoint Network Module
FP-AI-110	FieldPoint Analogue Input
FP-CTR-500/502	FieldPoint Counter
FP-TC-120	FieldPoint Thermocouple Module
I/O	Input and Output
ICSE	Industrial Computer Systems Engineering
kWp	Kilowatt peak (peak power output)
MACSB	Main AC Switchboard
MAX	Measurement and Automation Explorer
NI	National Instruments
PC	Personal Computer
PLC	Programmable Logic Controller
PV	Photovoltaic
RCD	Residual Current Device
RH	Relative Humidity
RISE	Research Institute for Sustainable Energy
V	Volts
Ω	Ohms

1.0 Introduction

Murdoch University has been involved with renewable energy studies for the last 40 years [1]. In the 1980s, the Photovoltaic (PV) Device Group was founded and began working on silicon solar cells [1]. The PV Device Group was joined by the PV Systems Group, and Murdoch University Energy Research Institute was established [1]. During the 1990s, Murdoch University was host to the Australian Cooperative Research Centre for Renewable Energy (ACRE) [1]. ACRE was supportive of creating a testing and standards facility, as well as educating people in renewable energy [1]. ACRE was subsequently shut down in 2004, and in its place Murdoch University created the Research Institute for Sustainable Energy (RISE) [1]. RISE continued the work of ACRE for the testing of renewable energy components for the wind and PV industries [1]. RISE was disbanded in 2010 and the building (known as Building 190) and facilities were inherited by the School of Engineering and Information Technology [1]. The School of Engineering and Information Technology now uses Building 190 for student experiments and various research projects. Building 190 is located on the eastern edge of Murdoch University's South Street campus, as shown in Figure 1.

Figure 1: Location of Building 190

Some facilities and equipment that can be found at Building 190 include [2]:

- Switchboards for AC and DC purposes;
- Computer (PC) based control system;
- Programmable logic controllers (PLCs) for the PC based control system;
- An environmental chamber that allows for control over ambient temperature and humidity;
- A 25kW simulated solar array;
- A 70kW DC power source;
- A 28kVA diesel generator;
- A 4.5kW peak (kWp) rooftop customisable PV array;
- Associated 'Patch Panel' for rooftop PV array;
- SMA Sunnyboy 5000TL transformerless inverter; and,
- Allen-Bradley Bulletin 1403 Powermonitor II monitoring equipment.

1.1 System Overview

The system in which this report focuses is the 4.5kWp PV array, its connection to the SMA Sunnyboy 5000TL transformerless inverter (which will be referred to as the inverter), the data acquisition (DAQ) system that will record the power produced by the PV array and the power delivered to the utility grid. Figure 2 shows a simplified overview of the system.

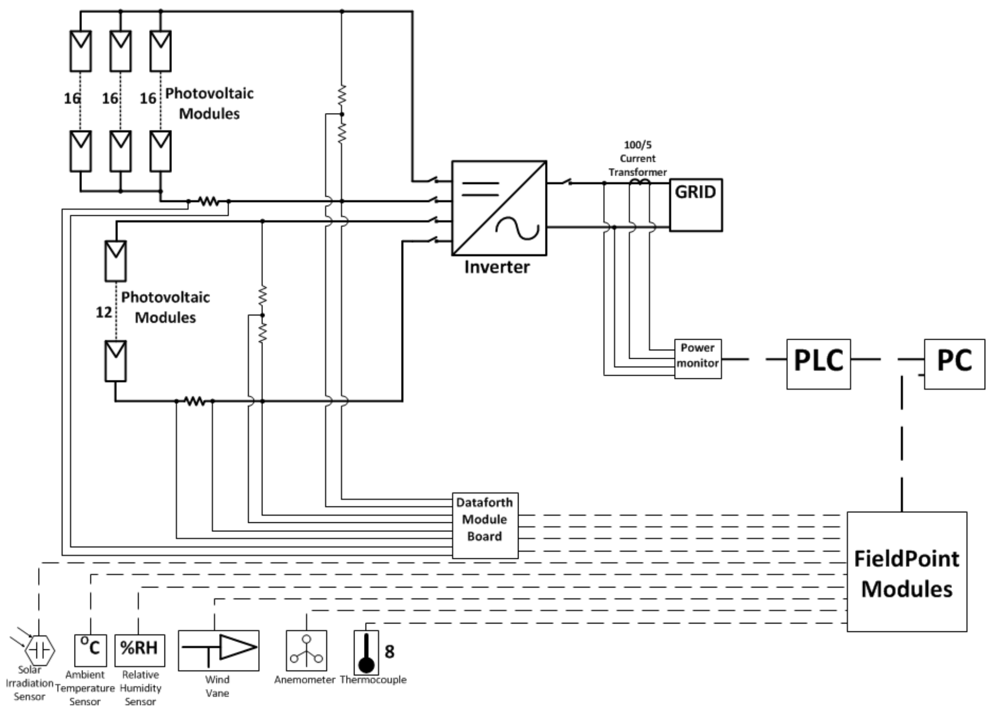

Figure 2: Simplified System Overview

The PV array consists of 60 BP275 75W PV modules spanned across four frames [3], as shown in Figure 3. These modules are able to be configured into many different PV circuits via the Patch Panel shown in Figure 4.

Figure 3: PV Array on Building 190 Rooftop

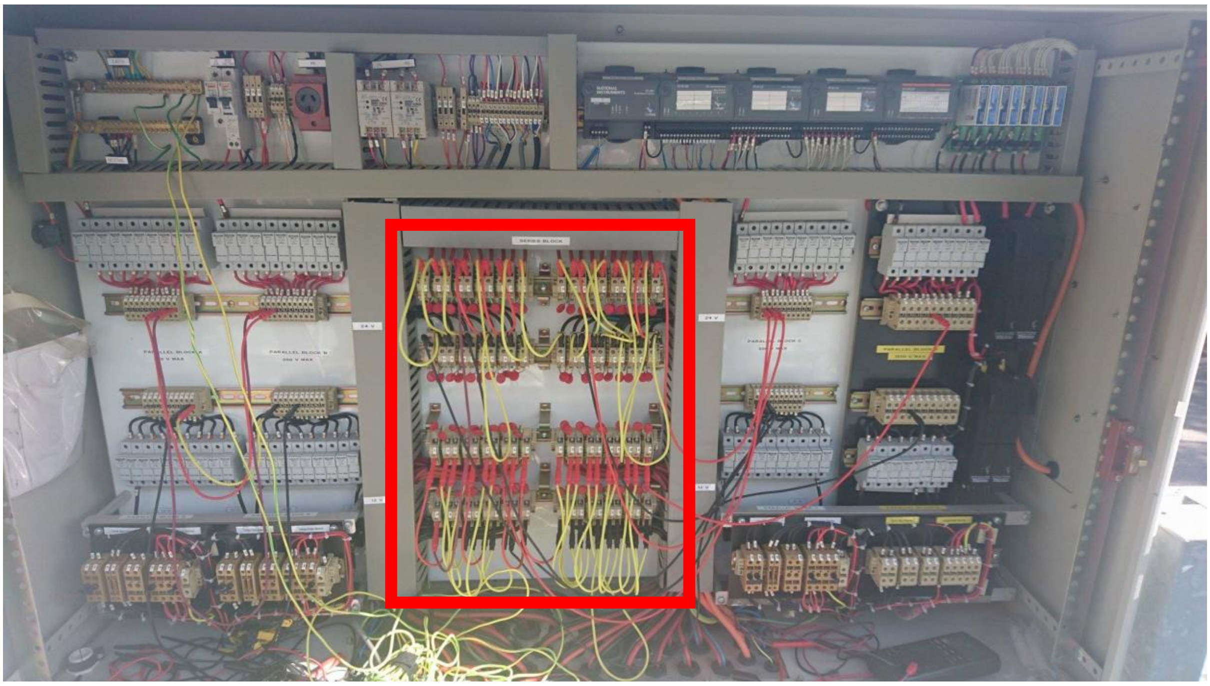

Figure 4: Patch Panel with Customisable PV Module Area Outlined in Red

Currently, the PV modules have been arranged so that there are three strings of sixteen PV modules in series and one string of twelve PV modules in series. The connections are shown in Figure 5. The three strings of sixteen PV modules in series have been connected in parallel to form one PV circuit, and the string of twelve PV modules in series forms a separate circuit. The two separate circuits are connected to one of four 'blocks' within the Patch Panel. The Patch Panel 'blocks' are labelled A-D; Blocks A-C are rated at 500V and Block D is rated at 1000V [3]. These blocks are connected to the inverter in the interior of the building, which is subsequently connected to the utility grid. A current shunt is connected within the negative conductor of each PV circuit. The current shunt allows for measurement of the current produced by each PV circuit. A voltage divider is connected to each PV circuit to allow for the measurement of the voltage produced by each PV circuit. The current shunt and voltage divider signals are fed into a set of signal isolators, known as Dataforth modules. The Dataforth modules scale the current and voltage signals to an extra low voltage (max 5V) that allows for measurement by the DAQ hardware.

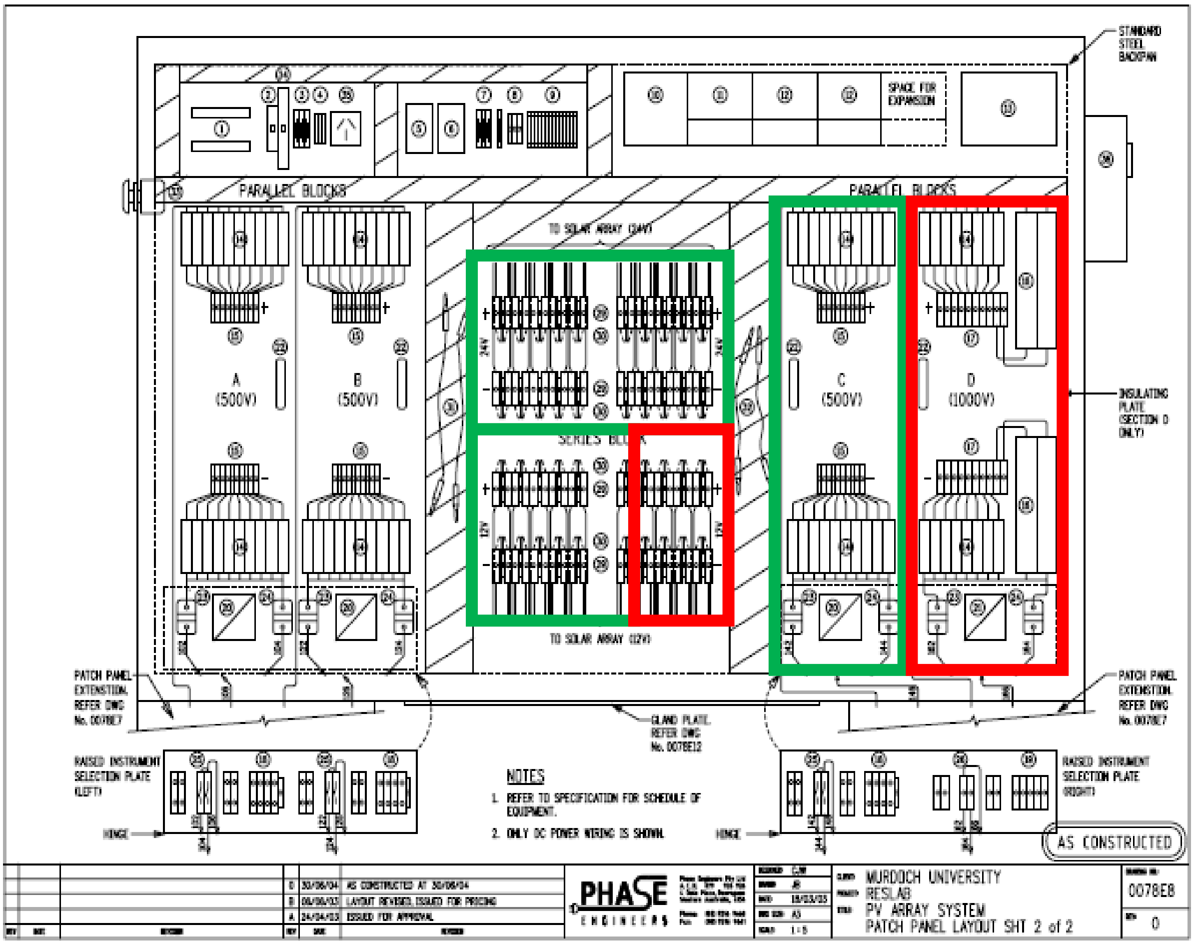

Figure 5: 3 Strings of 16 PV modules in series (Green); 1 String of 12 PV modules in series (Red); and Their Connections

The DAQ hardware comprises National Instruments FieldPoint modules. The FieldPoint modules relay the information received by the Dataforth modules via RS-485 serial communication to the host PC in the interior of the building. The FieldPoint modules not only relay the voltage and current information to the PC, but also relay the environmental sensor data and the PV module temperature data to the PC. The environmental sensors that are installed on the rooftop of Building 190 include:

- An anemometer, for measuring wind speed
- A wind vane, for measuring wind direction
- A pyranometer, for measuring solar irradiance and,
- A humitter, for measuring ambient temperature and relative humidity.

Furthermore, there are eight thermocouples spanned across the four frames, two thermocouples per frame, to monitor the temperature of the PV modules. The voltages that are fed into the FieldPoint modules from the environmental sensors and thermocouples range from μV to 5V.

Referring to Figure 2, the values of the power being delivered to the utility grid are measured by an Allen-Bradley Bulletin 1403 Powermonitor II. A voltage probe was connected to the AC side of the inverter to allow for AC voltage measurement. A current transformer was placed on the active line of the inverter to the utility grid circuit. The current transformer had a ratio of 100:5. The Allen-Bradley Powermonitors are able to measure many parameters, including [2]:

- Current (in Amperes), per phase and neutral;
- Voltage (in Volts), line-to-line and line-to-neutral;
- Frequency (in Hertz);
- Real power (in Watts);
- Reactive power (in Volts-Amps reactive);
- Apparent power (in Volts-Amps); and,
- Power factor.

This list is only a fraction of the capabilities of the Powermonitor. A full list of the Powermonitor measuring capabilities can be found in appendix A.6. The values obtained by the Powermonitor could to be accessed by the Allen-Bradley SLC500 PLC which, in turn was controlled by a program that was developed on the host PC. The values from the FieldPoint modules and the Powermonitor can be retrieved on the PC at any time. These values are written to a DAQ program written in National Instruments LabVIEW. As some of these values are not a true representation of the current conditions of the PV circuits, environmental sensors, thermocouples, or AC power, processing of these values was required in order to better represent the conditions in the different areas of the system.

1.2 Previous Work

Since the disbandment of RISE, a number of students have worked at the facility. A thesis completed by Woodard [2] titled 'RISE SCADA and Electrical System: A report pertaining to the condition and serviceability of the electrical and SCADA systems of the former RISE facility,' describes the challenges faced as the facility was in disuse for a number of years before the commencement of the project. For example, the personnel of RISE had long since left Murdoch University, so Woodard had no knowledge on the systems located in Building 190 [2]. Woodard's project focused on revitalising various equipment found within the facility. This project had little to do with the project covered in this report. However, Woodard developed the PLC program that was required to retrieve the values of power being delivered to the utility grid.

More work was performed on the facility by Sharpe [3]. Sharpe's thesis, entitled 'An Investigation into Installing a Solar Intermittency Monitoring System at Murdoch University: A Proposed Design for the Installation of a System at Building 190', included the foundations for the DAQ program described in this report. A brief list of Sharpe's work includes [3]:

- Restoring power to the SMA Sunnyboy 5000TL transformerless inverter;
- Repairing the circuit breakers connecting the inverter to the utility grid; and,
- An attempt to mount a pyranometer (solar irradiance sensor).

A group of fourth year students, Froese, Kenneday, and Murphy [4], studying Industrial Computer Systems Engineering, were required to perform work on the PV array and associated hardware and software. In their report, titled 'ENG454-RISE Facility Phase 4- Real PV Array,' these students described the work they performed in order to make their DAQ system operational. The list of works performed includes [4]:

- Installing an RS-485 to USB card for FieldPoint system
- Inspecting and repairing the Data Highway Plus (DH+) network for PC to PLC communication
- Developing the LabVIEW Object Linking and Embedding for Process Control (OPC) server
- Setting up the FieldPoint network for data communications
- Wired the environmental sensors to the relevant FieldPoint module and,
- Developing a DAQ program, which is a variation of the one discussed in this report.

1.3 Project Tasks

The overall goal of this project is to further develop the existing DAQ system. As mentioned, the DAQ system was originally worked on by Woodard [2], Sharpe [3], and Industrial Computer Systems Engineering (ICSE) students [4]. The DAQ program developed by Sharpe [3] only allowed for the recording of the environmental sensors and for the power produced by the PV array [3]. The power being delivered to the utility grid was a key feature that was required to be included in Sharpe's [3] DAQ program. Furthermore, as the facility was in disuse for a number of years [2-4], some of the equipment had malfunctioned. The tasks that were required for this project included:

- Repairing environmental sensors
- Installing a pyranometer
- Replacing faulty Patch Panel circuit connections
- Installing new FieldPoint hardware for environmental sensors
- Restoring the communications between the PC and PLC
- Extracting power delivered to utility grid values for DAQ purposes and,
- Upgrading existing DAQ program to include AC power values.

1.4 Approach

This project relied heavily on communication between many people. The three main people involved in the project, other than the author, were: Martina Calais, Simon Glenister, and Will Stirling. Martina was the supervisor for the project. Martina provided guidance and knowledge on renewable energy systems. Simon was heavily involved in the restoration of the environmental sensors and performing maintenance on the Patch Panel. Simon's skills and knowledge were crucial to the successful outcome of this project. Finally, Will's assistance was invaluable in restoring the communications between the PC and PLC.

There were many constraints placed on the project. As mentioned, the location of Building 190 was on the eastern edge of Murdoch University's South Street campus. This location was isolated from the rest of the campus and the nature of the work involved included working with dangerous voltages as well as working from heights. As a result, two people were required to be present to perform work on the DAQ system and related hardware. A meeting schedule was developed to minimise these constraints which allowed for the effective completion of the project.

1.5 Thesis Outline

Following on from this, the thesis discusses the replacement and installation of the environmental sensors. This is followed by the PV array and the functionality of the rooftop system. An important aspect of the project, the PLC issues, is discussed after the PV array topic. The final topic to be considered is the DAQ system as a whole and its user interface. Finally, this report will provide some concluding remarks and make some recommendations about future work that can be done to improve the system.

2.0 Weather Station

A key component to the data acquisition system is the weather station. The current status of the weather station allows for the measurement of different meteorological phenomena. Namely, ambient temperature, relative humidity, wind speed, wind direction and solar irradiance. These phenomena are measured by a humitter for ambient temperature and relative humidity, an anemometer for wind speed, a wind vane for wind direction, and a pyranometer for solar irradiance. Figure 6 shows the current weather station.

Figure 6: Weather Station

2.1 Anemometer

Anemometers are devices that allow for the measurement of wind speed. Many types of anemometers are available. A common version of an anemometer is the cup anemometer [5]. The cup anemometer, found on the roof of Building 190, rotates at a speed proportional to the speed of the wind [5]. The rotation of the anemometer can be measured by one of the following three mechanisms:

- mechanical counters [5]
- changes in a voltage output [5] and,
- photoelectric switching [5].

Mechanical counters are advantageous in remote areas where power is scarce. However, these types of anemometers do require a lot of maintenance, and spare parts can be expensive [5]. Electronic anemometers are connected to mini AC or DC generators. The output voltage from these generators can be converted into a wind speed by a simple calculation which is provided by the manufacturer [5]. The photoelectric anemometer contains a slotted disc with up to 120 slots, as well as a photocell [5]. The passing of the slots over the photocell produce a pulsing output, where the frequency of these pulses is proportional to the wind speed. The relationship between the pulses and wind speed is provided by the manufacturer [5]. As all anemometers are manufactured differently, each is unique and will have a different type of response and different accuracy [5]. Furthermore, any changes made to the anemometer, including (but not limited to) weight, physical dimensions, and internal friction, can change the overall response and accuracy of the anemometer [5]. If any of these factors have been changed, the anemometer will need to be recalibrated [5]. Finally, an anemometer must be checked and cleaned thoroughly in areas that are known for excessive amounts of dust in the air. Dust may be blown into the internal bearings of the anemometer, which can lead to an increase in friction or excessive wearing of the bearings [5]. Figure 7 shows the cup anemometer mounted on the weather station in motion.

Figure 7: Mounted Anemometer in Motion (Courtesy of Simon Glenister)

2.1.1 Issues

Upon commencement of the project, it was quickly discovered that the anemometer was not functioning properly. The model of anemometer that was being used produced a square wave pulse signal and not a varying voltage [6]. The anemometer was dismounted from the weather station to test if there was a hardware fault. The anemometer was connected to an oscilloscope and was spun. The output that was produced was a flat voltage and not the expected square wave output. The flat-line voltage output is illustrated in Figure 8. A new anemometer was acquired and tested in the same manner as the original anemometer. As the new anemometer was a photoelectric anemometer, when spun, the anemometer produced the expected square wave output; this output is shown in Figure 9.

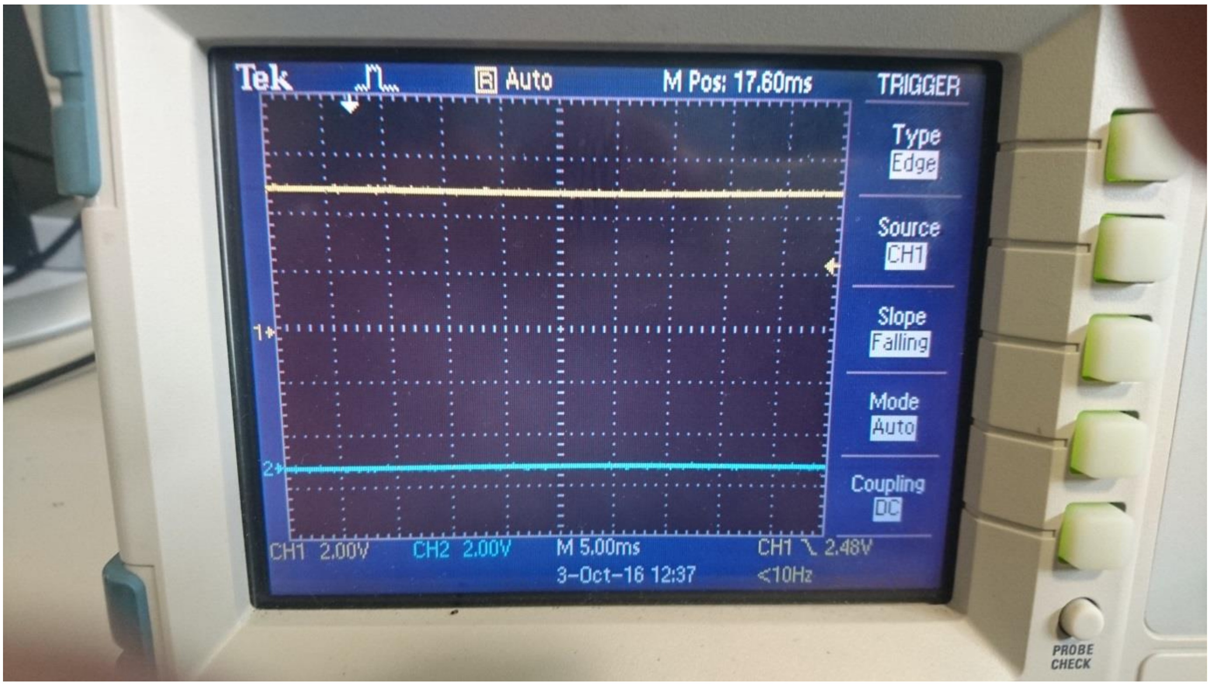

Figure 8: Constant Output Voltage (Yellow Line)

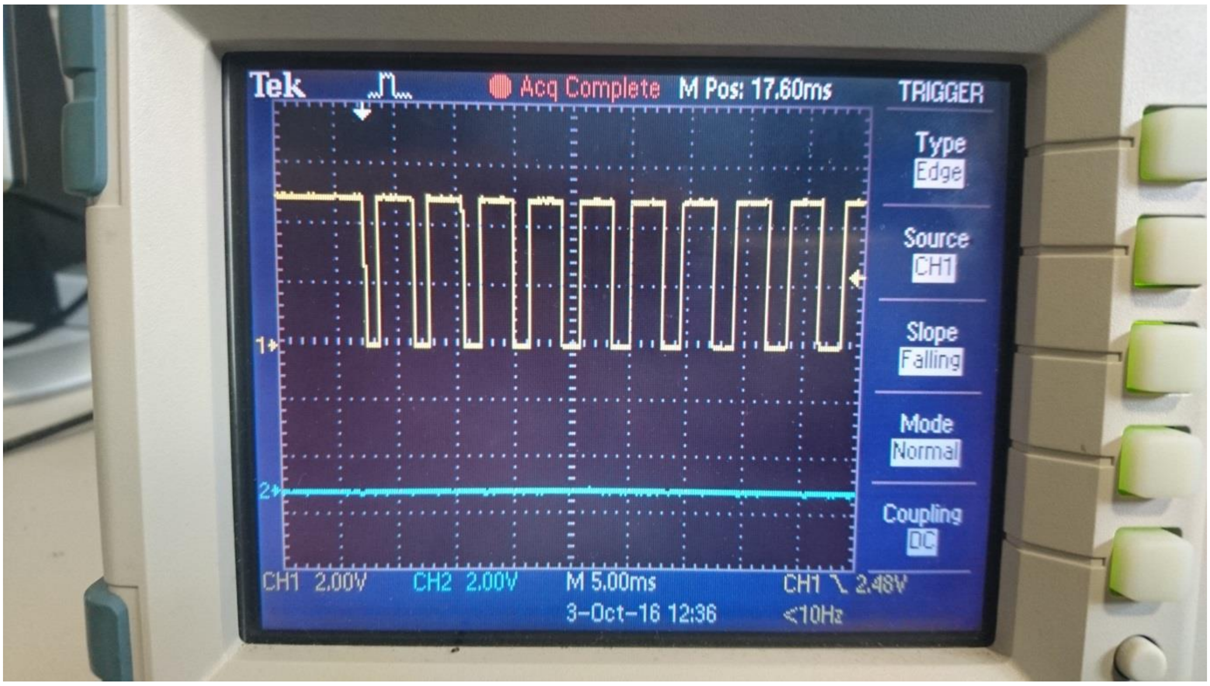

Figure 9: Working Anemometer Output (Yellow Line)

Originally, the anemometer was connected to a FieldPoint Analogue Input (FP-AI-110). The FP-AI-110 detects a varying voltage and sends a digital signal to the database where the weather station data is collected. As the anemometer had a varying frequency output and not a varying amplitude output, a FieldPoint Counter (FP-CTR-500) needed to be installed. The purpose of the FP-CTR-500 was to count the number of pulses the anemometer produces [7]. The count of the counter increase by 1 every time the signal voltage exceeds a threshold voltage [8]. The specifications for the FP-CTR-500 module indicated that the threshold for signal detection was typically 8V but may vary between 6V to 10V [7]. The anemometer was designed to produce a 4-5V square wave [6]. This is clearly below the required threshold for the FP-CTR-500 counter module. In order to address this issue, an amplifying circuit was designed to scale the output voltage. Figure 10 shows the circuit design.

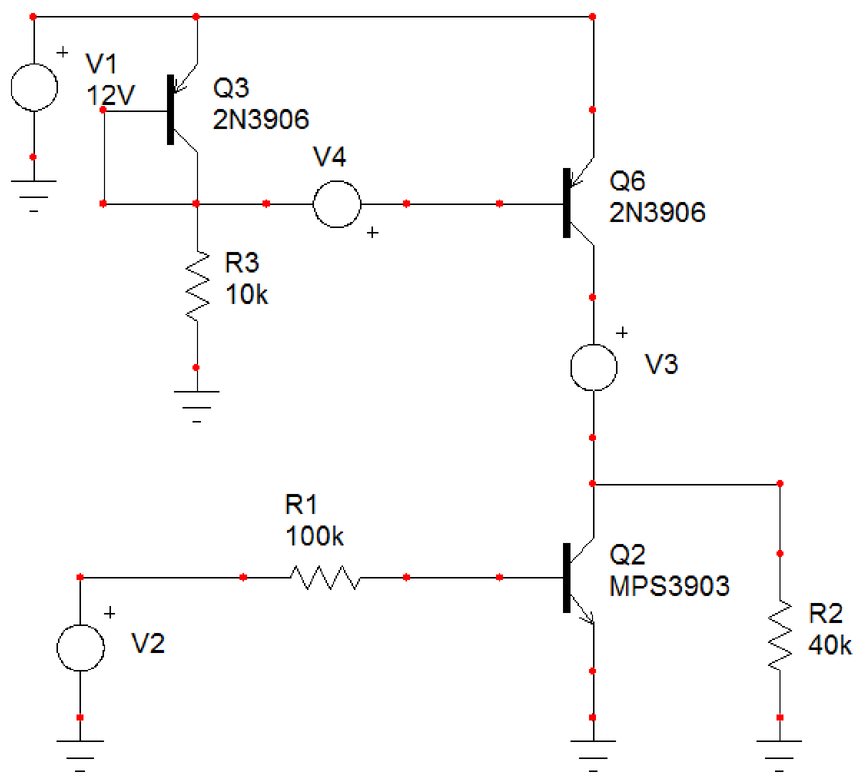

Figure 10: Proposed Current Amplifier for Anemometer Signal Output (Courtesy of Simon Glenister)

The amplifying circuit utilises the inverting nature of transistors. The main part of the circuit was the bottom half. The voltage source V2 represents the output signal from the anemometer. This signal is fed into the base (node 5) of the transistor, Q2. The amplified signal that would be fed into the FP-CTR-500 module is taken from the collector (node 3). The top half of the circuit behaves as a current mirror. The purpose of the current mirror is to keep the current constant regardless of the circuit loading (in this case, the counter module) [9]. The voltage sources V3 and V4 have been placed as such to allow for current measurements in the circuit simulation program, and do not add any voltage to the amplifying circuit.

Fortunately, a different counter module, an FP-CTR-502 module, was found which did not require the amplifying circuit. This module has slightly different specifications than the FP-CTR-500 module. The FP-CTR-502 module has thresholds which are dependent on the voltage powering the device. In this case, the source voltage available was 5VDC. In order to calculate the threshold limits, the following equations were used:

$$typicalV_{actualThreshold} = V_{sup} - V_{typicalThreshold} \qquad (1)[8]$$

$$maximumV_{actualThreshold} = V_{sup} - V_{maximumThreshold} \qquad (2)[8]$$

$$minimumV_{actualThreshold} = V_{sup} - V_{minimumThreshold} \qquad (3)[8]$$

The values for $V_{typicalThreshold}$, $V_{maximumThreshold}$ and $V_{minimumThreshold}$ are given as 2.5V, 2.0V and 3.0V, respectively [8]. Given that the supply voltage is 5VDC, the maximum and minimum threshold voltages were calculated to be 3.0V and 2.0V, respectively, with the typical threshold voltage calculated to be 2.5V. Clearly, this threshold level is acceptable to use as the output of the anemometer was a 4-5V square wave. Figure 11 shows the newly installed FP-CTR-502 module.

Figure 11: FP-CTR-502 Module Installed in Patch Panel

2.2 Wind Vane

Wind vanes are devices that measure wind direction. The majority of wind vanes have a broad tail that sits downwind of the wind vane, and a counterweight nose, which sits upwind of the wind vane [5]. Most commonly, the internal mechanism is a potentiometer which acts as a voltage divider [5]. The magnitude of the output voltage determines the bearing of the wind vane [10]. A wind vane must be checked and cleaned thoroughly in areas containing a lot of dust in the air, as the dust can create friction that wears down the internal bearings of the wind vane [5]. Figure 12 shows the wind vane mounted on the weather station.

Figure 12: Wind Vane

2.2.1 Issues

When checking the weather station for its integrity, it was revealed that the wind vane was not operating correctly. As the basic functioning of the wind vane was as a potentiometer, it was quite easy to determine the cause of the wind vane not performing as intended. By dismounting the wind vane from the weather station, the wind vane’s potentiometer could be tested. By measuring the resistance across the wind vane’s three pins, three constant resistances were measured. By turning the wind vane to a different orientation, the resistances across the three pins were measure again, which resulted in the same three resistance values. These two sets of identical values determined that the potentiometer of the wind wane was not working correctly. Dismantling the wind vane, it was discovered that, after many years of use, the potentiometer had become sticky and that the mechanism for transferring the wind vane’s movement to the potentiometer had become loose. A new NRG200P (NRG) wind vane was acquired. The NRG wind vane has a potentiometer, similar to the original, within the wind vane housing. Upon testing the three output nodes of the wind vane, it was found that at least two of the possible three measurement combinations produced a varying resistance when reorienting the wind vane. The range of resistance output was measured to be between 0 to 10,000Ω, which confirmed the value taken from the specifications of the NRG wind vane [10]. The wind vane signal output was directed to the FP-AI-110 module, which detects a varying voltage. Due to the voltage divider within the wind vane, the output was found to be between 0V and the supply voltage, which, in this case, was 5V. The magnitude of the output voltage corresponds to the bearing to where the air is traveling from, where north is equal to 0V.

2.3 Pyranometer

A pyranometer is a device that allows for the measurement of global or diffuse irradiance [11]. The pyranometer used for the weather station is shown in Figure 13. The pyranometer consists of a glass dome to allow the solar energy to be absorbed by an internal black disc [12]. The heat that is generated by the black disc streams through a thermal resistance to the body of the pyranometer [12]. The temperature difference that is detect across the thermal resistance of the disc is converted into a small voltage [12].

Figure 13: Mounted Pyranometer

Originally, the weather station did not have a pyranometer. Ideally, two pyranometers need to be installed: one pyranometer parallel to the horizon, and one pyranometer to be on the same plane as the photovoltaic (PV) array [3]. The horizontal pyranometer would be used as a control to determine the amount of solar power, per square metre, reaching the ground. The pyranometer that is in the plane of the PV array would indicate the amount of solar power reaching the array, per square metre [3]. Unfortunately, only one pyranometer was acquired. Due to time constraints, it was decided that the pyranometer would be mounted parallel to the horizon. This mounting style resulted in only an indication of the solar power reaching the PV array.

3.0 Photovoltaic Array

Two of the major components of the project are the photovoltaic (PV) array located at Building 190 and its associated Patch Panel. The PV array consists of sixty BP275 75W PV modules that spanned four frames. The sixty PV modules were connected to the Patch Panel located behind the array on the roof of Building 190. From the Patch Panel, shown in Figure 4, the PV modules could be configured into a variety of different circuits by altering the cables found in the 'Series Block' area of the Patch Panel, as shown in Figure 14. Currently, the modules are configured such that there are three strings of sixteen modules in parallel, and one series of twelve modules. These 'circuits' of PV modules are then wired into one of four 'Blocks' located in the Patch Panel. The 'Blocks' are labelled A-D. Blocks A-C are rated for 500V, and Block D is rated for 1000V. The Blocks are wired to a transformerless inverter located in the interior of the building. In order to obtain the values of the currents and the voltages produced from the strings of PV modules, current shunts and voltage dividers have been installed within the Patch Panel for current and voltage conditioning, shown in Figure 15 [3]. These conditioned signals are further conditioned by several Dataforth Modules.

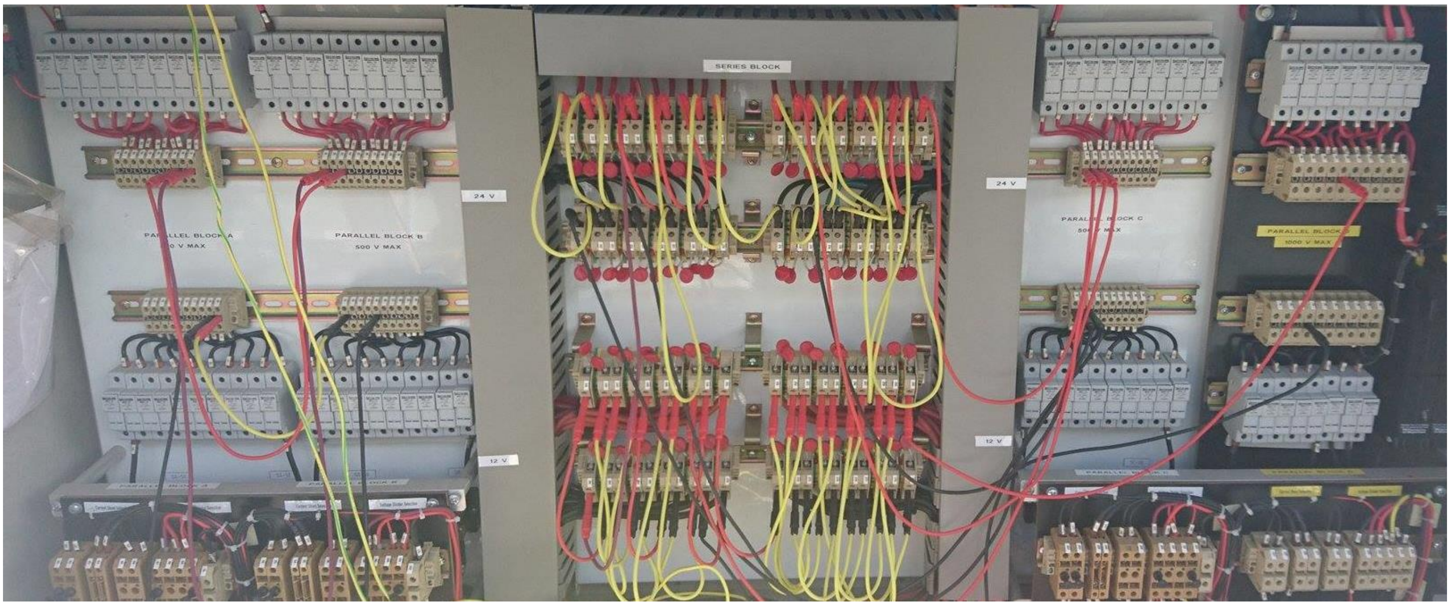

Figure 14: PV Module Circuit Customisation and Associated 'Blocks'

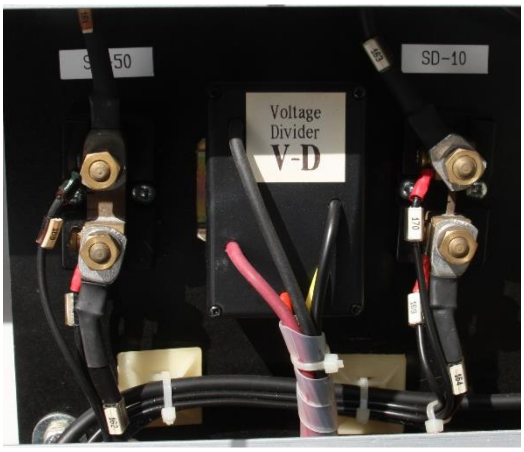

Figure 15: Current Shunts (On Sides) and Voltage Divider (Centre)

3.1 Voltage Dividers

As mentioned previously, the voltage dividers shown in Figure 2 are actually more complex than illustrated. Figure 16 shows the voltage divider circuit for the three strings of sixteen PV modules in parallel; this circuit consists of three resistors, two zener diodes and a junction box. Currently, the voltage divider is set to use the series combination of R1 and R2, of Figure 16, in parallel with R3 and in parallel with the zener diodes. This combination allows for the maximum DC voltage rating of 500V [3]. However, it is possible to change the DC voltage rating by changing the position of a jumper located on the junction box, shown in Figure 17.

Figure 18 shows the voltage divider set up for the string of twelve PV modules in series. Evidently, the circuit is quite different from the one in Figure 16 as it has omitted the zener diodes. Currently, the voltage divider has been set up to use the series combination of R0, R1 and R2, of Figure 18, in parallel with R3. This particular combination has a DC voltage rating of 1000V [3]. Similarly, with Figure 16, it is possible to change the voltage rating; however, instead of changing a jumper, the physical connection to the junction box is changed. The terminals to change the voltage divider connections are shown in Figure 19.

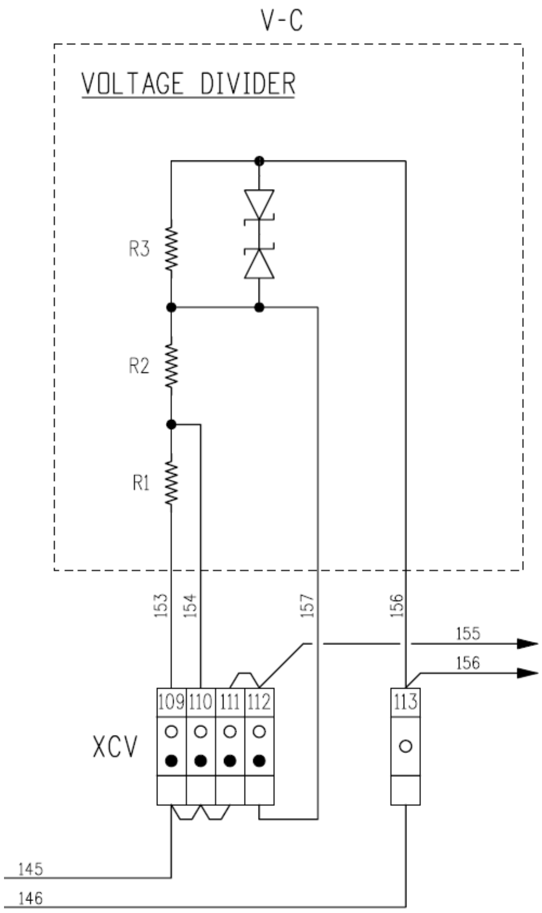

Figure 16: Voltage Divider Circuit for Three Strings of 16 PV modules in series (Block C)

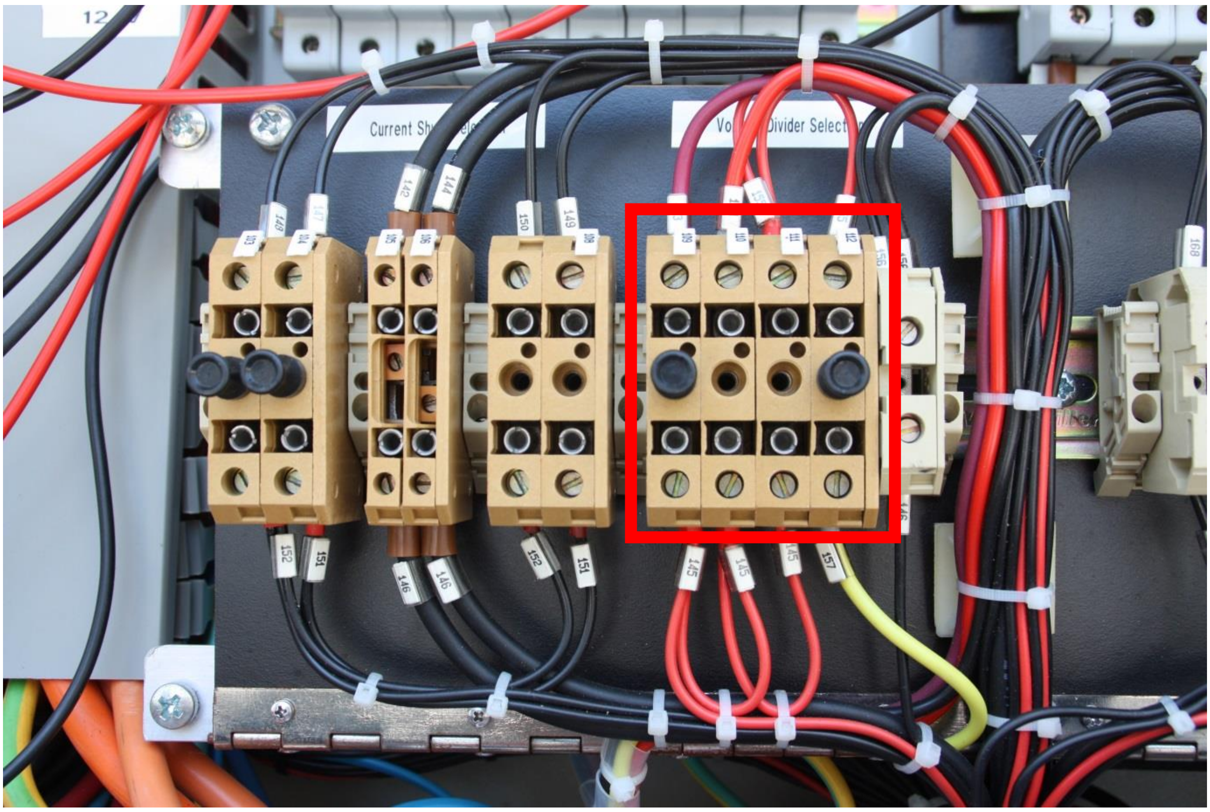

Figure 17: Voltage Divider Jumper Selection for Three Strings of PV modules in series (Block C) (Courtesy of Simon Glenister)

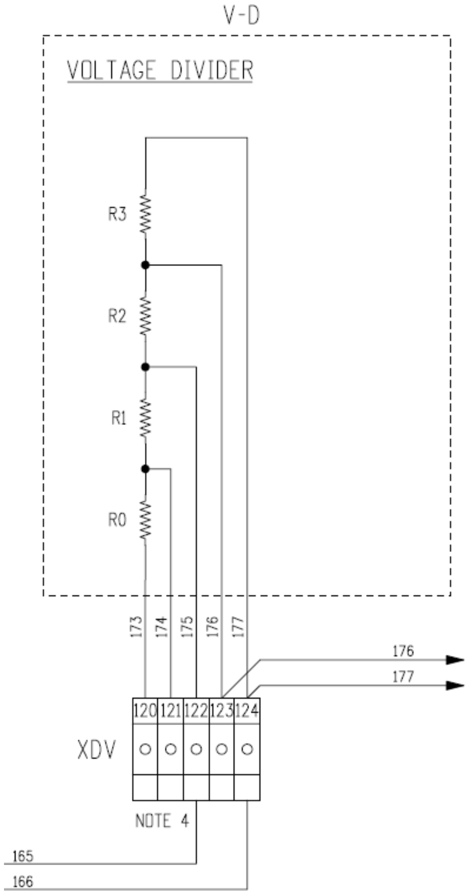

Figure 18: Voltage Divider Circuit for String of 12 PV modules in series (Block D)

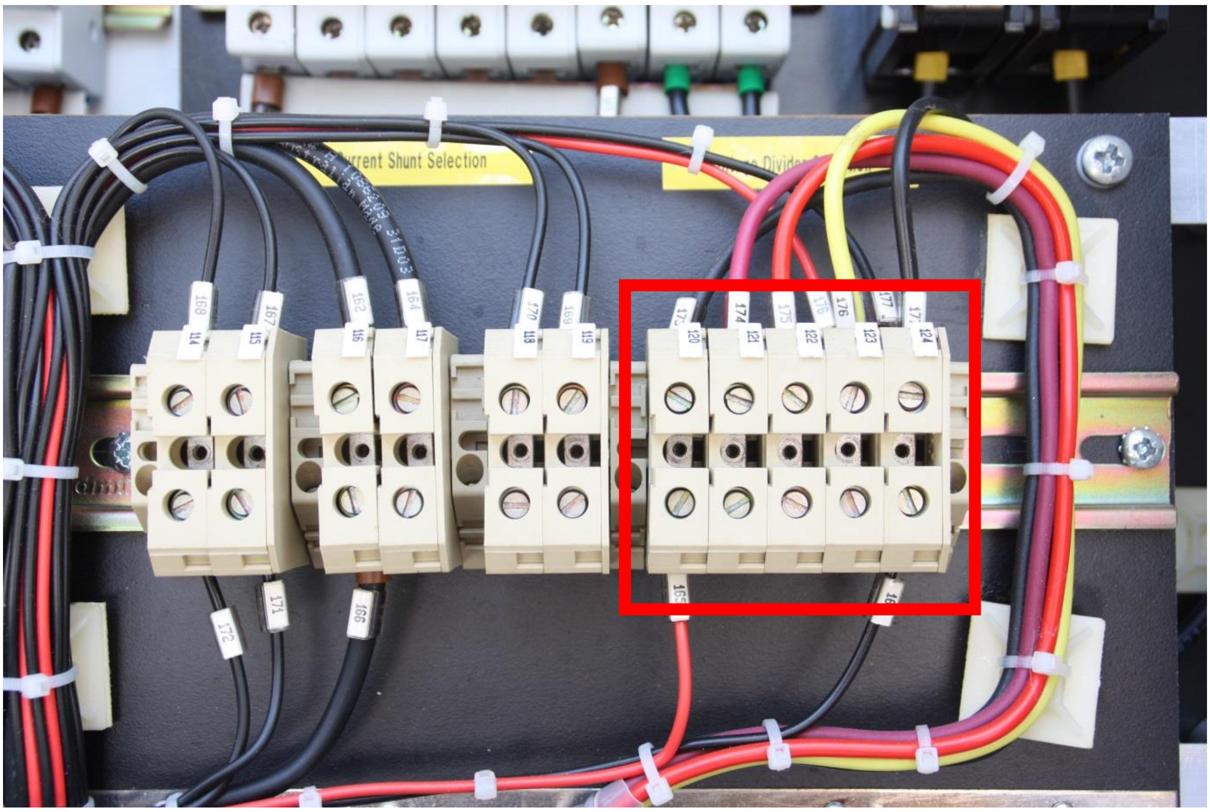

Figure 19: Voltage Divider Selection for String of 12 PV modules in series (Block D) (Courtesy of Simon Glenister)

3.2 Dataforth Modules

Within the Patch Panel there are eight Dataforth Signal Isolators. Four of these modules are Dataforth SCM5B-30s, which are used for low voltage applications (typically around ±50mV to ±100mV) which amplify the current signals received from the PV array. The other four modules are Dataforth SCM5B-31s, which are used for applications that involve voltage ranges of approximately ±40V [13]. The Dataforth modules amplify the input signal to produce a signal of magnitude ±5V [13]. These medium voltage signals are then directed to a FP-AI-110 module in order to be sent to the main PC.

3.2.1 Issues

It was discovered from prior reading and observation that the Dataforth signal isolator for current in Block D was faulty. The specific fault that occurred was that the FieldPoint recorded a voltage output that was greater in magnitude than the specified output magnitude for the signal isolator. The Dataforth signal isolators have an output range of ±5V; the FieldPoint recorded values in excess of -5V, specifically -7.5V. To remedy this issue, the Dataforth signal isolator was replaced. This rectified the issue for a short time before the error occurred again.

The Dataforth module that was originally installed in the Patch Panel was tested to see if it was faulty. Upon testing the Dataforth module, it was found that the module itself performed as was intended. The test setup and module output are shown in Figure 20 and Figure 21, respectively. Considering that the original Dataforth module was operating as expected, the Dataforth module board that the modules were inserted into was tested to check for any faults. Upon testing the board in the same manner as the original Dataforth module, it was discovered that the board had no faults. This result lead to the conclusion that the wiring prior to the Dataforth modules was not implementing the Patch Panel setup correctly. This issue will be addressed in Section 3.3.

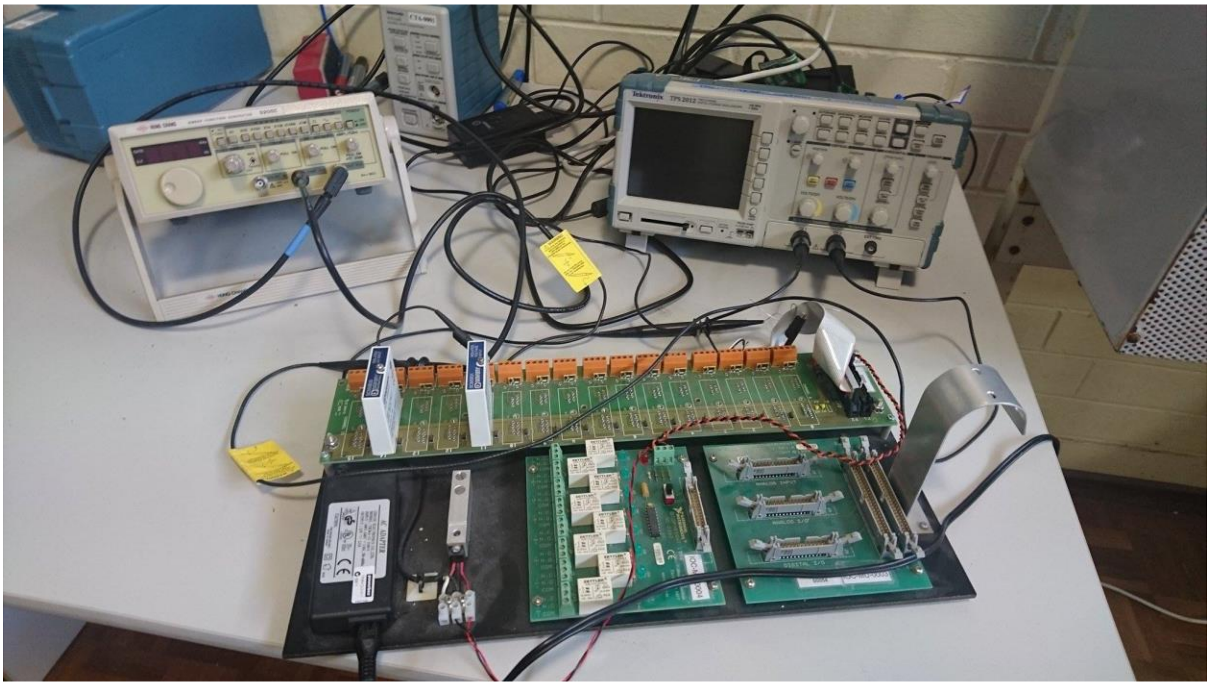

Figure 20: Dataforth Module Test Setup

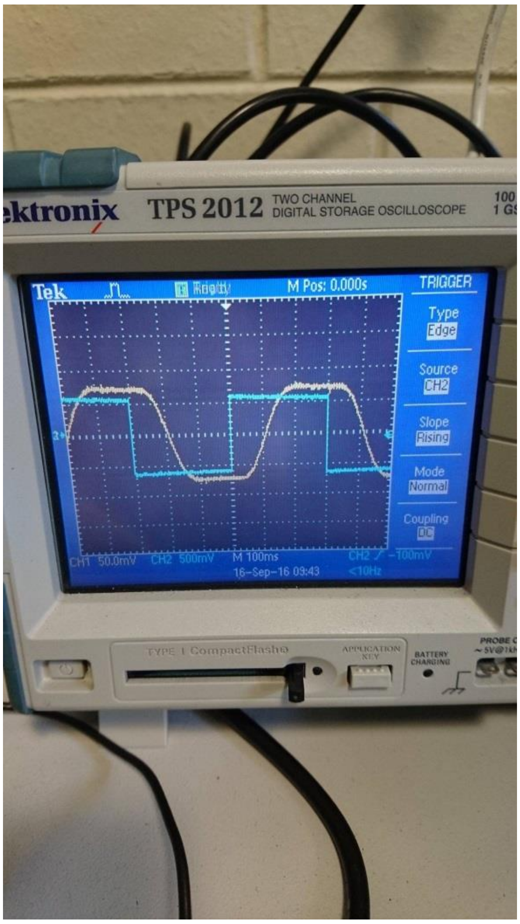

Figure 21: Dataforth Module Output (Blue Line is Signal; Yellow Line is Output)

3.3 Other Issues

3.3.1 50A/50mV Current Shunt D

During the inspection of the Patch Panel, it was discovered that one terminal for the 50A/50mV current shunt for Block D had been blackened. The insulating material covering the thin wire also appeared to have melted. The cause for this charring and melting was unknown but suspected to be caused by arcing due to connection tightness or by excessive heating caused by the current traveling through several unnecessary washers and nuts. To remove any potential hazard that this may cause, the 50A/50mV current shunt was disconnected from the circuit and the current path was redirected through a 10A/50mV shunt on the same block. Figure 22 shows the blackened 50A/50mV current shunt.

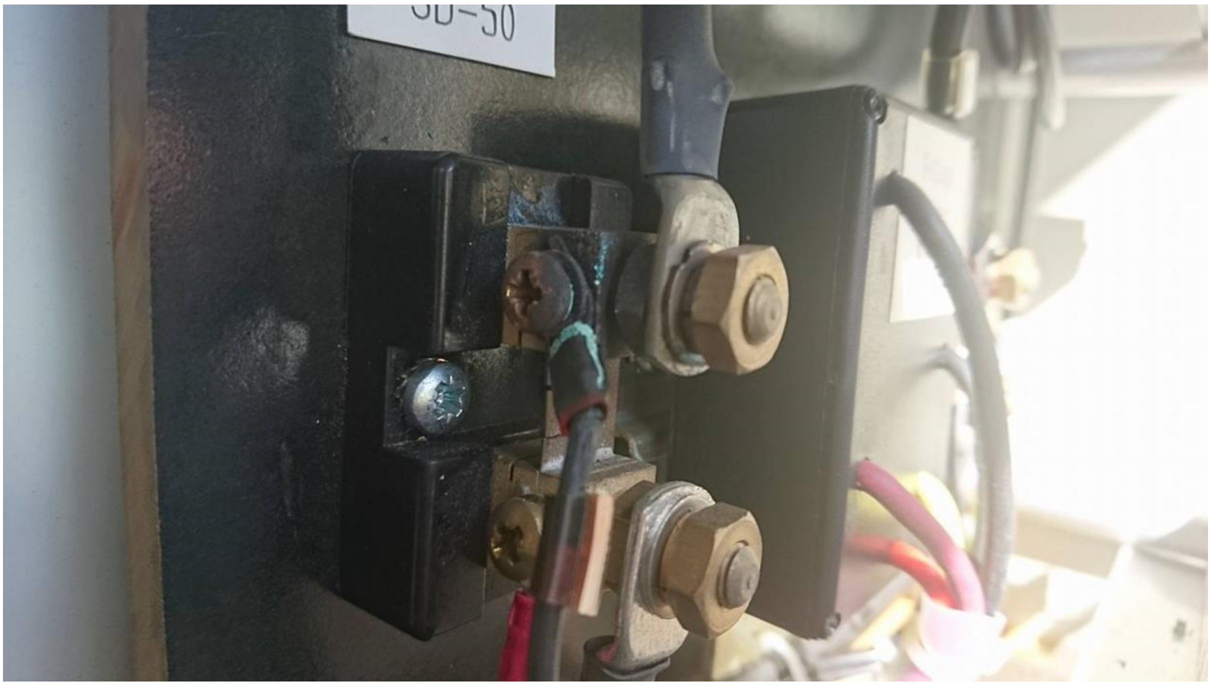

Figure 22: Blackened 50A/50mV current shunt on Block D

It was decided that the 50A/50mV shunt should be replaced for safety and performance reasons. The original shunt was removed and the types of fixtures used to secure the lugs on the shunt were noted. The order of the fixtures was as follows:

1. Shunt plate
2. Brass nut
3. Steel washer
4. Lug

5. Brass spring washer
6. Brass nut.

The order of the fixings was thought to be poor at best due to the fact that the current needed to pass through a brass nut and steel washer to reach the shunt plate which continues the circuit. The new 50A/50mV shunt was installed and the fixings were altered in the following way:

1. Shunt plate
2. Lug
3. Steel washer
4. Brass spring washer
5. Brass nut.

This configuration was thought to offer a less resistive pathway than the original setup, hence, would reduce the chance of charring. Figure 23 shows the newly installed shunt.

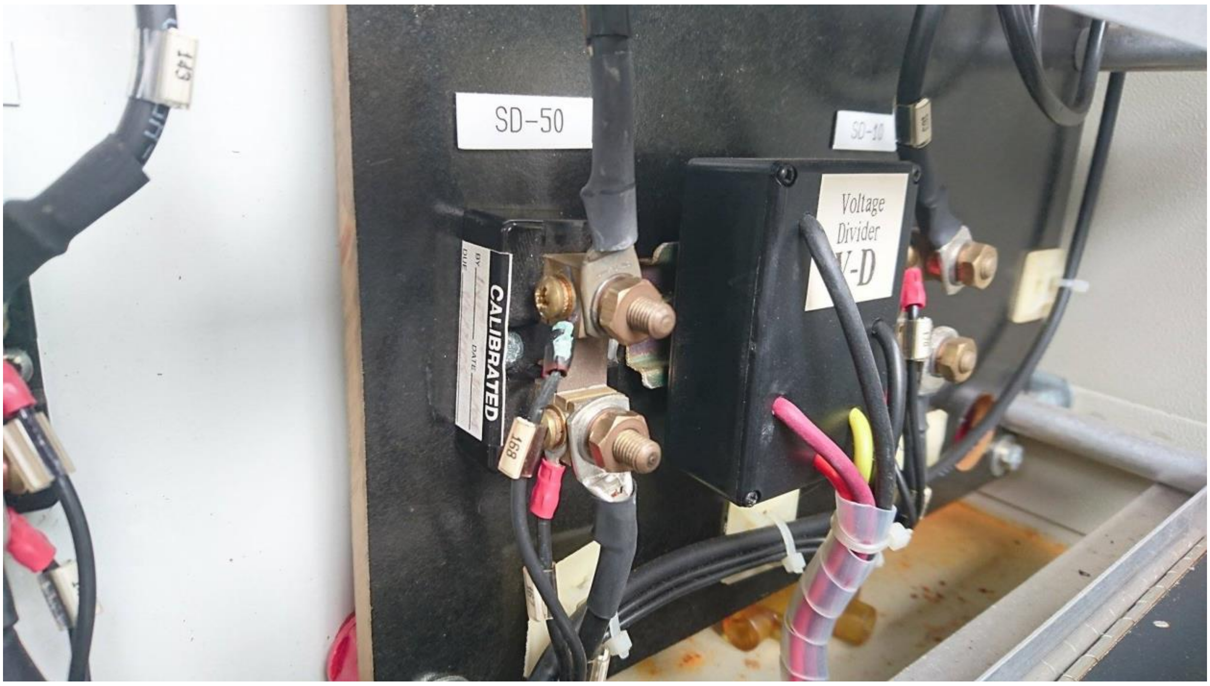

Figure 23: Newly Installed Current Shunt

The circuit was rewired so that the current was passing through the 50A/50mV shunt. The output of the Dataforth module was no longer clipping at the -7.5V mark and began producing an accurate reading of the current produced from the PV array.

4.0 Programmable Logic Controller

The key device used for retrieving the voltage and current outputs from the transformerless inverter was the programmable logic controller (PLC). A PLC is a digital controller that is commonly used in industry [14]. The PLC located in the main AC switchboard (MACSB) in Building 190 was an Allen-Bradley SLC500 and consists of the following elements: a backplane, for power and data transfer; a central processing unit (CPU), which controls all logic operations and mathematical computations; a power supply, which supplies power to the CPU and other connected modules; a programming device, to allow for developed programs to be downloaded to the PLC; and an input and output (I/O) interface, which allows for communication between the PLC and various sensors, switches, relays and valves [14].

4.1 Issues

Initially, the PLC was found to be in a faulted state. On the front of the CPU, the indicators showed a solid red fault light and a solid red battery light, shown in Figure 24. New batteries were requested for the PLC. A new CPU was located while waiting for the batteries to arrive. Replacing the CPU removed the solid red battery light but the solid red fault light remained. The batteries of the old CPU and new CPU were then replaced. The old CPU was reinserted into the PLC which resulted in a flashing red fault light and a solid green DH+ light, illustrated in Figure 25, indicating that a fault was still present but there was some form of communication between the PLC and the PC. Attempting to download the program to the PLC resulted in a timeout error. Another piece of equipment, an Allen-Bradley PanelView, was also connected to the PLC. This connection was thought to be masking the host PC. The connection between the PLC and the PanelView was terminated, indicated in Figure 26. A second attempt the download the program to PLC was performed. The program was unable to be downloaded successfully. It was then found that the baud rate of the PC was set a 57kbaud and the baud rate of the PLC was set at 230kbaud. The baud rate of the PC was changed to match that of the PLC via the program RSLinx. Now that the baud rates of the PC and PLC were equal, another attempt to download the PLC program was performed. The PLC program downloaded successfully which removed all faults from the PLC. The Allen-Bradley PanelView was reconnected to the data communication network with no other faults occurring within the PLC.

Figure 24: Initial PLC Fault Conditions

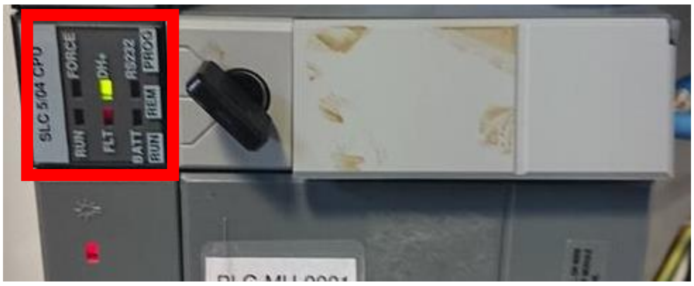

Figure 25: Flashing Fault Light, Green DH+ Light

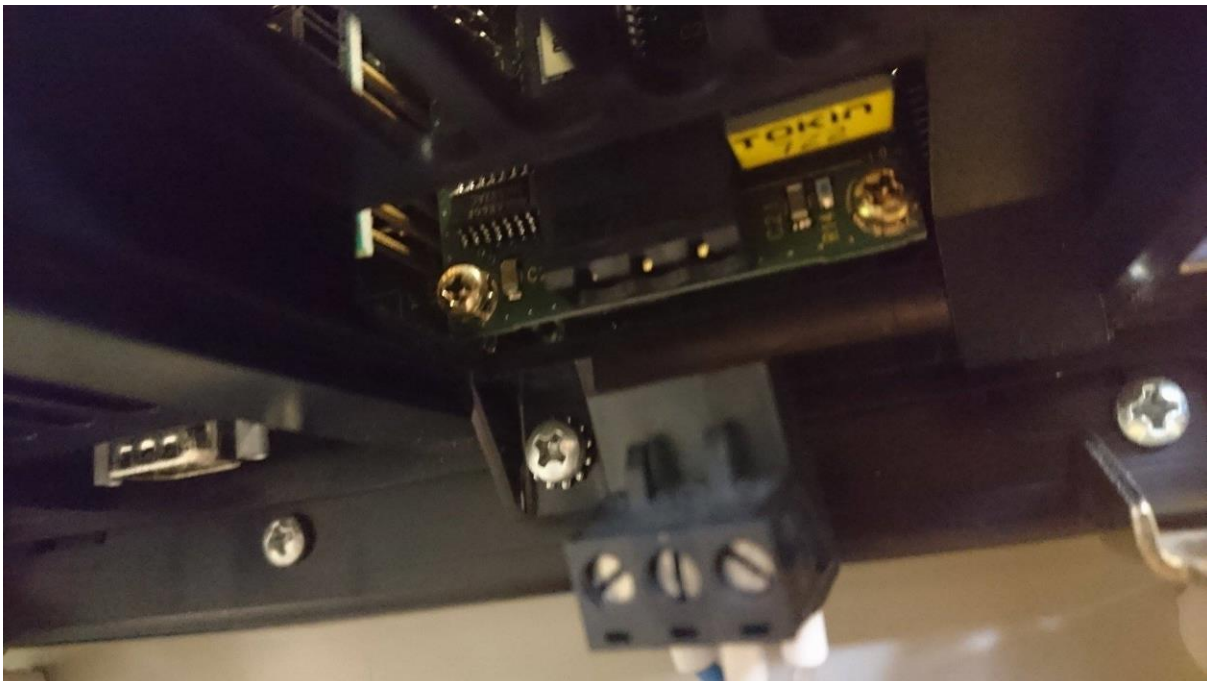

Figure 26: PanelView Disconnection Point

5.0 Data Acquisition

The National Instruments LabVIEW was the program used for the data acquisition system. Using the LabVIEW program, the power data received from the FieldPoint modules and the PLC was able to be recorded. Using the front panel of the data acquisition program, shown in Figure 27, the user can select the file to which that data will be recorded. The user is able to view, in real time, the values of the power being produced by the PV array and the apparent power being delivered to the utility grid. Also available on the front panel of the program is the current status of the weather in the courtyard on the south side of Building 190. The temperatures of select PV modules can also be viewed. Visual indicators are included for the PV module temperatures, the ambient temperature, the relative humidity, and the wind speed. A plot is also available for displaying the current horizontal solar irradiance, the total power produced by the PV array, the power produced by each PV 'circuit', and the apparent power delivered to the utility grid.

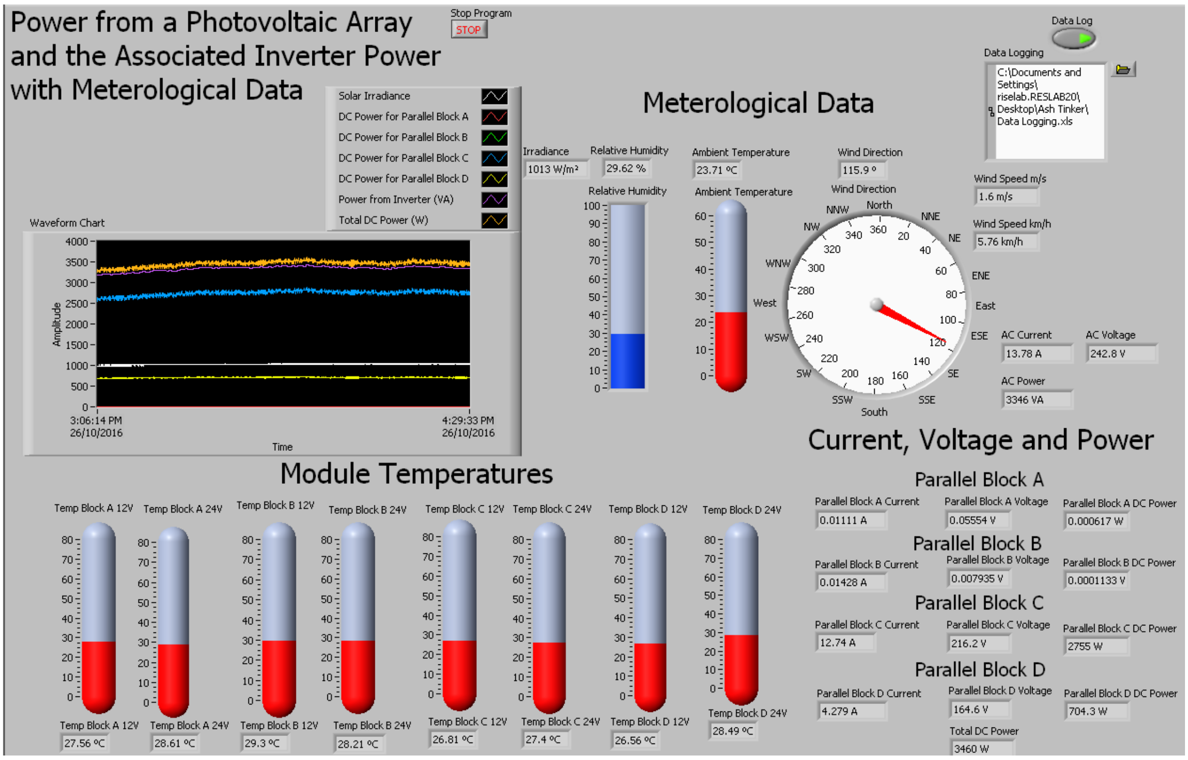

Figure 27: Front Panel for Data Acquisition Program

5.1 FieldPoint Modules

The FieldPoint modules are responsible for the data acquisition of the power produced by the PV array and the current environmental status retrieved from the environmental sensors. Figure 28 shows the FieldPoint modules in the Patch Panel.

Figure 28: FieldPoint Modules

Beginning on the left of Figure 28, the first FieldPoint module was a network module (FP-1001) responsible for relaying the data produced by the PV array and environmental sensors. The FP-1001 communicates to the host PC via RS-485 serial communication [15]. The next module in the chain is the thermocouple module (FP-TC-120). This module retrieves the voltages from the numerous thermocouples on the PV modules. The module internally converts the voltages to a temperature reading so no further data manipulation was required. The two centre modules were analogue input modules (FP-AI-110). These modules retrieve the voltage signals from the various environmental sensors (excluding the anemometer) and the Dataforth modules, transmits the magnitude of the voltage as a digital value to the FP-1001. Referring to Figure 28, the left FP-AI-110 was responsible for handling the environmental sensor voltage signals, while the right FP-AI-110 was responsible for handling the PV array voltage and current signals. The last FieldPoint module on the right in the chain is a counter module (FP-CTR-502), previously mentioned in Section 2.1.1. This module is responsible for counting the pulses produced by the anemometer. The count number is sent to the FP-1001 and relayed to the host PC for data manipulation.

5.1.1 National Instruments Measurement & Automation Explorer

The data sent by the FieldPoint modules to the host PC can be accessed through National Instruments Measurement & Automation Explorer (NI MAX). The user is able to view the raw data values sent by the FieldPoint modules. The user is also able to rename the ‘channels’ where data was received to allow for ease of access and to prevent confusion when performing data manipulation operations. NI MAX did not have any data recording capabilities.

5.2 Powermonitor

The Allen-Bradley Bulletin 1403 Powermonitor II was responsible for acquiring the data from the grid side of the inverter. As previously stated, the Powermonitor communicates with the host PC via an Allen-Bradley PLC. The communication schematic for the Powermonitor network is shown in Figure 29.

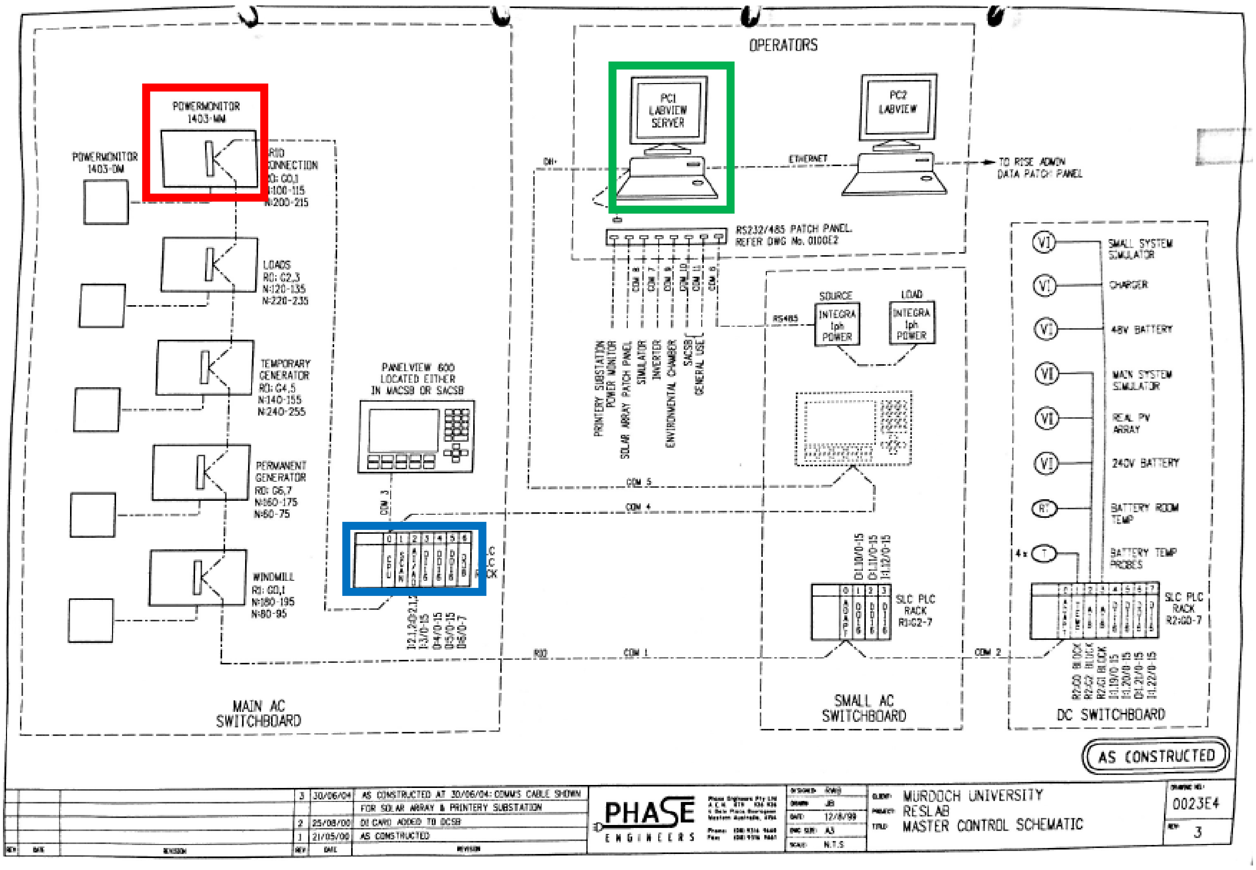

Figure 29: Powermonitor Data Communication Network

The boxes shown in Figure 29 are the key components of the Powermonitor communication network. The red box indicates the location of the Powermonitor in relation to the network, not the physical location of the Powermonitor. The Powermonitor responsible for the retrieval of the power being delivered to the utility grid was connected to four other Powermonitors, each with their own individual purpose, within the main AC switchboard (MACSB). The Powermonitor responsible for the retrieval of the power being delivered to the utility grid data was also directly connected to the PLC, shown as the blue box on the bottom portion of Figure 29. The PLC relays the data retrieved from the Powermonitor directly to the host PC, the green box, where data manipulation could be carried out.

5.3 Issues

5.3.1 Writing to LabVIEW

There was an issue regarding LabVIEW being able to read the data sent via the FieldPoint modules. Upon PC start up, NI MAX was opened to check that the FieldPoint modules were still sending and receiving expected voltage values depending on the current weather conditions. Attempting to run the LabVIEW program would result in an error as shown in Figure 30,. It was discovered that the data received from the FieldPoint modules could only send to either NI MAX or LabVIEW, not to both at the same time. During testing times, it was important to not have NI MAX running in the background so that the LabVIEW program could run successfully.

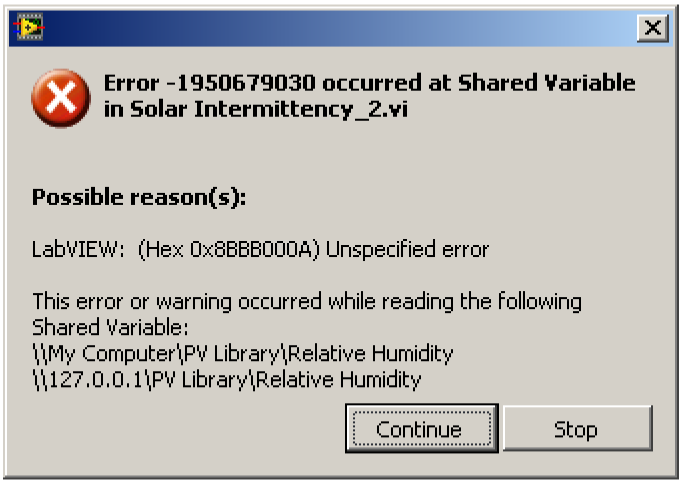

Figure 30: COM Binding Error

5.3.2 Reading from FP-CTR-502

As the FP-CTR-502 module was not pre-existing in the Patch Panel setup, NI MAX was unable to obtain the data from the module. In order to overcome this issue, this FieldPoint module needed to be added to the NI MAX FieldPoint library. The procedure for adding a new FieldPoint module to the FieldPoint library can be found in appendix A.5.

NI MAX performs a check to determine if any FieldPoint modules have been added or removed or if the order of the modules had been changed. After performing the check, the FieldPoint module FP-CTR-502 appeared and was given the tag 'FP-CTR-502@4', as it was the fourth module in the FieldPoint module chain.

In order for LabVIEW to read the data collected from FP-CTR-502, a bound variable was required to be created in the LabVIEW project explorer. The steps to create a bound variable can be found in appendix A.5. Attempting to insert the variable into LabVIEW resulted in the variable being unreadable. The variable data type was required to be changed from type 'UInt16' to type 'Double' to allow LabVIEW to properly use the variable in the DAQ program. The procedure for changing the variable data type can be found in appendix A.5.

5.3.3 Allen-Bradley Powermonitor

Upon restoring data communications between the PC and PLC, the Allen-Bradley Powermonitor responsible for measuring and storing the values of power delivered to the utility grid encountered a fault. During operation, the Powermonitor would perform an internal fault check. Most of the time that the Powermonitor would perform the check, the Powermonitor would detect a 'fault'. The 'fault' would force the Powermonitor to effectively 'factory reset', as no data could be measured and the ability to program the device was lost. The precise cause of the fault was unknown. A temporary fix was found in the thesis of Woodard [2]. One of the other four Powermonitors in the data communication network was removed and the entire system reset. The removal of one of the Powermonitors prevented the Powermonitor responsible for measuring and storing the values of power delivered to the utility grid from performing the internal check and subsequently faulting. Figure 31 and Figure 32 shows the Powermonitor in question.

Figure 31: Powermonitor Responsible for Measuring Power Delivered to Grid in MACSB

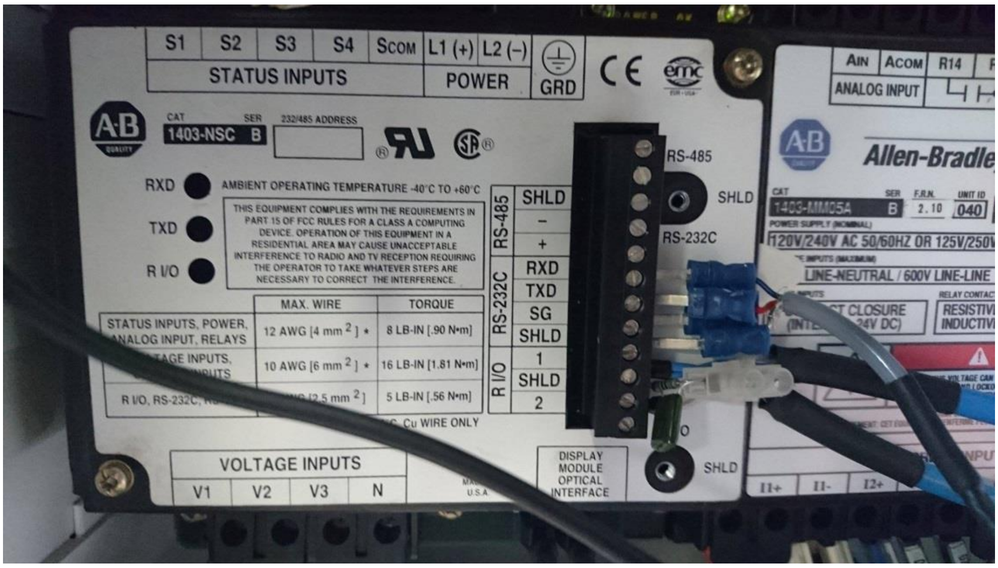

Figure 32: Allen-Bradley Bulletin 1403 Powermonitor II

5.3.4 PLC Program Update Rate

During the DAQ testing, it was discovered that the refresh rate of the PLC program was extremely sluggish. The exact cause for the delayed update rate was unknown. The delayed update of the AC current and AC voltage values resulted in stepped responses, which masked the true variability of the power being delivered to the utility grid.

5.3.5 PLC Power Values

Unfortunately, the real power being delivered to the utility grid could not be determined and thus, could not be recorded via the DAQ program. The current PLC program was unable to extract the real power values, nor the power factor values from the Powermonitor. Knowledge on how to alter the PLC program to allow access to these values was unknown during the project period.

6.0 Results

Figure 33 shows an example plot of the data acquired using the DAQ program developed during the project.

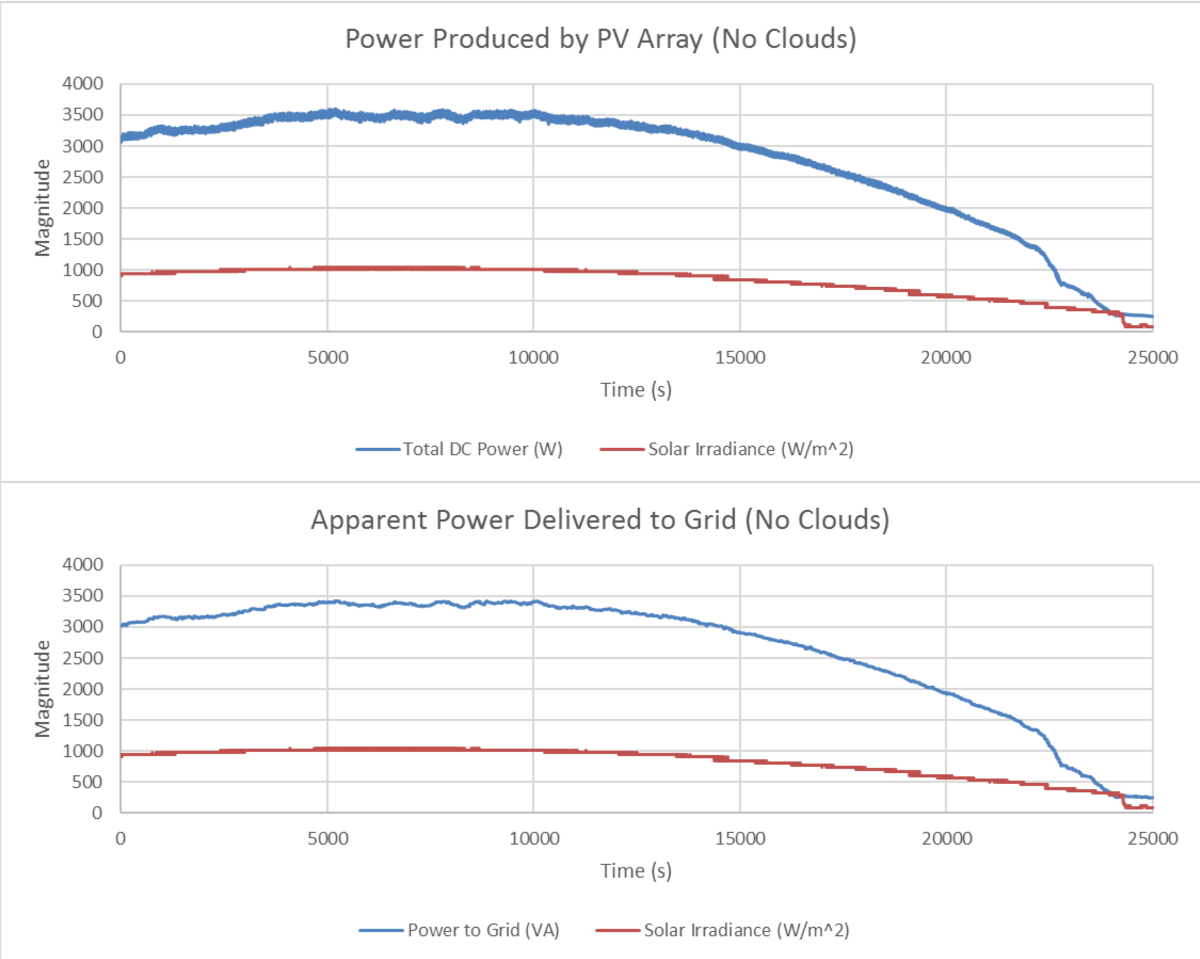

Figure 33: Power Produced by PV Array and Apparent Power Delivered to Utility Grid

Focusing on the upper plot, the blue line is representative of the power produced by the PV array, and the red line is representative of the horizontal solar irradiance. On the particular day that the data was recorded, the maximum power produced by the PV array was approximate 3.5kW and the maximum horizontal solar irradiance that was achieved was approximately 1kW/m^2. The recording of data began at approximately 10am on that particular day. In the lower plot, the blue line is representative of the apparent power delivered to the utility grid, and the red line is also horizontal solar irradiance. Again, the apparent power delivered to the utility grid was just under 3.5kVA. At approximately 22,500 seconds, there was a significant drop in power produced by the PV array. There was a similar drop in apparent power delivered to the utility grid. The suggested cause for these drops was that the PV array experienced shading in the late afternoon on that particular day.

Furthermore, there was a significant drop in horizontal solar irradiance at approximately 24,500 seconds. The suggested cause was the pyranometer experiencing shading at that point of time. Comparing the blue lines of each plot, confirmation that the DAQ program works is evident given the similar shapes of the blue lines. To see the affect that the solar irradiance has on the power produced by the PV array and, subsequently, the apparent power delivered to the utility grid, the DAQ program was operating during intermittent clouding of the array. The results are shown in Figure 34.

Figure 34: Power Produced by PV Array and Apparent Power Delivered to Utility Grid During Intermittent Cloud Cover

It is apparent that a small change in solar irradiance results in a large change in power output from the PV array. The same can be said for the apparent power being delivered to the utility grid, a small change in solar irradiance results in a large change of apparent power being delivered. Also note that there were different thicknesses of cloud covering the system, resulting in the amount of power produced to vary greatly from cloud to cloud. Finally, it is important to note the block effect on the blue line of the lower plot of Figure 34. This is due to the low sample rate of the PLC program.

7.0 Conclusion

The current DAQ program is fully operational and is able to record the power produced by the PV array and the apparent power delivered to the utility grid. Referring to Figure 27, the user is able to choose the path of the data with a simple click of a button. Also, the user is able to record every value that was displayed in each box on the DAQ program.

Originally, most of the environmental sensors that had been installed on the roof of Building 190 had malfunctioned. The potentiometer within the original wind vane was no longer rotating smoothly with the changing wind direction, thus the wind vane was replaced. The new wind vane, an NRG200P, was installed. Prior to installation, the new wind vane was tested to determine functionality of the device. Upon testing, it was found that the wind vane performed to expectations and qualified as a replacement for the original wind vane.

The original anemometer that was installed on the roof of Building 190 had also malfunctioned. The expected output signal of the anemometer was a square wave; however, when the original anemometer was tested, it was revealed that the pulsing mechanism was not operating correctly as the output of the original anemometer was a fixed voltage. A new anemometer (of similar make) was acquired. This new anemometer was tested to determine if the output was, in fact, a square wave. Upon discovering that the new anemometer produced a square wave pulse output, the new anemometer was promptly installed with the other environmental sensors on the roof of Building 190.

A new problem arose regarding the new anemometer. As the output for the new anemometer was a square wave, a FieldPoint counter needed to be installed to allow for DAQ. After locating a FP-CTR-502, the output from the new anemometer was able to be measured via counting the number of pulses produced by the anemometer.

Lastly, a new pyranometer was installed to allow for the measurement of the solar irradiance. As the pyranometer was acquired toward the end of the project timeline, it was decided that, to avoid complication, the pyranometer be installed in the horizontal plane. However, the horizontal solar irradiance is not a true representation of the solar energy reaching the PV array.

The Dataforth module that was tasked with the conditioning of the current from the twelve string PV circuit was thought to be faulty. After testing the module, it was found to be operating correctly. It was theorised that the circuitry prior to the signal conditioner was incorrect. Upon inspecting this circuitry, the current shunt responsible for producing the current signal to the Dataforth module was found to be extremely damaged. The current shunt was subsequently replaced allowing correct operation of the PV circuit and signal conditioning.

The PLC responsible for relaying the power data being delivered to the grid data was initially in a faulted state. In an attempt to rectify the issue, the batteries of the PLC were replaced. The battery replacement only removed part of the fault. The Allen-Bradley PanelView was removed from the communications network as it was hypothesised that the PanelView was masking the PC on the communications network. Upon removing the PanelView from the network, a basic form of communication was established, although the PLC program was unable to be downloaded at that point in time. The baud rate of the PC was found to be 57kbaud, whereas, the baud rate for the PLC was at 230kbaud. The baud rate of the PC was changed to 230kbaud and the second attempt to download the PLC program was successful.

Currently, the DAQ system is not perfect. In order to fully complete this system, the real power being delivered to the utility grid will need to be calculated and recorded. The system is able to record the local environmental conditions as well as the power produced by the PV array. Hopefully, the DAQ system developed during this project will aid future research projects or assist in educating the renewable energy engineers of tomorrow.

8.0 Future Recommendations

As there were so many aspects to the project, it was impossible to get the entire system perfect within the given time frame. These are some of the recommendations that should be considered for future operation of and extensions to the system.

8.1 Unresolved Issues

Some of the issues encountered during the project had no permanent fix and were recurring during system operation and should be kept in mind. Other issues described are problems that were unable to be fixed within the time frame of the project.

8.1.1 Hardware Issues

8.1.1.1 Sensitive Safety Measures

It was discovered that after a rainstorm the circuit breaker protecting the switch S2 in the Grid Connection box in the interior of the building would trip. Figure 35 shows the circuit breaker that trips after a rainstorm. Furthermore, two switches that are located under the Patch Panel on the roof of the building also tripped after the rainstorm. These switches govern whether or not the PV array is connected to the inverter in the interior of the building. Figure 36 shows the rooftop switches which are prone to tripping after a rain storm. Also note that after a power outage, these breakers will also trip.

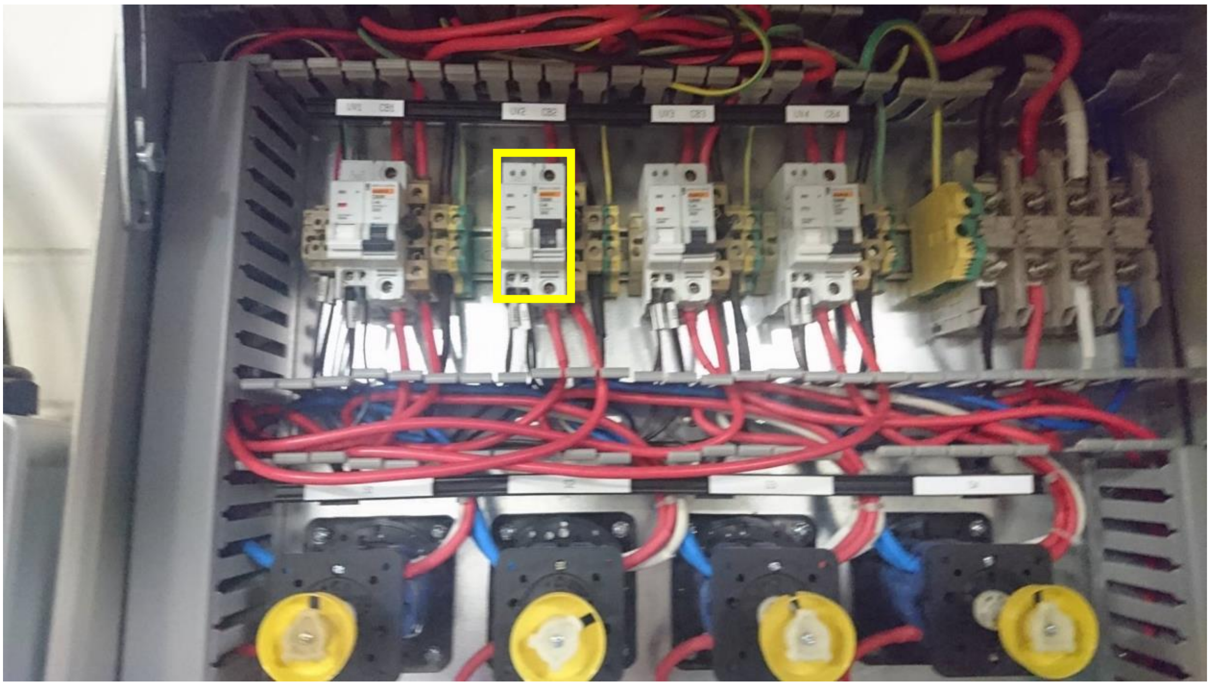

Figure 35: S2 Circuit Breaker

Figure 36: Rooftop Switches Prone to Tripping

8.1.1.2 Powermonitor Faults

As stated previously, when data communications between the PC and PLC were re-established, the Powermonitor responsible for measuring and storing the values of power delivered to the utility grid began to fault. The precise cause for the fault was unknown. As per Woodard's thesis [2], as a temporary fix, one of the unused Powermonitors was disconnected from the communications network. The removal of one Powermonitor prevented the Powermonitor that is responsible for measuring and storing the values of power delivered to the utility grid from faulting. Currently, all Powermonitors except the Powermonitor that measures and stores the power delivered to the utility grid values have been disconnected from the communications network in an attempt to increase the PLC program update rate (which will be discussed later in this section). The Powermonitors that are disconnected are shown in Figure 37. It is highly recommended that the fault regarding the Powermonitor internal check be rectified to resume full functionality of the facilities at Building 190.

Figure 37: Powermonitors That Have Been Disconnected

8.1.1.3 Disconnected Earthing Wire on PV Array Ducting

Late into the project, it was discovered that an earthing wire on the PV array ducting had become detached and was hanging freely. It is highly recommended that this earth wire is reattached to comply with AS5033 [16]. Figure 38 shows the disconnected earth wire.

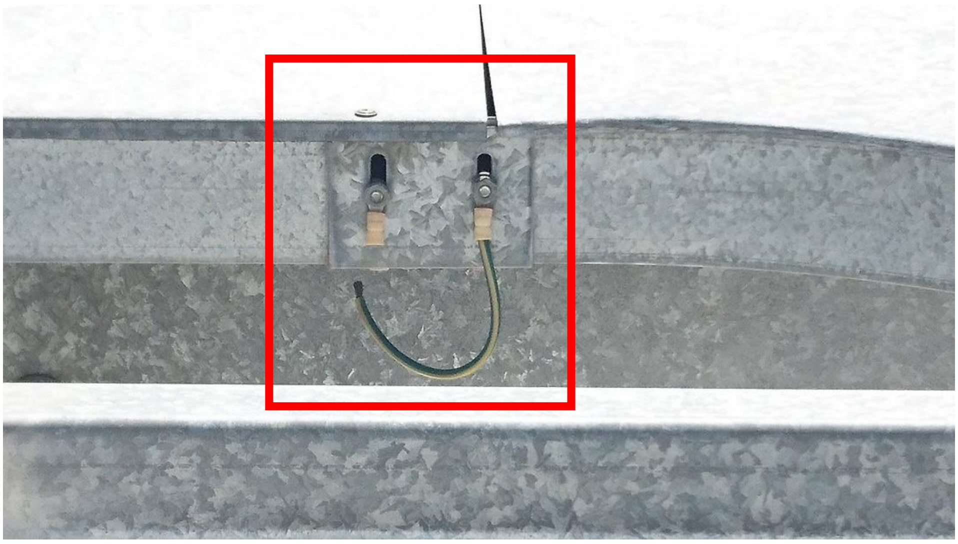

Figure 38: Detached Earthing Wire on PV Array Ducting

8.1.2 Software Issues

8.1.2.1 PLC Program Update Rate

The LabVIEW DAQ loop was set at 1 second. Unfortunately, for reasons unknown, the PLC program was updated at a rate of 36 seconds. Obviously, the large update rate was inconvenient when attempting to record the power delivered to the utility grid, as the true signal was aliased. Figure 38 compares the variability of update rate of the DAQ loop to the slow responsiveness of the PLC program. Figure 39 is a 60 second snapshot of Figure 34.

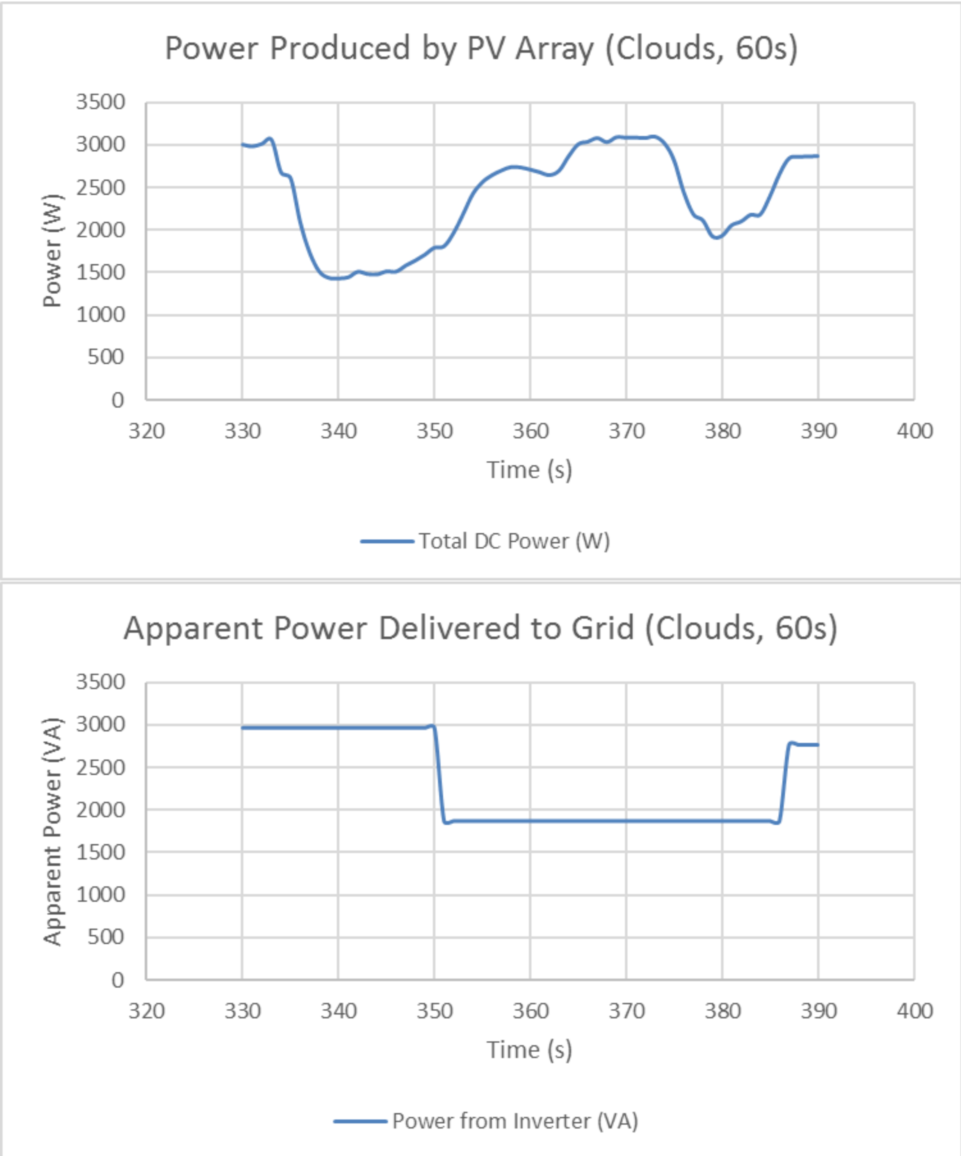

Figure 39: Comparison of DAQ Update Rate to PLC Program Update Rate

As is quite plain to see, the true representation of the power being delivered to the utility grid has been masked by the excessive update time of the PLC program. If it is possible, it is highly recommended that the PLC update rate be reduced to be approximately the same as the DAQ loop rate.

8.1.2.2 Calculating Real Power Delivered to Utility Grid

The Allen-Bradley Powermonitor has many measuring capabilities [2]. These measuring capabilities include the determination of power factor and power (apparent, real, and reactive) [2]. Unfortunately, the PLC program is currently unable to extract the power factor and real power. It would be advantageous to retrieve the power factor and/or the real power values, and to replace the apparent power currently being recorded with real power.

8.1.2.3 Data Storing Limitations

The application used for reading the LabVIEW data is Microsoft Excel. The version of Microsoft Excel (1997-2003) that is installed on the host computer of the DAQ program only allows for approximately 18 hours of data (65,536 rows of data). A potential solution to increase data storage would be to allow LabVIEW to write to multiple Microsoft Excel worksheets, if possible. If this solution is not possible, it is recommended to upgrade to the latest version of Microsoft Excel, as the latest version of Microsoft Excel allows for approximately 12 days of data (1,048,576 rows of data), so extended data recording time (compared to the original data recording time of 18 hours) would be possible.

8.1.2.4 FieldPoint Compatibility

It has been discussed amongst the technical staff at Murdoch University that the latest version of LabVIEW no longer supports FieldPoint. This causes an obvious problem when attempting to upgrade the PC operating system from Microsoft Windows XP Professional. It is important to keep in mind that, if upgrading the host PC, the latest version that is compatible with the FieldPoint software is LabVIEW 2015. If it is not possible to run LabVIEW 2015 on the upgraded host PC, a new DAQ system will need to be used and the FieldPoint modules will need to be replaced.

8.2 Maintenance

It is important that the system be continually maintained for high performance of the system. In particular, the Patch Panel requires a lot of attention regarding cleanliness and inspection of electrical connections to prevent future component damage. A recommended maintenance schedule can be found in appendix A.1.

8.3 Solar Irradiance Measurements

As recommended in Sharpe's thesis [3], two pyranometers should be used to perform solar irradiance measurements, one on the horizontal (which has already been installed) and one at an angle equal to the angle of the PV array [3]. Installing a new pyranometer will also require the DAQ program to be updated to include the new information, as well as performing a Patch Panel upgrade to allow for the new pyranometer signal wires.

8.4 Wire Scheduling

Currently in the Patch Panel, the wires are distinguished by a numbering system. However, it was discovered that some of these wire tags have been doubled up, thus creating some minor confusion when rewiring the signal circuits. Table 1 indicates the doubled up wire labelling. It is recommended that the environmental sensor signal wires be relabelled to prevent future confusion.

Table 1: Repeated Wiring Schedule

Wire Number	PV Array Signal	Environmental Sensor Signal
211	Current signal*	Ambient temperature signal
212	Shunt ground*	Ambient temperature ground
213	Voltage signal	Wind vane signal
215	Current signal**	Wind vane ground
216	Shunt ground**	Anemometer signal
217	Voltage signal	Anemometer ground

*connected to the same shunt
**connected to the same shunt

8.5 FieldPoint Module Order

Currently, the FieldPoint modules have been ordered as per Figure 28. It was suggested that the thermocouple module should not be next to the network module as the network module emits more heat than the other modules [15]. This extra amount of heat may produce small errors when reading the PV module temperatures via the thermocouples. It is recommended that the order of the FieldPoint modules be changed to minimise the potential error cause by the FieldPoint network module.

9.0 References

[1] Murdoch University. (2016, 11/11). *Murdoch University Energy Research and Innovation Group*. Available: http://www.murdoch.edu.au/School-of-Engineering-and-Information-Technology/Research/Murdoch-University-Energy-Research-and-Innovation-Group/

[2] C. Woodard, "Rise SCADA and Electrical System A report pertaining to the condition and serviceability of the electrical and SCADA systems of the former RISE facility," Bachelor of Engineering, School of Engineering and Information Technology, Murdoch University, Murdoch University, 2013.

[3] M. Sharpe, "An Investigation into Installing a Solar Intermittency Monitoring System at Murdoch University: A Proposed Design for the Installation of a System at Building 190," Bachelor of Engineering, School of Engineering and Information Technology, Murdoch University, Murdoch University, 2013.

[4] M. K. Nathan Froese, Daniel Murphy, "ENG454 RISE Facility Phase 4- Real PV Array," 2013.

[5] J. G. M. a. A. L. R. J.F. Manwell, *Wind Energy Explained: Theory, Design and Application*. Chippenham, Wiltshire, Great Britain: Antony Rowe Ltd., 2002.

[6] Vector Instruments, "Low Power Anemometer Type: A100LK, A100LM Operating Instructions," ed. 115 Marah Road, Rhyl, N. Wales, LL18 2AB, United Kingdom: Vector Instruments, 2001.

[7] National Instruments, "FieldPoint Operating Instructions FP-CTR-500 and cFP-CTR-500," ed: National Instruments Corp., 2002.

[8] National Instruments, "FieldPoint Operating Instrucations FP-CTR-502 and cFP-CTR-502," ed: National Instruments Corp., 2002.

[9] C. Cytera, "Current Mirror Circuit," USA Patent, 1992.

[10] Renewable NRG Systems, "RNRG 200P Wind Vane Specifications," ed, 2016.

[11] Kipp & Zonen, "CM11 Pyranometer," ed. Netherlands: Kipp & Zonen B.V.

[12] Kipp & Zonen, "Instruction Manual Pyranometer/Albedometer," ed. Holland: Kip & Zonen B.V.,, 2000.

[13] Dataforth Corporation, "SCM5B30/31 Analog Voltage Input Modules, Narrow Bandwidth," ed, 2011.

[14] G. J. S. James A. Rehg, *Programmable Logic Controllers*, 2nd ed. Upper Saddle River, New Jersey 07458: Pearson Prentice Hall, 2009.

[15] National Instruments, "FP-1000/1001 User Manual," ed. 11500 North Mopac Expressway Austin, Texas: National Instruments,, 1999.

[16] Standards Australia, "Installation and safety requirements for photovoltaic (PV) arrays," in *Appendix C*, ed: SAI Global Limited,, 2014.

[17] BP Solar, "BP 275F," B. Solar, Ed., ed, 2001.

Appendix

A.1 Maintenance Recommendations

As the hardware of PV array degrades over many years of operation, it is important to conduct regular maintenance and testing of sensors and current carriers. Table A1 gives a guide on maintenance intervals for different elements of the system. This table is largely based upon the maintenance table C1 in Standard AS5033 [16]. It is important to note that in order to perform maintenance on the PV modules and Patch Panel that the system must first be isolated via the switches located under the Patch Panel.

Table A1: Maintenance Guide

Component	Maintenance Required	Frequency	Required Action
Site	Verify: (i) Site cleanliness. (ii) Array shading.	3-4 months	Remove any/all debris. Reduce shading.
PV modules	Clean modules (check for dust and fungus build up)	3-4 months	Clean as required.
	Check for any defects present, including: (i) module fractures; (ii) module browning; (iii) moisture build up; and (iv) frame corrosion.	Yearly	Modules with defects detected should be inspected further to determine performance and safety of modules and whether new modules are required
Patch Panel	Determine integrity of cables	5 years	Replace damaged cables
	Check patch panel for the following. (i) Tightness of all connections; (ii) corrosion of connections; (iii) integrity of seals; (iv) integrity of cable entrances and glands; and (v) water build up. Check bypass diodes.	Yearly	Replace defective seals, connections and bypass diodes as required. Remove water as required.

Cont.

Table A1: Maintenance Guide (continued)

Weather station	Check integrity of: (i) humitter; (ii) wind vane; (iii) anemometer; (iv) pyranometer; and (v) thermocouples.	Yearly	Replace as required.
Electrical characteristics	Measure: (i) open circuit voltages; and (ii) short circuit currents.	Yearly	Probe necessary points.
Protective instrumentation	Check: (i) integrity of fuses; (ii) operation of circuit breakers (CBs) and residual-current devices (RCDs); (iii) operation of earth fault protection system; and (iv) solar array isolator.	Yearly	Replace and repair as necessary.
Array mounting	Check tightness and condition of all bolts and other fasteners	Yearly	Replace and repair as necessary.
	Check for corrosion on frame	5 years	Repair as necessary.
	Check equipotential bonding	5 years	Discharge as required

A.2 Wiring Schedule for Weather Sensors

This section contains the wiring schedule for the anemometer and wind vane. For both sensors, extension cabling has been added in order for the sensors to be connected within the Patch Panel. It is important to note that the colour of the extension wires that the sensor wires are connected to may not necessarily be the colour of the wires that are connected within the patch panel. Lastly, no wires are doubled up (i.e. each wire is individually connected to another wire).

Table A2: Anemometer Wiring Schedule

Anemometer	Beginning of Extension	End of Extension
Red (supply positive)	White with blue	White
White (output)	White	White with blue
Blue (supply negative)	Black	Black
Yellow (output negative)	Black	Black

Table A3: Wind Vane Wiring Schedule

Wind Vane	Extension
Red	Red
Black	Blue
Clear	Yellow

A.3 Specifications

This section contains specifications for various sensor and modules discussed throughout the report.

A.3.1 Anemometer

Table A4: Wire Colours and Functions for Anemometer [6]

Wire Colour	Wire Function
Red	Supply positive (4.75VDC to 28VDC)
Blue	Supply negative (0V)
Green	Not used (insulated)
Yellow	Output negative (0V)
White	Pulse output (nominal 4V square wave)
Black	Connected to instrument case

Table A5: General Specifications of Anemometer [6]

Range of Operation	Threshold	0.15Kts
	Max. wind speed	75m/s
	Standard measuring range	0m/s to 75m/s
Pulse Output	Rotor speed measurement	Interruption of optical beam
	Accuracy	0.1m/s (0.1m/s to 10m/s), 1% of reading (10m/s to 55m/s), 2% of reading (55m/s to 75m/s)
	Non-linearity	0.4% output frequency
	Output range	0 to 750Hz for 0 to 75m/s (10Hz per 1m/s)
	Resolution	10cm
	Pulse output	High: 4.2V max., 3.6V min.
		Low: <0.2V
General	Operation temperature	-30 to +70°C
	Supply voltage	4.75VDC to 28VDC
	Power up time	2 seconds

A.3.2 Wind Vane

Table A6: Wire Colours and Functions for Wind Vane [10]

Wire Colour	Wire Function
Red	Supply positive (1VDC to 15VDC)
Black	Supply negative (0V)
Clear	Signal output

Table A7: General Specifications of Wind Vane [10]

Output signal	Signal type	Analog DC, 10kΩ potentiometer
	Accuracy	1%
	Dead band	4°
	Output signal range	0V to excitation voltage
Power	Supply voltage	1VDC to 15VDC
General	Temperature	-55°C to +60°C
	Humidity	0% to 100%
	Lifespan	50 million revolutions (2-6 years)

A.3.3 Pyranometer

Table A8: Pyranometer Specifications [11]

Output	4.62µV/W/m^2
Spectral Range	305-2800nm
Operating Temperature	-40°C-60°C

A.3.4 PV Modules

Table A9: PV Module Specifications [17]

Electrical	Power rating	75W
	Open circuit voltage	21.4V
	Short circuit current	4.75A
	Voltage a maximum power	17V
	Current at maximum power	4.45A
General	Dimensions	1188.0 x 530.0 x 44.0mm
	Cells	4 cells by 9 cells
	Normal operating temperature	47.0°C
	Temperature range	-40.0°C to 85.0°C

A.3.5 Dataforth Modules

Table A10: Dataforth Module Specifications [13]

SCM5B30 (Current Signal Conditioner)	
Input range	±10mV to ±1V
Output range	±5V
SCM5B31 (Voltage Signal Conditioner)	
Input range	±1V to ±40V
Output range	±5V

A.4 Procedures and Troubleshooting

A.4.1 National Instruments Measurement & Automation Explorer

Many times during the beginning of the project, the data being sent from the FieldPoint modules was not being read in National Instruments Measurement & Automation Explorer (NI MAX). NI MAX was returning an 'Out of Range' error when attempting to access the FieldPoint values. To remedy this error, the following steps were performed.

1. In NI MAX select: My System → Data Neighbourhood → FieldPoint Items → FP@COM15 → FP-AI-110@3 (see the red box in Figure A1).
2. Find 'Go To' button in the ribbon appearing on the top of the I/O Data window and select (see the green box in Figure A1).

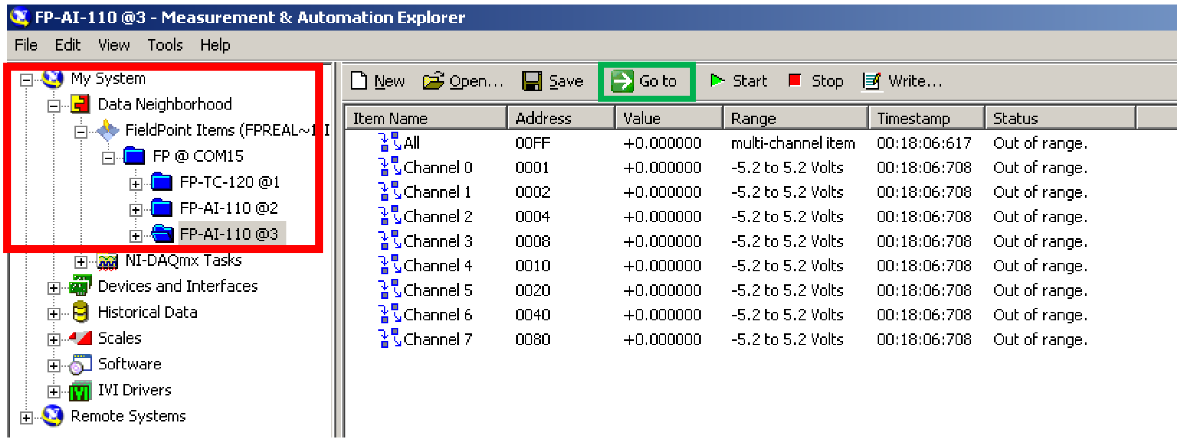

Figure A1: NI MAX data location

3. A warning will pop-up, click OK. Figure A2 shows the warning.

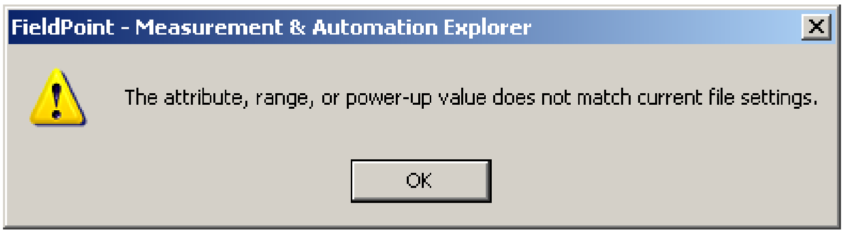

Figure A2: Pop-up warning

4. Upon entering the proceeding window, find the ‘File/Device Conflict Resolution’ section under the ‘Channels’ section. Check that the ‘Files’ radio button is checked and select ‘Use These Settings’ (see the blue box in Figure A3).

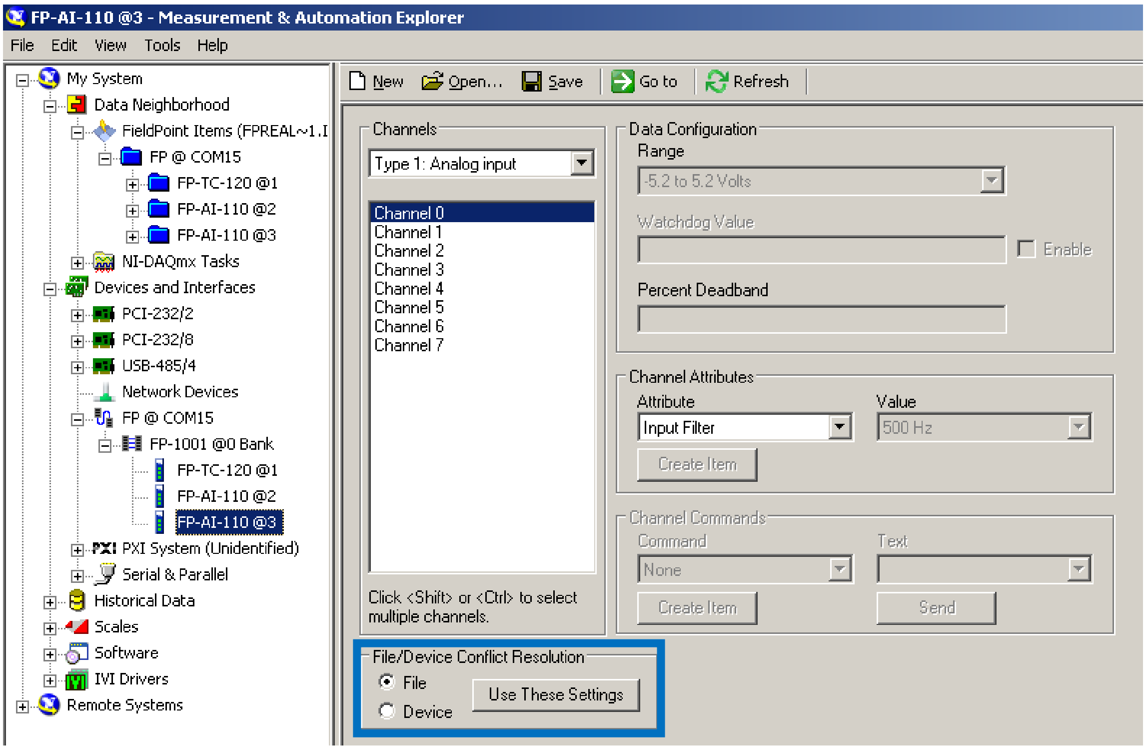

Figure A3: Conflict Resolution Page

5. Repeat these processes for FP-TC-120@1 and FP-AI-110@2 if necessary.

A.4.2 Adding New FieldPoint Module

1. In the left column, expand ‘My System’ → expand ‘Data Neighbourhood’ → expand ‘FieldPoint Items’ → right-click ‘FP@COM15’.
2. From the list of options, select ‘Go To Comm Resource Configuration’.
3. In the top toolbar find and select ‘Find Devices’.

A.4.3 Creating Bound Variable

1. In the LabVIEW project explore, expand ‘Project’, expand ‘My Computer’, expand ‘PV Library’, right-click the item titled ‘FlieldPoint PV Library’.
2. In the list of options that appear, select the option ‘Create Bound Variables..’

3. In the new window that appeared expand ‘Project’, expand ‘My Computer’, expand ‘PV Library’, expand ‘FlieldPoint PV Library’, expand ‘FP @ COM15’, expand the relevant FieldPoint module and select the appropriate item where the data is being written to.

A.4.4 Changing Variable Data Type

To change the variable data type, the newly created bound variable was double-clicked to bring up the variable properties window. Shown in Figure A4, the data type was changed, via a drop-down box, from type ‘UInt16’ to type ‘Double’. This allowed LabVIEW to properly read the newly created variable.

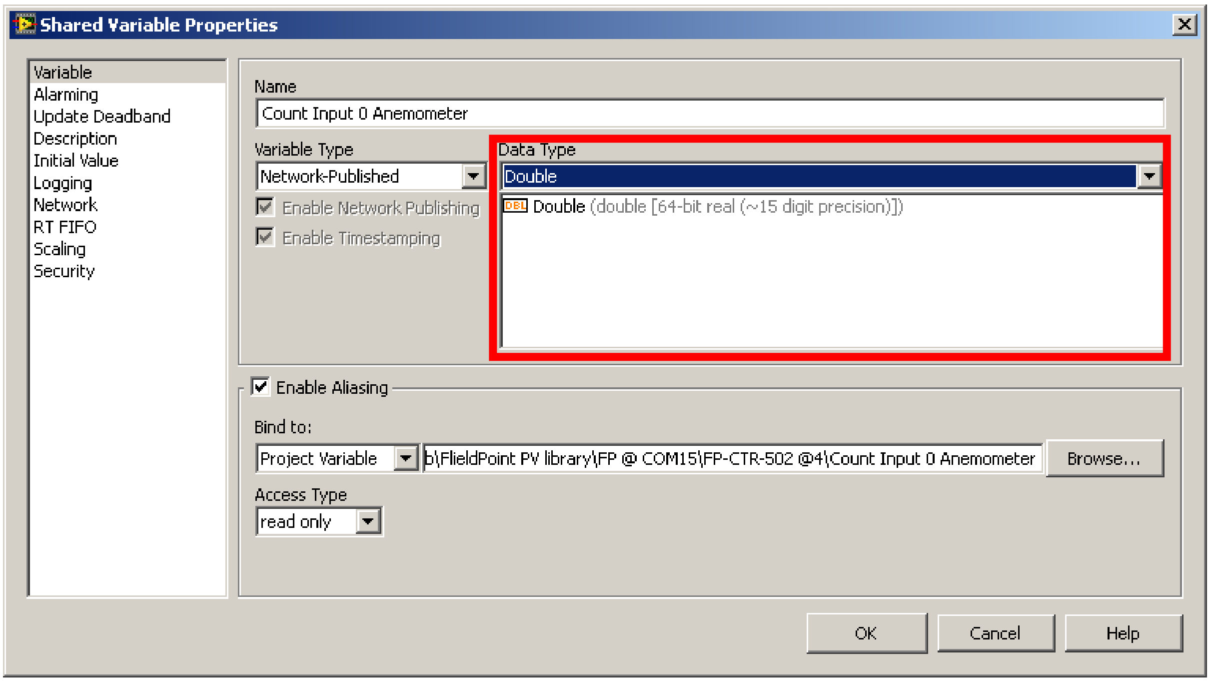

Figure A4: Changing Variable Data Type in LabVIEW

A.5 Powermonitor Capabilities

This section provides a complete list of the measuring capabilities of the Allen-Bradley Bulletin 1403 Powermonitor II. The full list of capabilities of the Powemonitor are [2]:

- Current: per phase and neutral (in Amperes);
- Average current (in Amperes);
- Positive sequence current (in Amperes);
- Negative sequence current (in Amperes);
- Per-cent current unbalance;
- Voltage: line-to-line and line-to-neutral (in Volts);
- Average voltage: line-to-line and line-to-neutral (in Volts);
- Auxiliary voltage input;
- Positive sequence voltage (in Volts);
- Negative sequence voltage (in Volts);
- Per-cent voltage unbalance;
- Frequency (in Hertz);
- Phase rotation (ABC, ACB);
- Total real power (in Watts);
- Per phase real power (in Watts);
- Total reactive power (in Volts-Amps reactive);
- Per phase reactive power (in Volts-Amps reactive);
- Total apparent power (in Volts-Amps);
- Per phase apparent power (in Volts-Amps);
- Total true power factor;
- Per phase true power factor;
- Total displacement power factor;
- Per phase displacement power factor;
- Total distortion power factor;
- Per phase distortion power factor;
- Power consumption: forward, reverse, net (in kWh);
- Reactive power consumption: forward, reverse, net;
- Demand (in Amperes, Watts, Volts-Amps reactive, Volts-Amps);
- Instantaneous demand (in Amperes, Watts, Volts-Amps reactive, Volts-Amps);
- First order projected demand (in Amperes, Watts, Volts-Amps reactive, Volts-Amps);

- Second order projected demand (in Amperes, Watts, Volts-Amps reactive, Volts-Amps);
- Per-cent distortion (up to 41st harmonic);
- IEEE per-cent total harmonic distortion;
- IEC per-cent total harmonic distortion;
- IEEE-19 compliance;
- Telephone interference factor;
- Crest factor; and,
- K-factor.