DREXEL UNIVERSITY
Senior
Design
Electrical and Computer Engineering

FINAL REPORT
Spring 2014-2015

Team Number **ECE-22**

Solar Power Distribution System

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Abstract

Collecting energy from renewable sources is a rapidly growing industry, especially as traditional fuel sources are becoming scarce and expensive. Due to this increased interest, Solar Photovoltaic Distributed Generation (PV-DG) has become very popular in North America. PV-DG differs from more traditional generation systems in that PV-DG systems are highly variable because of the unpredictable nature of weather and sunlight on any given day. This is one of the main factors preventing the widespread deployment of PV-DG systems. One way to encourage PV-DG utilization is to provide methods for analyzing the influence distribution level solar power generation has on the overall distribution network.

The objective for this project is to provide a repeatable hardware experimental procedure that recreates an isolated solar power distribution system. This will provide a method for analyzing the effects of PV-DG on conventional neighborhood distribution systems. This project will be using the solar panels on top of the main building of Drexel University as the solar energy source. The LabVIEW software suite will be used to monitor the distribution system in real time. The hardware test will be carried out in the Reconfigurable Distribution Automation and Control Laboratory (RDAC) in Drexel University.

This experiment will provide voltage data, current flow, and efficiency metrics that can be used for a comparison between loads under the isolated solar powered distribution system versus loads under the normal utility power sources. The modifiable loading profile of the single house model will also be included with the experiment in order to allow further customization in future research conducting using this newly developed process.

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Problem Description

The process of producing electricity for an electrical network at the distribution level is called distributed generation. Distributed generation does not only come from solar power. Reciprocating engines and small hydro power plants have been connected to distribution systems and have been constant power sources since the passage of the Public Utility Regulatory Policies Act (PURPA) in 1978 [1]. However, the invariability and intermittency of solar power adds several challenges to the analysis of a distribution system. The following figure illustrates just how rapidly solar energy can fluctuate:

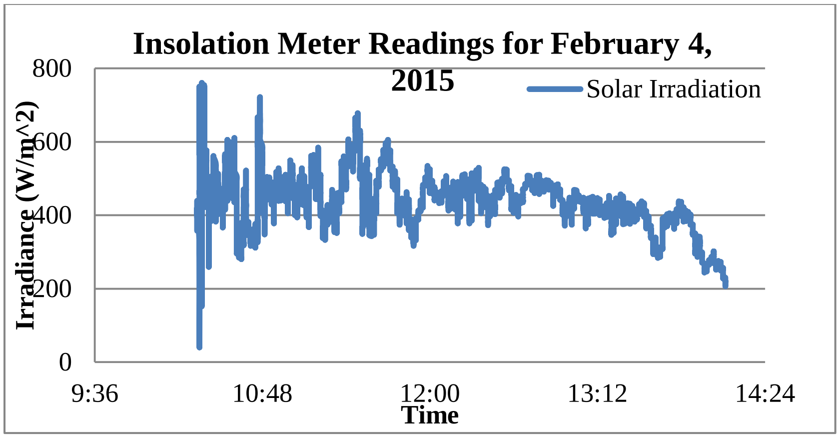


Figure 1: Solar Insolation Measurements from Drexel University, Parking Lot F

These fluctuations affect standard distribution system factors such as voltage, the power factor, and the levels of real and reactive power being produced [1]. Therefore, the expansion of distributed generation requires studies into the impact the fluctuation of these changing factors have on the electrical grid and the distribution network.

The main goal of the design project is to create a repeatable hardware experiment that allows for the testing of these fluctuations by utilizing the existing equipment in the Drexel University Power lab. It has an installed Solar Panel with a 1.6 KW rated output in Main Building. It also has the Reconfigurable Distribution Automation and Control Laboratory (RDAC), which is an adjustable hardware that can be utilized for analysis on the PV-DG system. RDAC is a 36 bus, 48 branch, reconfigurable laboratory that can form many different multiphase distribution networks [2]. Additionally, the lithium-ion battery bank will be used in order to provide backup power if needed.

The project will connect the solar panel with the RDAC and be able to run tests with it as an isolated photovoltaic distribution system. The performance of an isolated photovoltaic system powering the distribution system in the RDAC will be explored and examined. Real-world homes will be modeled via the use of resistors (in the form of light banks), and actual devices frequently used in homes. This type of configuration will allow an extremely realistic simulation of situations that could be seen on a larger distribution system. Peak demand times and low demand times will also be analyzed during experimentation. The results of these experiments will be recorded, compared, and analyzed to gain insight into the impact that solar photovoltaic distributed generation has on a distribution network.

Deliverables

The problem that this project will address is the need for an analysis method for solar photovoltaic distributed generation (PV-DG). In order to see to this challenge, the team has decided to design and implement an experiment on solar microgrids to be carried out in the RDAC at Drexel University.

Load Profiles

For the purpose of the entire project, load profiles have been constructed for the models to be used in the hardware experiment with RDAC. This includes two model load profiles of a single home using various loads throughout a four hour period in different rooms. Each profile utilizes the resistive load banks in specific arrangements along with controllable loads in the form of real world appliances. Nameplate data for each appliance will be provided for load calculations. The total load demand will be calculated with estimated power losses for typical load profile graphs. Estimates will be made for the lithium-ion battery starting state of charge (SOC %) so that enough power will be available for each experiment. The two load profiles will model the same power use. However, one will have lower power draws from simulated loads in order to prepare for cloudy conditions, while the other will call for higher load settings that can be supported by a high solar insolation output. In order to choose the appropriate profile, the weather forecast on the testing day will be checked and the appropriate load profile will be used.

Software

National Instruments (NI) LabVIEW will be utilized to communicate with the NI drivers and Data Acquisition (DAQ) card to show real time root mean square (RMS) voltages and currents and calculated power values. The final visual interface (VI) will be made available to future senior design groups who wish to further improve upon its functionality and robustness.

Hardware Experiment

The experiment will take the house load profiles and apply it to the RDAC hardware. First, the LabVIEW interface will be connected to the NI DAQ card for proper data collection. The solar power source will then be wired from the inverter and lithium-ion battery in Interconnected Power Systems Laboratory (IPSL) through the newly installed cable into the RDAC. The load profile will then be used to determine the load settings throughout the course of the experiment.

The LabVIEW interface will produce a table of voltage, current, and power results from the four predetermined measurement points in RDAC. Additionally, the HOBO micrometer will be set up and the insolation data from the testing day across the same time period as the testing will be recorded. Lastly, the Battery Management System (BMS) will be used to collect the power information of the lithium-ion battery. All of this data will then be used to analyze and research the performance of the isolated solar powered single home distribution network.

Results

Solar Panel Output Power Testing- Spring Profile

Description of Solar Panel Output Power Testing

The Solar Panel Output Power (SPOP) tests were conducted on February 4, 2015 that modeled a winter day profile and April 23, 2015 for the spring day profile. The same procedures and analysis methods were used (see Appendix C). The Battery Management System (BMS) recorded the voltage and current levels feeding into the lithium-ion battery bank from the inverter. The HOBO micrometer was placed in the same location and positioned in an identical manner in order to collect the solar insolation data. Together, the data collected by the BMS and the HOBO meter was used to put together a full winter day and a full spring day profile with expected levels of solar insolation, respectively.

Collecting this data was important to setting up the load profile on the RDAC and ensuring that the loads to be used would not draw substantially more power than the system could support. Additionally, the SPOP test provided the group with an estimation of the amount of power that the battery would need to supply. This way, the battery could be properly charged before being used to supply the RDAC without the risk of fully discharging or over-charging the battery. The following schematic shows the basic configuration of this test:

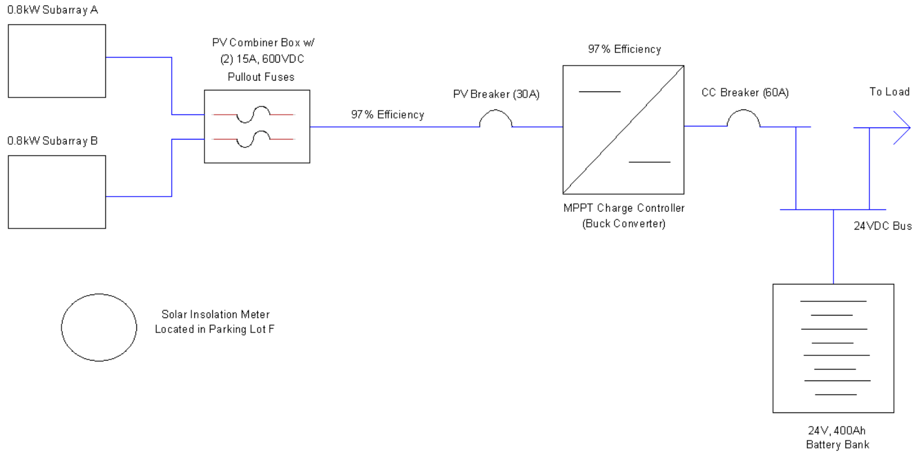


Figure 2: Single-Line Diagram of the SPOP Testing

The solar power was calculated by taking the DC voltage and the DC current measurements going into the battery using the BMS. This provides the following equation:

$$P_{solar} = P_{battery} = V_{DC}I_{DC}$$

In the initial stage of the test, more power was being produced by the solar panels than the battery could handle. The state of charge of the battery on the BMS interface was shown to be rising too fast for the duration of the test. When the battery was approaching

90% of its capacity, the battery needed to be discharged in order to prevent overcharging. Therefore, as in the winter test, a backup load consisting of thirteen light bulbs was set up in order to draw power out of the battery. The AC voltage and AC current going into the light bulb bank was consequently measured as P_{load}, making the total power equation the following:

$$P_{solar} = P_{battery} + P_{load}$$

These two equations allowed for the total solar power output to be observed, recorded, and analyzed and were used to set up the load profile in order to ensure that the total power drawn from the solar panels would not eclipse the maximum power that the panels could produce.

Part of the post processing of the data required taking and analyzing the data collected from the HOBO insolation meter. The solar irradiation was measured in Watts per square meter (W/m^2). The maximum potential power output of the solar panel from the insolation data can be found using the following equation:

$$P_{potential} = Solar\ Irradation * Solar\ Panel\ Area$$

Both of the insolation collection and Solar Panel Output Power test were conducted on April 23, 2015 from 10:00AM to 2:00PM. The total time period for this test was four hours.

Results of Solar Panel Output Power Testing (Spring Profile)

The following graph shows the results from the insolation meter testing:

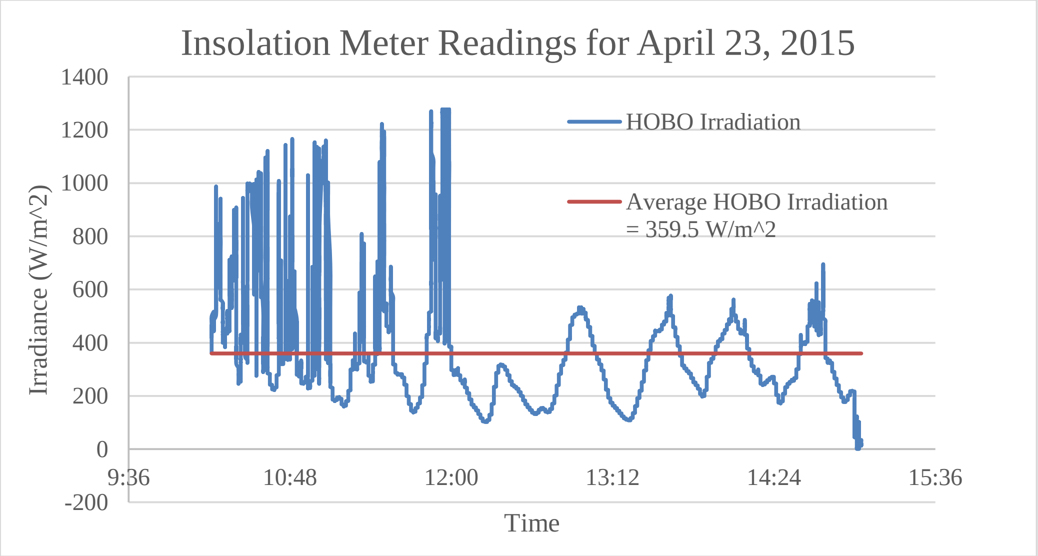


Figure 3: Solar Insolation Measurements from Drexel University, Parking Lot F

As shown in Figure 3, the solar irradiation varied tremendously during the test day. This was due to the cloudy weather conditions on April 23, 2015. During the early part of the day, the skies were relatively clear with a few passing clouds. In the afternoon, however, more clouds rolled in, lowering the total solar insolation.

It was found that the average solar irradiation on April 23, 2015 was 359.5W/m^2. Using the solar panel power potential equation and the average solar irradiation data, the potential power can be found. The solar array on the top of the Main Building has an area of 11.9m^2. Therefore, the total potential solar power for the solar array on April 23, 2015 was 4278.1W. The following figure shows the actual solar power produced during the spring testing:

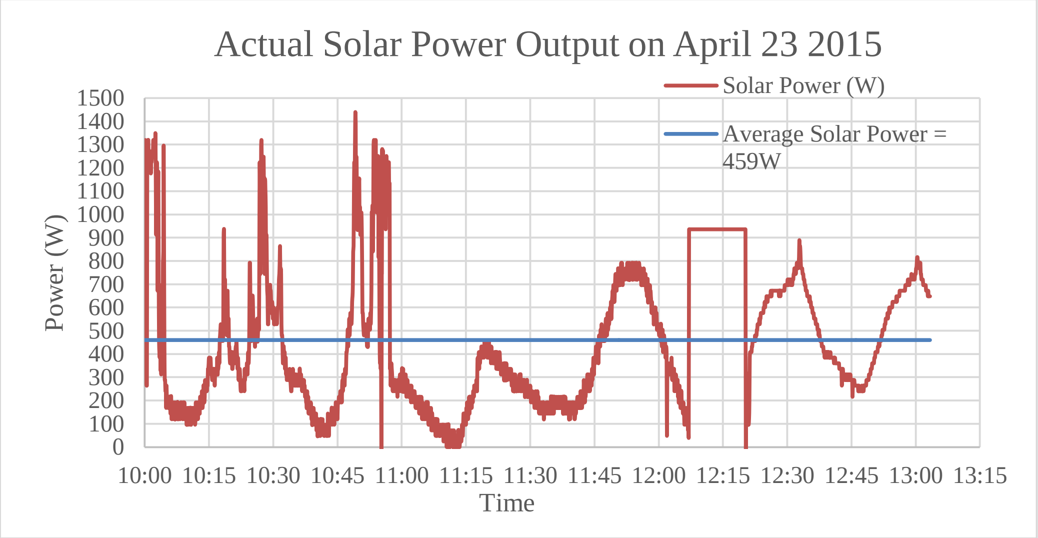


Figure 4: Solar Power Output from Main Building Solar Array

Analysis of the data displayed in Figure 4 shows that the average solar power output from the solar panel was 459W on April 23, 2015. The following graph shows the winter day output and the spring day solar output profiles:

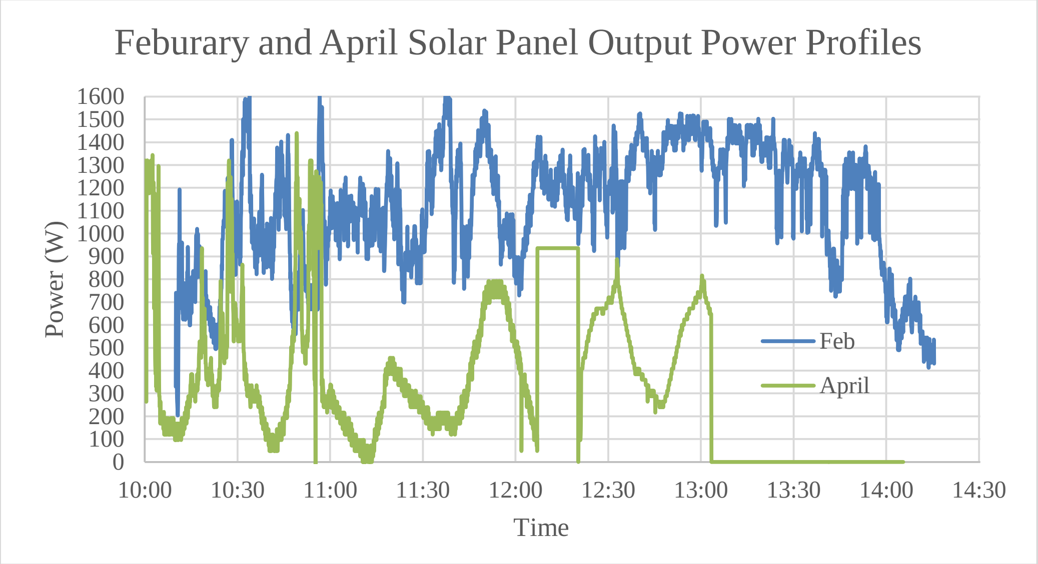


Figure 5: Comparison Plot with the Winter Test and the Spring Test Data

As easily seen on Figure 5, the SPOP test from February produced more power than the same test repeated in April. Though it is generally true that spring weather conditions are more favorable for producing solar power, the weather on the winter test was much sunnier and produced a higher average irradiation despite the lower azimuth angle of the sun. The cloud cover and eventual overcast conditions of the spring SPOP test were too severe to allow the higher azimuth angle of the sun to produce more electricity. The spring solar panels during the spring SPOP test also performed at a much lower efficiency of 10.7% compared to 21.0% in the winter. Ultimately, the spring SPOP data, along with the winter SPOP data, were used to inform the creation of load profiles that could be adjusted if the weather conditions on the day of the testing were less than ideal.

Load Profiles

Development for the load profiles used in the project was carefully planned based on the limitations of RDAC. One such confine is the physical number of resistive load banks that can be used in a single phase system with RDAC. Another restriction is the actual power that the PV system is able to supply. A final restraint is the maximum current that can safely pass through the newly installed cable between IPSL and RDAC and the maximum allowed phase current on a single phase in RDAC. Too high of a current would cause the protection fuses to trip, thus disrupting the experiment.

The resistive load banks are composed of light bulbs, consisting of up to 5 bulbs per bank connected in parallel. Each additional bulb that is turned on reduces overall resistance and increases power consumption. There are 12 banks each with 5 bulbs for a total of 60 bulbs for use at a given station (see Figure 6). A maximum of 2 banks can safely be connected in series, allowing 10 bulbs with 720W maximum power draw.

The PV system has a rated maximum output at 1.6kW. The real power has never been observed to exceed 1.4kW so far during testing, and the range of produced power has varied greatly. Therefore, the loading profile produced for this experiment was designed with these limitations in mind. The connected loads could also be supplied with battery power when the produced solar energy was less than the consumed RDAC energy. However, a load profile that would not drain the battery too quickly was desired.

Figure 6: Load Bank Light Bulbs

The total current that is allowed to be fed through the new cables is 15A. Although total load demand will not exceed 1.4 kW, (thus a maximum current draw of 12A, roughly) it must be kept in mind that losses and small unobserved loads in the entire system could increase total current draw from the IPSL and RDAC connection.

Several load profiles were created using known parameters found from power data of typical loads used in a home [4]. Though an RDAC station contains eight bus connections, only four buses will be used to model the four rooms in the home being modeled. These rooms are a living room, a kitchen, a bathroom, and a bedroom. The loads were categorized in each room as per the following tables:

Tables 1, 2, 3, 4, & 5: Room Subdivisions and Relative RDAC Locations and Loads

Bedroom (Bus B1)	
Load	**Wattage per unit (W)**
Floor Lamp	23
CPU	125
Monitor	125
Heating (central, gas)	400

Living Room (Bus A1)	
Load	**Wattage per unit (W)**
Floor Lamp	23
Television (plasma 36-inch to 42-inch)	250
Stereo System	250
Ceiling Fan	120

Kitchen (Bus A3)	
Load	**Wattage per unit (W)**
Microwave	800
Refrigerator	2 41 725

Bathroom (Bus B3)	
Load	**Wattage per unit (W)**
Hair Dryer (travel size)	300
Ceiling Light	25
Clothes Washer	425

Removable Appliance	
Load	**Wattage per unit (W)**
phone charger	36
laptop	180

Both a high load profile and low load profile for four hour testing periods were created, with a maximum energy draw of 3.29 kWh and a minimum energy draw of 2.35kWh, respectively (refer to Appendix for the complete Load Profiles). A couple of loads are under fixed control schedules (e.g. the refrigerator) which are set to turn on at least once an hour. However, the other loads in the home must be planned carefully in order to avoid too large a power demand. Considering that two or three loads are on in each 15 minute interval, the high load profile load was designed to stay below 1000 W during any given 15 minute interval. The low load profile was more conservative and stayed below a 500-700W demand range with the exception of a scheduled large load every hour during these 15 minute intervals. The following tables show the high and low load profile loading curves:

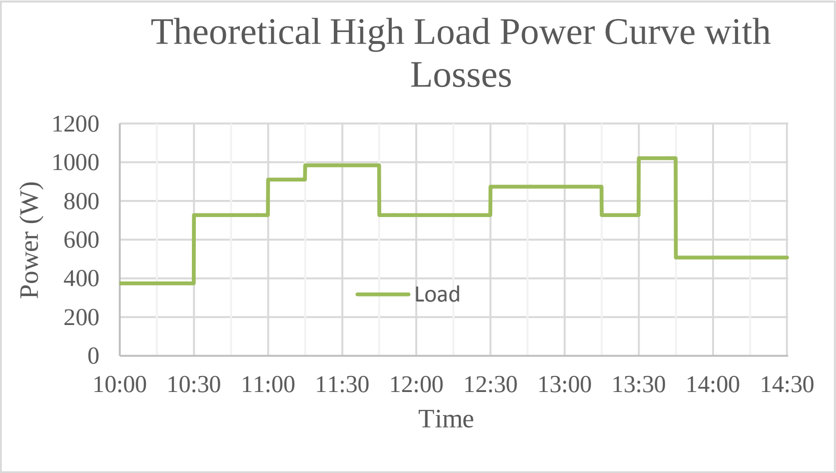


Figure 7: High Loading Profile Load Curve

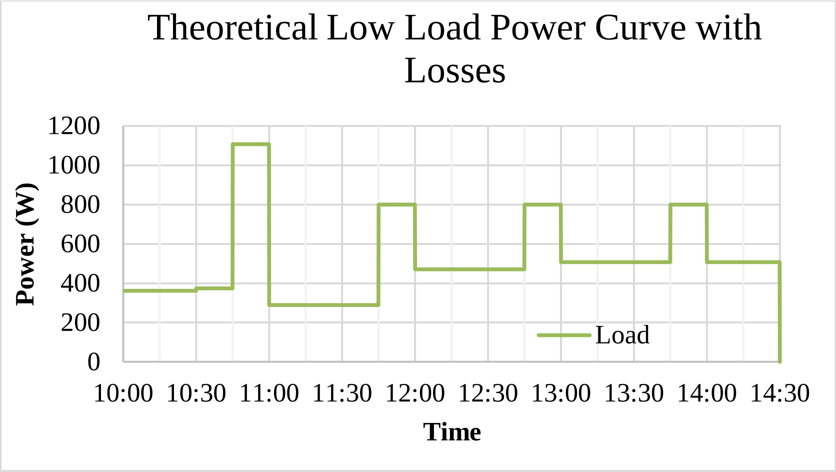


Figure 8: Low Loading Profile Load Curve

National Instruments Signal Conditioning and LabVIEW Interface

Before any hardware testing could be performed, the measurement capabilities of the RDAC needed to be researched and understood. In basic terms, a single load station in RDAC consists of eight separate busses split evenly on two sub-feeder busses. These eight busses are then connected to a main feeder bus, which is then connected to the auto-transformer and ultimately the power source. The two sub-feeder busses are classified as Feeder A and Feeder B, with each feeder having four load connection points. Therefore, a total of nine possible measurement locations exist; the four busses on both Feeder A and Feeder B (A1, A2, A3, A4, B1, B2, B3, and B4) along with the main feeder bus. However, only four of these points can be measured at once due to the number of available signal conditioning boards connected to the RDAC stations. One measurement point is always connected to the main feeder bus, while the other three can be changed depending on the experiment and the desired measurement locations.

Previous research and documentation about RDAC shows that the four measurement points are all set up in the same manner, meaning that they each collect, process, and send data in the same way. To put it into more practical terms, each of the four measurement points from the four signal conditioning boards arrange the voltage and current information in the same order. This is important because LabVIEW reads specific analog pins from the National Instruments (NI) PCI-6071 Data Acquisition (DAQ) card. The NI PCI-6071 has 64 analog input pins, so narrowing down the pins necessary to this test was important. However, it wasn’t until empirical testing was carried out that the specific measurement locations were known and the actual pins were determined. This testing involved putting the three customizable measurement points on busses A1, B1, and B3, and attaching various loads. Using a simple LabVIEW visual interface (VI) that was set up only to read and display the DAQ card data, the loads at these locations were varied and the corresponding pin locations were determined. After the testing, the following output pin mapping was established:

Table 6: RDAC to NI-DAQ Card Pin Mapping Locations

	Signal Conditioning Board I (MI)	Signal Conditioning Board II (MII)	Signal Conditioning Board III (MIII)	Signal Conditioning Board IV (MIV)
Bus Location	Feeder	A1	B1	B3
V_a	25	17	8	0
V_b	26	18	9	1
V_c	27	19	10	2
V_n	28	20	11	3
I_a	29	21	12	4
I_b	30	22	13	5
I_c	31	23	14	6
I_n	40	32	15	7

Once these pin assignments were determined, a full software interface needed to be designed and tested to ensure that the results collected from the hardware testing were accurate and documented in a useable manner. As mentioned above, the team decided to design an interface using LabVIEW because it gave the greatest amount of flexibility with processing, recording, and displaying hardware measurements. Additionally, the fact that the DAQ and LabVIEW are both made and supported by NI would make the interfacing process between LabVIEW and the DAQ relatively simple and straightforward.

The first phase of designing the LabVIEW interface was the determining of the specific pin outputs from the DAQ based off of the mapping shown in Table 2. Once the particular pin assignments were known, the LabVIEW interface could be fully programmed. In order to create a specific RDAC VI, three overarching tasks needed to be completed. First, the new interface needed to actively sample and process data from RDAC. Second, the interface needed to scale that data from the sampled magnitude into the actual values. Lastly, the interface needed to have a construct that would record the sampled data into a useable form for data analysis.

Establishing communication between LabVIEW and the NI PCI-6071 DAQ card proved to be relatively simple. Several pre-loaded VIs were designed exclusively for communicating with NI-DAQ cards. These VIs were researched and wired together in order to sample to RDAC at determined locations and output the data in a useable form. This sampled data was collected in a one-dimensional array, with each array entry corresponding to a measurement pin along the DAQ. Using other pre-existing VIs, the desired data point was extracted from this one-dimensional array and scaled using known calibration values. Due to the fact that the interface sampled the data at 1000Hz and the sinusoidal nature of data being sampled, it was required to include a set of functions to calculate the root mean square (RMS) value of the data. Once this calculation was completed, the RMS value was wired to be exported into a tab-delaminated format. All 32 of the separate RMS values were combined together and stored into the same document in order to make the post-processing analysis easier. The interface was programmed so that every second, one new line of data would be created. Appendix E contains screen captures the interface.

Once these three separate tasks were created and wired together, the interface was tested using PECO power and predetermined load settings with known power and current draws and voltage values. The designed interface was successfully able to sample, process, display, and record the data for this test, indicating that it was ready to be used for the full-fledged solar test.

Solar Power Distribution Test

The culmination of this project was the testing of the load profile in the RDAC using the solar power as the energy source. This test was carried out May 18, 2015. As outlined in the load profile section, specific load settings were designated for fifteen minute intervals. Using this load profile, the LabVIEW interface, and the BMS, the power from the solar panels was monitored and recorded. After the testing was completed, the data was analyzed and processed so it could be compared against collect HOBO insolation data.

The following graph shows the solar irradiation data for May 18, 2015:

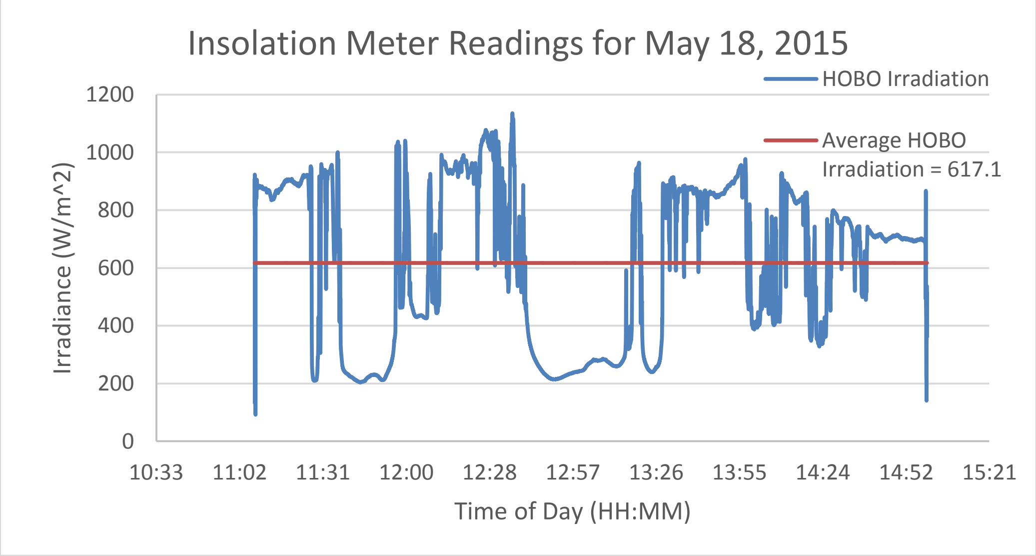


Figure 9: Insolation Meter Results

As indicated in Figure 6, the average irradiation for May 18, 2015 was 617.1 W/m^2. Also observable in Figure 6 is the fact that there were substantial periods of cloud cover during this test. The conditions of this test provided an interesting environment in which both long periods of cloud cover and abundant sunshine were observed during experimentation. The graph below shows the total solar power produced during the test:

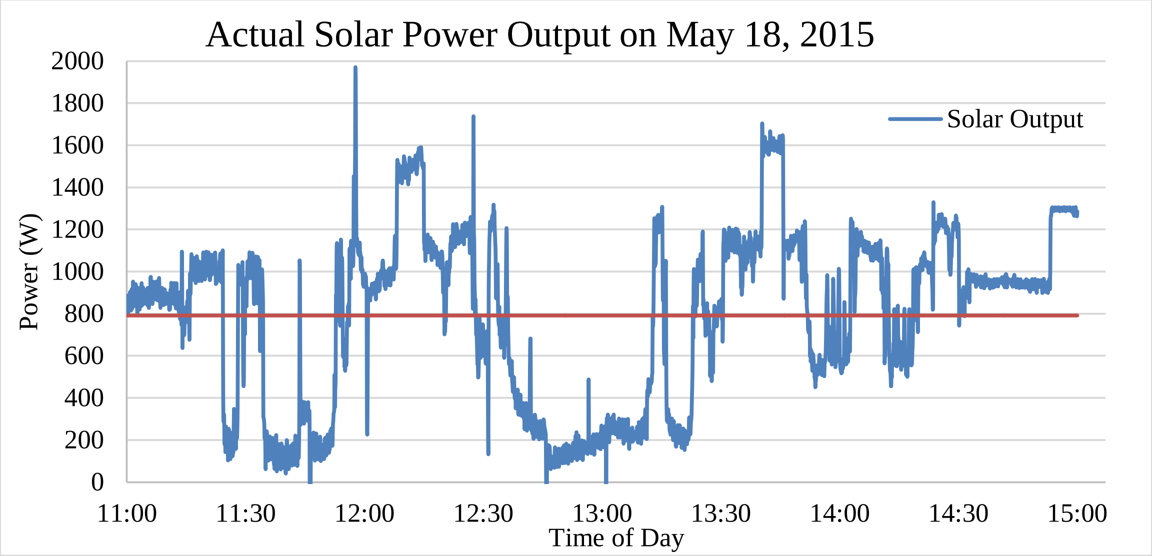


Figure 10: Solar Power Results

Figure 7 shows that the average solar power produced on May 18, 2015 was 791W, which is quite a high number considering the relative long periods of cloud cover. Observing Figure 7 in reference to Figure 6 clearly shows that the times of cloud cover and reduced solar irradiation produced lower solar power outputs. The data used to create Figure 7 was collected from the BMS.

The final graph of collected data shows the actual solar power produced overlaid with the real power consumed by the prescribed load profile and the expected real power to be consumed by the distribution network:

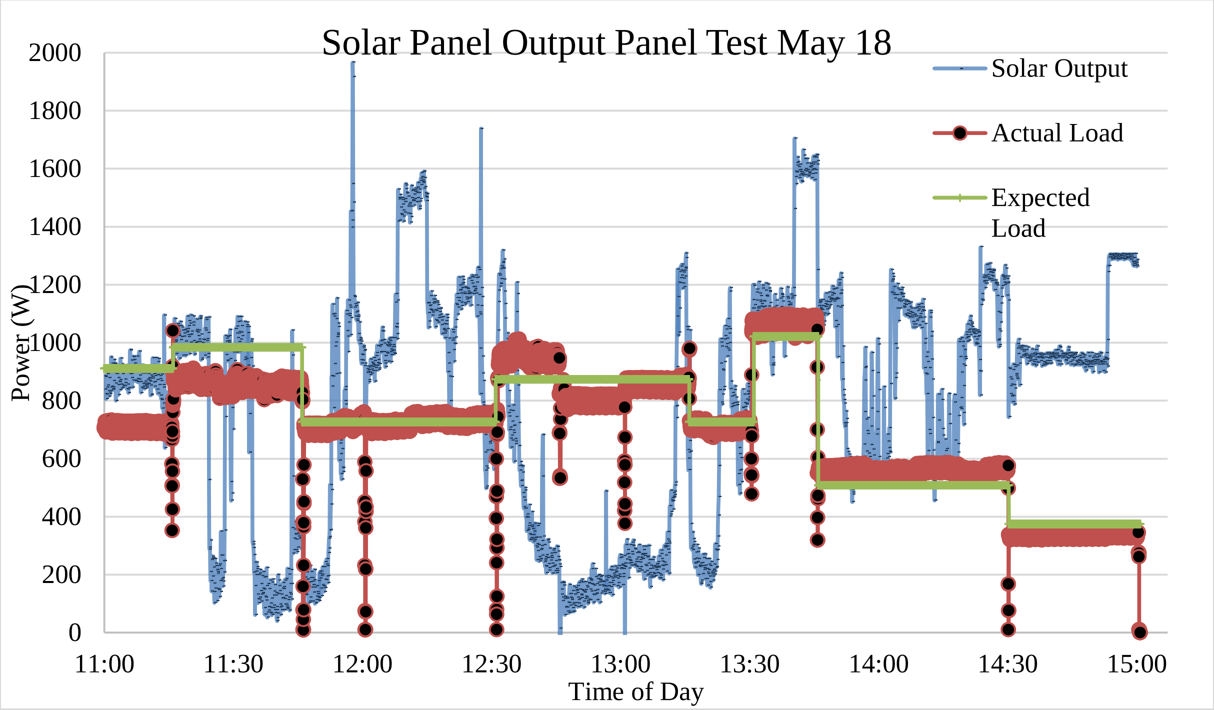
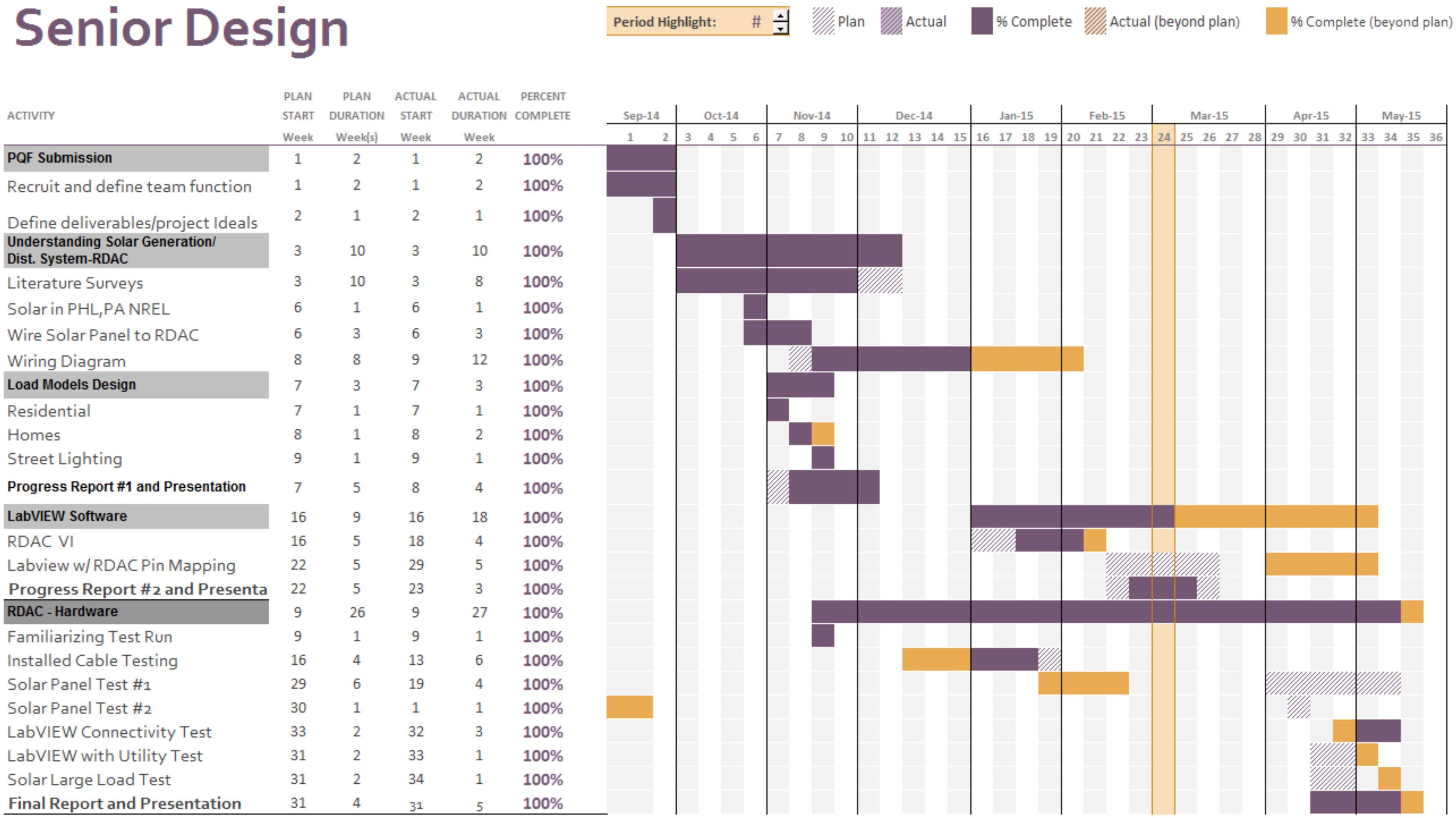


Figure 11. Solar Power Measurements versus the Load Profile Measurements

Work Schedule / Proposed Timeline



Senior Design

ACTIVITY	PLAN START Week	PLAN DURATION Week(s)	ACTUAL START Week	ACTUAL DURATION Week	PERCENT COMPLETE
PQF Submission	1	2	1	2	100%
Recruit and define team function	1	2	1	2	100%
Define deliverables/project Ideals	2	1	2	1	100%
Understanding Solar Generation/ Dist. System-RDAC	3	10	3	10	100%
Literature Surveys	3	10	3	8	100%
Solar in PHL,PA NREL	6	1	6	1	100%
Wire Solar Panel to RDAC	6	3	6	3	100%
Wiring Diagram	8	8	9	12	100%
Load Models Design	7	3	7	3	100%
Residential	7	1	7	1	100%
Homes	8	1	8	2	100%
Street Lighting	9	1	9	1	100%
Progress Report #1 and Presentation	7	5	8	4	100%
LabVIEW Software	16	9	16	18	100%
RDAC VI	16	5	18	4	100%
Labview w/ RDAC Pin Mapping	22	5	29	5	100%
Progress Report #2 and Presenta	22	5	23	3	100%
RDAC - Hardware	9	26	9	27	100%
Familiarizing Test Run	9	1	9	1	100%
Installed Cable Testing	16	4	13	6	100%
Solar Panel Test #1	29	6	19	4	100%
Solar Panel Test #2	30	1	1	1	100%
LabVIEW Connectivity Test	33	2	32	3	100%
LabVIEW with Utility Test	31	2	33	1	100%
Solar Large Load Test	31	2	34	1	100%
Final Report and Presentation	31	4	31	5	100%

Figure 12: Proposed Work Schedule

Budget Information

Industrial Budget

First Quarter - Three Months						
Category	**Expense**			**Cost Per Hour**	**Total Hours**	**Total Cost**
Initial Design	Labor	Electrical Engineer	Ryan	$42.28	440 hrs	$18,603.20
		Electrical Engineer	Ruben	$42.28	440 hrs	$18,603.20
		Electrical Engineer	Lixin	$42.28	440 hrs	$18,603.20
		Electrical Engineer	Yichen	$42.28	440 hrs	$18,603.20
		Consultant	Dr. Miu	$275.00	12 hrs	$3000.00
		Consultant	Nick	$275.00	12 hrs	$3000.00
	Materials		Use of Drexel Power Lab	$30	33 hrs	$990

Second Quarter - Three Months						
Category	**Expense**			**Cost Per Hour**	**Total Hours**	**Total Cost**
Software Design and Hardware Testing	Labor	Electrical Engineer	Ryan	$42.28	440 hrs	$18,603.20
		Electrical Engineer	Ruben	$42.28	440 hrs	$18,603.20
		Electrical Engineer	Lixin	$42.28	440 hrs	$18,603.20
		Electrical Engineer	Yichen	$42.28	440 hrs	$18,603.20
		Consultant	Dr. Miu	$275.00	12 hrs	$3000.00
		Consultant	Nick	$275.00	12 hrs	$3000.00

Software Design and Hardware Testing	Materials		Drexel Power Lab	$30	33 hrs	$990
			Software applications	**Quantity**	**Cost**	**Total Cost**
			Mathworks Matlab	1	$1,900	$1,900
			LabView	1	$1,100	$1,100
			Microsoft Office 2010	4	$140	$560

Third Quarter - Three Months						
Category	**Expense**			**Cost Per Hour**	**Total Hours**	**Total Cost**
Hardware Testing and Documentation	Labor	Electrical Engineer	Ryan	$42.28	400 hrs	$16,912.00
		Electrical Engineer	Ruben	$42.28	400 hrs	$16,912.00
		Electrical Engineer	Lixin	$42.28	400 hrs	$16,912.00
		Electrical Engineer	Yichen	$42.28	400 hrs	$16,912.00
		Consultant	Dr. Miu	$275.00	10 hrs	$3000.00
		Consultant	Nick	$275.00	10 hrs	$3000.00
	Materials		Drexel Power Lab	$30	40 hrs	$1200.00

Out-of-Pocket Budget

The out-of-pocket budget expenses for this project are relatively low due to the fact that the Drexel power lab already owns almost all of the equipment needed, including software applications and the Reconfigurable Distribution Automation and Control Laboratory (RDAC). For software expenses, the laboratory computers already have LabVIEW installed, which is the software being used to design the simulation program. For the hardware testing, there are several model substations, electric equipment and cables in the lab. The only considerable cost is the wire cable interconnection from the rooftop solar panels to the RDAC. This improvement cost $2500 and was already carried out at the expense of the Drexel power lab. Other minor supplemental expenses, such as stationery, will funded by individual team members.

Societal, Environmental or Ethical Impacts

The social impacts of this project are vast. The results of this project can be used to provide real world data that could impact designing and planning decisions for distribution networks. The location and development of larger solar panel generation centers often requires considerably more space and real estate than fossil fueled counterparts. Thus, the data collected from this project could have severe negative effects on the land value of neighborhoods due to the presence of a generating station. However, positive impacts that encouraging solar power have greatly outweigh the negative consequences. Modeling distribution systems could also lead architects to incorporate solar power to the design of a building or a neighborhood in the final product. Additionally, the proven economic benefits of solar powered distribution provide positive influences on all those who are connected to the solar panel network.

Because solar panels use a lot of development space, the environmental impacts of this presents a problem to preservationists who wish to keep human development off of untouched landscape. Animal and plant species could suffer from the destruction of habitat. However, solar panels generate very clean and low polluting electricity, which is beneficial to both human and non-human organisms alike. Furthermore, the destruction of habitat that solar panels do cause is considerably less than when compared to the habitat destruction caused by mining and drilling for fossil fuels and has a smaller carbon footprint comparatively. Lastly, any technology which helps humans start to undo the disasters that are caused by anthropogenic climate change can be seen as a positive benefit to the environment.

Due to the fact that this project deals with power generation and encouraging solar panel power, these themes are what are considered in determining the ethical implications of this project. A strong argument can be made that, in this day and age, access to electricity is becoming less of an unnecessary luxury and more of an essential component to survival. Thus, easing access to power can be seen as promoting a basic ethical right that humans are becoming entitled to. This project certainly advances this ethical matter by providing useful empirical data needed to design and support solar panel networks. Additionally, because so many ethical and environmental issues overlap, any technology that reduces the impact of humankind on the environment is also defensible.

Summary/Conclusions

This project represented the combination of most of the engineering design methods, mathematical and engineering principles, and power systems modeling approaches learned by the senior design team at Drexel University. Several crucial engineering skills were utilized in order to fully create this experiment, including specific engineering research methods, load modeling and planning using engineering approaches, software preparation and development, data collection and processing, and report writing.

This project is unique in that it produced a process that will be used for several years after the current design team has graduated. The goal of this project was to design an experiment that tested the effect of solar powered microgrids on a distribution system and that was repeatable. Based solely upon the results gathered from the tests carried out by the senior design team, it was demonstrated that this designed experiment was successfully operated as an isolated solar microgrid. The load profile developed was shown to work with the solar power input and was demonstrated to run safely within RDAC. The software designed by the team successfully took and recorded real time voltage, current, and power measurements and presented them in a manner that could easily be processed and analyzed. Additionally, the process has shown to be repeatable, as several other tests using the load profile and LabVIEW interface were carried out before the isolated solar test in order to ensure the design compatibility within the constraints of RDAC.

These achievements can be used and modified by professors, researchers, and other design teams in the future to even further study how solar power can be safely and reliably utilized on a distribution network. The inherent flexibility with which the process was designed, coupled with the customizability of RDAC, will allow future students to modify their load profiles, power outputs, and network configurations to best fit emerging power distribution systems. While creating single products or theoretical designs is an interesting approach to the senior design project, the approach that the design team took to create an experiment and provide the necessary components for carrying out that experiment is truly unique and will also benefit research in the long term. As solar power and PV-DG become more widespread, researching platforms such as the one designed for this project will be essential. Providing society and the engineering community with such a process is truly a great accomplishment, and further showing that this experiment works and is repeatable will truly benefit science in the years to come.

References

[1] F. Katiraei, “Solar PV integration challenges”, IEEE Power Eng Rev. vol. 9 issue 3, pp. 1-10, May 2011.

[2] X. Yang, S. Carullo, K. Miu, C. Nwankpa, “Reconfigurable Distribution Automation Control Laboratory: Multiphase Radial Power Flow Experiment”, IEEE Trans. Power Syst., vol. 20, no. 3, August 2005.

[3] “Wattage Calculator”, Consumer Reports, <https://www.consumerreports.org/cro/resources/images/video/wattage_calculator/wattage_calclulator.html>. April 2015.

Appendix A: Design Constraints Summary

Team Number: ECE-22
Project Title: Solar Power Distribution Management System

Summary of the Design Aspects:

The project design for the system that would be used is the lab-made distribution system in Drexel University's Reconfigurable Distribution Automation and Control Laboratory (RDAC). The only change being made to it is the wiring of the Solar Panel Array in Main Building to the RDAC system for ready use in experimentation. Software will be created in LabVIEW to connect with the measuring instruments already in the RDAC to run the test simulations more functionally. Research about the distribution system and distributed generation has been the center focus for the team.

Design Constraints:

Economic:

Solar panels are not all made with the same materials and they aren't cheap enough that they can be tested and switched often with other models. Low maintenance is a beneficial factor that lower costs to clean and upkeep it.

Manufacturability:

The distribution system is a long time standing system that can add connections to the existing line. The size of an actual generation plant may be of a larger scale for higher outputs compared to the lab tests, but the understanding of weather effects on the system will allow a PV-DG designer where to best construct this system.

Sustainability:

Use of Photovoltaic systems have average lifetimes of about 20-25 years. This means that maintenance of the material is low and costs for replacement are only periodical.

Environmental:

Photovoltaic systems have a very small carbon footprint and would help reduce generation in power plants that use fossil fuels which puts less pollutants in the air. The downside is their necessity for space, which leaves them with large amounts of land area being needed for large scale plants.

Ethical, health, and safety:

Similar to the environmental, less pollutants are and greenhouse gases are introduced to the atmosphere and the quality of air is protected better. Solar panels do not require a lot of maintenance, and don't need much human interaction for any accidents to occur. Additionally, solar panels can be used to create an energy infrastructure in parts of the world that are remote, enabling distant populations access to electricity.

Social:

Solar Power and any other renewable energy is looked upon in a positive light in the public so there won't be much resistance against its implementation. If, however, the facility is within the range of public areas, the community may not want it in plain view.

Political:

Government incentives for programs that support the implementation of this system would help to push the idea behind the study and increase motivation and productivity to further research in it.

Standards and Regulations

- Standard for Interconnecting Distributed Resources with Electric Power Systems, IEEE Standard 1547, October 2003

- Standard for Conformance Tests Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems, IEEE Standard 1547.1, 2005

- Application Guide for IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems, IEEE Standard 1547.2, 2008

- Guide For Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems, IEEE Standard 1547.3, 2007

- Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems, IEEE Standards 1547.4, 2011

- Recommended Practice For Interconnecting Distributed Resources With Electric Power Systems Distribution Secondary Networks, IEEE Standards 1547.6 , September 2011

Appendix B: Resumes

Please see attached.

Appendix C: Solar Panel Output Power Test Procedure

Solar Panel Output Power (SPOP) Testing Lab Manual

Purpose:

Acquire solar power output data from the 1.6kW set of PV Panels currently situated on the roof of Drexel's Main Building.

Equipment:

24V Lead Acid/Lithium Ion Inverter System
24V Lithium Ion Battery equipped with Battery Management System (BMS)
1.6 kW Solar Panel

Overview

This test will directly relay the output power of the PV Panels as measured by the BMS located in the Lithium Ion battery bank, in the Drexel Power Lab. For reference, the total area of the PV Panels is 11.9 m^2 and has a rated efficiency is 18%.

The PV Panels outputs 72VDC while the Battery operates at 24VDC. The load will be operated at 120VAC. The process begins at the PV Panels, where a Buck Converter steps down the 72VDC input to 24 VDC at 97% efficiency. The 24VDC input will pass current into a bus that will charge up the connected battery bank and move on to the Inverter System to change 24VDC into 120 VAC and follow the connection to the attached load in the system.

Low loads will not need all the available current in the system and thus that current will be diverted to charging the battery bank. Excessive loads will require more current than the generated amount from the PV Panels and thus the BMS will turn on the battery to discharge and supply the necessary current.

Basic power equations will be utilized such as:

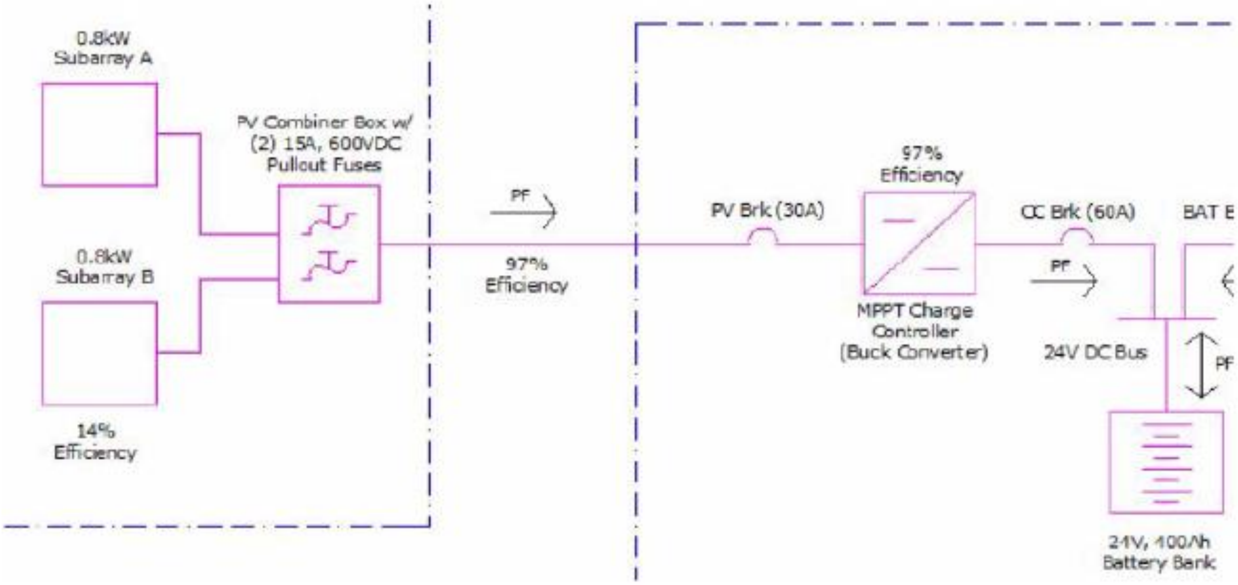
$$\text{Irradiance (W/m\^{}2)} = P\ (W) / (A\ (m^2) * \text{Efficiency})$$

$$P = I\ V = Wh / t\ (h)$$

$$E = Wh = Ah * V$$

$$Ah = I\ (A) * t\ (h)$$

Lab Setup/ One Line Diagram:



Battery Setup:

1. Open 20A CHG Breaker
2. Open 60 A CC Breaker
3. Open 175A Battery Breaker
4. Disconnect 24 V Lead Acid Battery (if connected)
5. Connect 24V Lithium Ion Battery
6. Turn on 24 V Lithium Ion Battery BMS (located on midsection of battery)
7. Close 175A Battery Breaker
8. Close 60CC Breaker

BMS Setup:

1. Connect RS232 Port to USB Connector to Computer/Laptop
2. Load Tera Term program on Computer/Laptop
3. Select Serial Port Connection for Tera Term
4. Press enter to load BMS GUI
5. View graphical or numerical depiction of Battery status Screen

Solar Setup:

1. Close 30A PV Breaker

*Note: Leave the Load center breakers open throughout the testing in order to only receive Solar Data.

Data Acquisition:

1. Allow system to run as described above for as long as data acquisition is desired (Note: Compare time of BMS to real time and record for future calculations and data offsetting. BMS records samples every 5-6 seconds)
2. Monitor battery voltage throughout. If battery voltage rises too high, or falls too low, the BMS will trip and shutdown the system

3. Computer not required to acquire the data, but will make monitoring while testing much easier.
4. (Optional) (If Battery State of Charge (SOC) is above 90%) Connect the Solar Panel Output Leads on the Main Transfer Panel to any station in the Power Lab and connect an available Light Bank and turn on the necessary bulbs (for reference, 1 bulb is 200Ω, and are connected in parallel operating at 120 VAC) that will draw current away from charging the battery. Record how many bulbs are turned on and calculate the Load Wattage that you are subtracting from the system. (This will be used to add back into the system for calculations afterwards)

<u>System Shutdown</u>:

1. Open 30A PV Breaker
2. Open 60A CC Breaker
3. Open 175A Battery Breaker
4. Shut down 24V Lithium Ion Battery BMS
5. Disconnect 24V Lithium Ion Battery from inverter setup

<u>Data Extraction</u>:

1. Remove SD card from Lithium Ion Battery BMS
2. Insert SD Card Into Computer/Laptop
3. Download .txt file to the Computer/Laptop
4. Columns in the .txt file are as follows:

Col1:DateTime

Col2-8:CellV1-V7

Col9:CellVn (mV)

Col10:PackV (mV)

Col11:AvgCellV (mV)

Col12-18:CellT1

Col19: CellTn

Col20: Balancing info

Col21: AmbientT

Col22: Avg.Battery.Current (A)

Col23: Peak.Battery.Current (A)

Col24: Instantaneous.Battery.Current

Col25: SOC

Col26: Ah remaining

Col27: Ah discharged

Col28: Ah charged

Col29: Total lifetime Ah

Col30: discharge limit in Amps

Col31:Charge limit in Amps

Col32: Regen limit in Amps

Col33:Leakage in ohms/volt
Co34: Load sw state
Col35: Charge on State
Col36:Contactor state
Col37:Charger control state
Col38:Faults for each string
Col39:Faults for Supervisor

Deliverable:

1. Using the data from the .txt file open in an Excel file and extract Columns 1, 9,22,24 and 26-28.
2. Find the appropriate date and time period from recorded time period (Remember time offset)
3. Change time data to correct time sampling points, spread by 5 seconds and copy down to end of sampling period (Note: Excel time sample setting will be under actual sampling time from inability to trend 5 or 6 second sampling rate of BMS)
4. Change Voltage data from mV to V.
5. Calculate instantaneous Power and Average Power from Solar by using the voltage and current data + PLoad (if light bank connection was used).
6. Plot time of day vs. Psolar(instantaneous, average)

Appendix D: Load Profile

Load Profile

General calculations for the loads and their bulb settings are performed by taking the tested resistance per bulb at 200 Ω [X]. The resistive load light bank is known to be connected in parallel per bulb. Thus the equation to find equivalent resistance

$$R_{total} = (\Sigma(1/R_1 + 1/R_2 + \dots + 1/R_n))^{-1}$$

Is utilized and an equivalent resistance according to the bulb arrangements that are allowed by RDAC are compared and used to simulate a cluster of loads being on together in the bus or room which they are simulated to be in. Table 1 below is the equivalent load bulb arrangement. Because there will be plug in loads that will be used too, the nameplate data from the load was recorded and are placed in Table 2 below. To factor in power losses, $P_{loss} = I^2 * R_{cable}$, the cable measured cable resistance is factored in and included in the Power demand totals. Note: Nominal Voltage operation is at 120VAC.

Table 7: Load Bulb Arrangement Legend

Bulb Legend	R (Ω)	Wattage
(5 parallel) parallel to (5 parallel)	20.0	720
(4 parallel) parallel to (5 parallel)	22.2	648
(4 parallel) parallel to (4 parallel)	25.0	576
(3 parallel) parallel to (4 parallel)	28.6	504
(3 parallel) parallel to (3 parallel)	33.3	432
5 parallel	40.0	360
4 parallel	50.0	288
3 parallel	66.7	216
2 parallel	100	144
1 bulb	200	72

Table 8: Nameplates of Removable Loads

Nameplates	Input (V)	Input (A)	Power (VA)	Time on (h)	Total Energy (Wh)
Laptop Charger	120.0	1.5	180	1	180.0
Phone Charger	120.0	0.3	36	0.75	27.0
Conair Mini Hair Dryer	120.0	2.50	300	0.5	150.0

Table 9: Average calculated Cable Resistance from IPSL to RDAC

Cable Resistance (Ω)
0.1815

For the single home loads, it has been planned to have the bathroom loads, such as the hair dryer, and the removable loads to have a connectable plug in socket for actual appliances specified for use. The removable loads will be connected to Bus B3 for the bathroom and bus A1 for the bedroom load section. Two separate profiles have been made for simulation; A high load profile, and a low load profile. Each one will be used with a specific SOC for the BMS connected with the SPDMS that would be safe to use depending on outside weather conditions. Sunny days, will utilize the High Load profile with a battery SOC at 75%, and Cloudy Days will utilize the Low Load profile with a battery SOC at 60%. Further analysis on the estimates is provided at the end of this section. The following tables are the High load, and Low load profiles, with each room represented in a particular bus in RDAC, in observation for a full four hour time period with loads being switched per 15 minutes. Total demand and a load curves are provided. Note: Current values calculations are made based on nominal voltage rating stated earlier.

Table 10, 11, 12, and 13: Bus Loads Schedule for High Load Profile Curve

time (mins)	Bathroom Loads (BUS B3)				
	Bulb Config Connection @ 1-I+1-II (RED)	Equivalent Household Load	Removable Load	Power (W)	Current (A)
10:00	1 bulb	ceiling light(2 on)	Hair Dryer	372	3.10
10:15	1 bulb	ceiling light(2 on)	Hair Dryer	372	3.10
10:30	None	None	None	0	0
10:45	(3 Bulb) parallel to (3 Bulb)	ceiling light(2 on), clothes washer	None	432	3.60
11:00	(3 Bulb) parallel to (3 Bulb)	clothes washer	None	432	3.60
11:15	None	None	None	0	0
11:30	None	None	None	0	0
11:45	None	None	None	0	0
12:00	None	None	None	0	0
12:15	None	None	None	0	0
12:30	None	None	None	0	0
12:45	(3 Bulb) parallel to (3 Bulb)	clothes washer	None	432	3.60
13:00	(3 Bulb) parallel to (3 Bulb)	clothes washer	None	432	3.60
13:15	(3 Bulb) parallel to (3 Bulb)	clothes washer	None	432	3.60
13:30	None	None	None	0	0
13:45	None	None	None	0	0
14:00	None	None	None	0	0
14:15	None	None	None	0	0

time (mins)	Kitchen Loads (BUS A3)				
	Bulb Config Connection @ 2-I+2-II (RED)	Equivalent Household Load	Removable Load	Power (W)	Current (A)
10:00	None	None	None	0	0
10:15	None	None	None	0	0
10:30	(5 Bulb) parallel to (5 Bulb)	refrigerator condenser on	None	720	6.00
10:45	None	None	None	0	0
11:00	None	None	None	0	0
11:15	(5 Bulb) parallel to (5 Bulb)	microwave	None	720	6.00
11:30	(5 Bulb) parallel to (5 Bulb)	refrigerator condenser on	None	720	6.00
11:45	None	None	None	0	0
12:00	None	None	None	0	0
12:15	None	None	None	0	0
12:30	(5 Bulb) parallel to (5 Bulb)	refrigerator condenser on	None	720	6.00
12:45	None	None	None	0	0
13:00	None	None	None	0	0
13:15	None	None	None	0	0
13:30	(5 Bulb) parallel to (5 Bulb)	refrigerator condenser on	None	720	6.00
13:45	None	None	None	0	0
14:00	None	None	None	0	0
14:15	None	None	None	0	0

time (mins)	Living Room Loads (BUS A1)				
	Bulb Config Connection @ 2-I+2-II (Blue)	Equivalent Household Load	Removable Load	Power (W)	Current (A)
10:00	None	None	None	0	0
10:15	None	None	None	0	0
10:30	None	None	None	0	0
10:45	None	None	None	0	0
11:00	None	None	laptop	180	0
11:15	1 bulb	Floor Lamp (3)	laptop	252	0
11:30	1bulb	Floor Lamp (3)	laptop	252	0
11:45	(5 Bulb) parallel to (5 Bulb)	ceiling fan, floor lamp(4 light on), TV, Stereo	None	720	6.00
12:00	(5 Bulb) parallel to (5 Bulb)	ceiling fan, floor lamp(4 light on), TV, Stereo	None	720	6.00
12:15	(5 Bulb) parallel to (5 Bulb)	ceiling fan, floor lamp(4 light on), TV, Stereo	None	720	6.00
12:30	2 bulb	ceiling fan	laptop	144	1.20
12:45	None	None	None	0	0
13:00	None	None	None	0	0
13:15	None	None	None	0	0
13:30	None	None	None	0	0
13:45	None	None	None	0	0
14:00	None	None	None	0	0
14:15	None	None	None	0	0

time (mins)	Bedroom Loads (BUS B1)				
	Bulb Config Connection @ 3-I+3-II (Red)	Equivalent Household Load	Removable Load	Power (W)	Current (A)
10:00	None	None	None	0	0
10:15	None	None	None	0	0
10:30	None	None	None	0	0
10:45	4	CPU open, Monitor on, phone charger	None	288	2.4
11:00	4	CPU open, Monitor on, phone charger	None	288	2.4
11:15	None	None	None	0	0
11:30	None	None	None	0	0
11:45	None	None	None	0	0
12:00	None	None	None	0	0
12:15	None	None	None	0	0
12:30	None	None	None	0	0
12:45	(3 Bulb) parallel to (3 Bulb)	CPU open, Monitor on, laptop	None	432	3.6
13:00	(3 Bulb) parallel to (3 Bulb)	CPU open, Monitor on, laptop	None	432	3.6
13:15	4 bulb	CPU open, Monitor on	None	288	2.4
13:30	4 bulb	CPU open, Monitor on	None	288	2.4
13:45	(3 Bulb) parallel to (4 Bulb)	CPU open, Monitor on, laptop, phone	None	504	4.2
14:00	(3 Bulb) parallel to (4 Bulb)	CPU open, Monitor on, laptop, phone	None	504	4.2
14:15	(3 Bulb) parallel to (4 Bulb)	CPU open, Monitor on, laptop, phone	None	504	4.2

time (mins)	Demand (W)	current draw (A)	power losses (W)	total power (W)
10:00-10:15	372	3.10	1.69	373.7
10:15-10:30	372	3.10	1.69	373.7
10:30-10:45	720	6.00	6.34	726.3
10:45-11:00	720	6.00	6.34	726.3
11:00-11:15	900	7.50	9.90	909.9
11:15-11:30	972	8.10	11.55	983.5
11:30-11:45	972	8.10	11.55	983.5
11:45-12:00	720	6.00	6.34	726.3
12:00-12:15	720	6.00	6.34	726.3
12:15-12:30	720	6.00	6.34	726.3
12:30-12:45	864	7.20	9.12	873.1
12:45--13:00	864	7.20	9.12	873.1
13:00-13:15	864	7.20	9.12	873.1
13:15-13:30	720	6.00	6.34	726.3
13:30-13:45	1008	8.40	12.42	1020.4
13:45-14:00	504	4.20	3.10	507.1
14:00-14:15	504	4.20	3.10	507.1
14:15-14:30	504	4.20	3.10	507.1

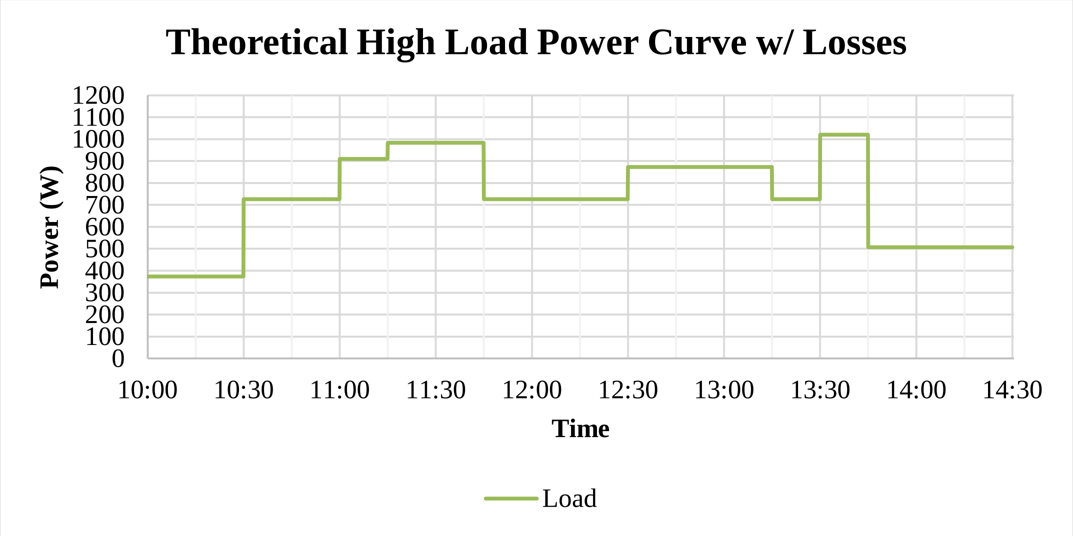
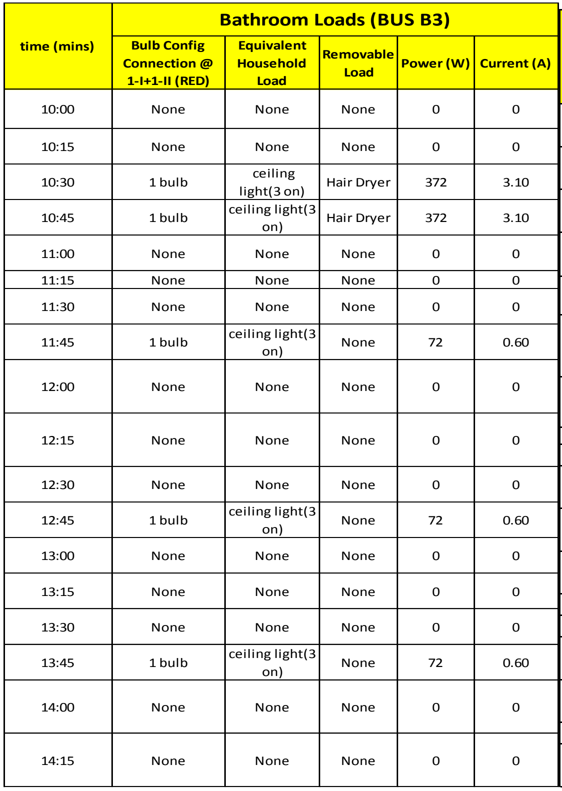


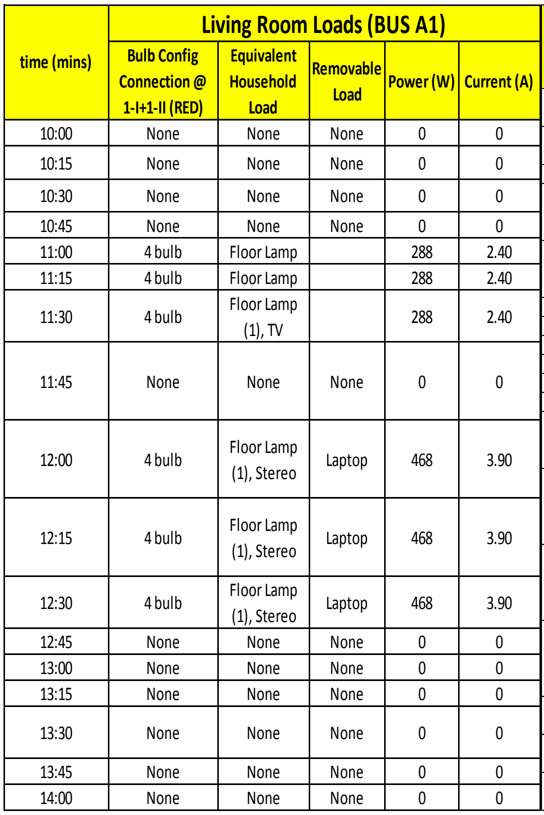
Figure 13: Large Load Curve Profile Theoretical

Table 14, 15, 16, and 17: Bus Loads Schedule for Low Load Profile Curve

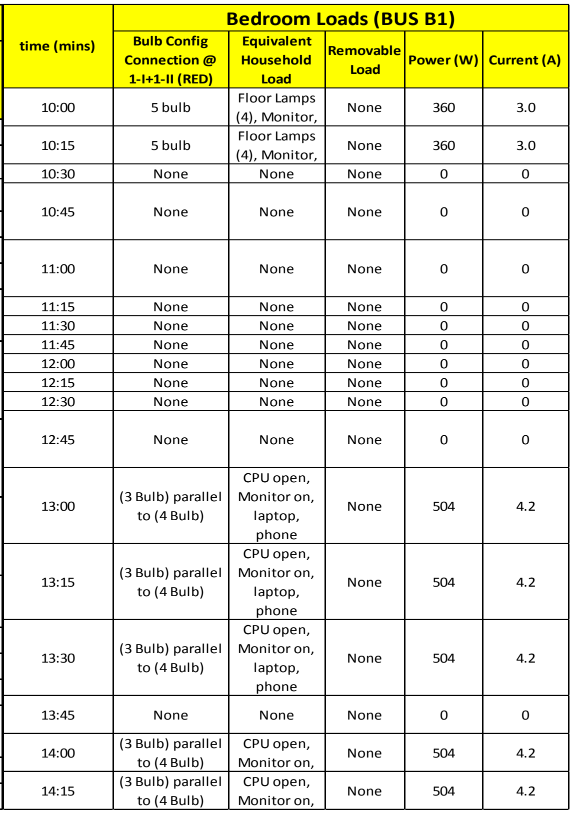


time (mins)	Bathroom Loads (BUS B3)				
	Bulb Config Connection @ 1-I+1-II (RED)	Equivalent Household Load	Removable Load	Power (W)	Current (A)
10:00	None	None	None	0	0
10:15	None	None	None	0	0
10:30	1 bulb	ceiling light(3 on)	Hair Dryer	372	3.10
10:45	1 bulb	ceiling light(3 on)	Hair Dryer	372	3.10
11:00	None	None	None	0	0
11:15	None	None	None	0	0
11:30	None	None	None	0	0
11:45	1 bulb	ceiling light(3 on)	None	72	0.60
12:00	None	None	None	0	0
12:15	None	None	None	0	0
12:30	None	None	None	0	0
12:45	1 bulb	ceiling light(3 on)	None	72	0.60
13:00	None	None	None	0	0
13:15	None	None	None	0	0
13:30	None	None	None	0	0
13:45	1 bulb	ceiling light(3 on)	None	72	0.60
14:00	None	None	None	0	0
14:15	None	None	None	0	0

time (mins)	Kitchen Loads (BUS A3)				
	Bulb Config Connection @ 1-I+1-II (RED)	Equivalent Household Load	Removable Load	Power (W)	Current (A)
10:00	None	None	None	0	0
10:15	None	None	None	0	0
10:30	None	None	None	0	0
10:45	(5 Bulb) parallel to (5 Bulb)	refrigerator condenser on	None	720	6.00
11:00	None	None	None	0	0
11:15	None	None	None	0	0
11:30	None	None	None	0	0
11:45	(5 Bulb) parallel	refrigerator	None	720	6.00
12:00	None	None	None	0	0
12:15	None	None	None	0	0
12:30	None	None	None	0	0
12:45	(5 Bulb) parallel to (5 Bulb)	refrigerator condenser on	None	720	6.00
13:00	None	None	None	0	0
13:15	None	None	None	0	0
13:30	None	None	None	0	0
13:45	(5 Bulb) parallel to (5 Bulb)	refrigerator condenser on	None	720	6.00
14:00	None	None	None	0	0
14:15	None	None	None	0	0



time (mins)	Living Room Loads (BUS A1)				
	Bulb Config Connection @ 1-I+1-II (RED)	Equivalent Household Load	Removable Load	Power (W)	Current (A)
10:00	None	None	None	0	0
10:15	None	None	None	0	0
10:30	None	None	None	0	0
10:45	None	None	None	0	0
11:00	4 bulb	Floor Lamp		288	2.40
11:15	4 bulb	Floor Lamp		288	2.40
11:30	4 bulb	Floor Lamp (1), TV		288	2.40
11:45	None	None	None	0	0
12:00	4 bulb	Floor Lamp (1), Stereo	Laptop	468	3.90
12:15	4 bulb	Floor Lamp (1), Stereo	Laptop	468	3.90
12:30	4 bulb	Floor Lamp (1), Stereo	Laptop	468	3.90
12:45	None	None	None	0	0
13:00	None	None	None	0	0
13:15	None	None	None	0	0
13:30	None	None	None	0	0
13:45	None	None	None	0	0
14:00	None	None	None	0	0



time (mins)	Bedroom Loads (BUS B1)				
	Bulb Config Connection @ 1-I+1-II (RED)	Equivalent Household Load	Removable Load	Power (W)	Current (A)
10:00	5 bulb	Floor Lamps (4), Monitor,	None	360	3.0
10:15	5 bulb	Floor Lamps (4), Monitor,	None	360	3.0
10:30	None	None	None	0	0
10:45	None	None	None	0	0
11:00	None	None	None	0	0
11:15	None	None	None	0	0
11:30	None	None	None	0	0
11:45	None	None	None	0	0
12:00	None	None	None	0	0
12:15	None	None	None	0	0
12:30	None	None	None	0	0
12:45	None	None	None	0	0
13:00	(3 Bulb) parallel to (4 Bulb)	CPU open, Monitor on, laptop, phone	None	504	4.2
13:15	(3 Bulb) parallel to (4 Bulb)	CPU open, Monitor on, laptop, phone	None	504	4.2
13:30	(3 Bulb) parallel to (4 Bulb)	CPU open, Monitor on, laptop, phone	None	504	4.2
13:45	None	None	None	0	0
14:00	(3 Bulb) parallel to (4 Bulb)	CPU open, Monitor on,	None	504	4.2
14:15	(3 Bulb) parallel to (4 Bulb)	CPU open, Monitor on,	None	504	4.2

time (mins)	Load usage (W)	Total Current (A)	Power Losses (W)	Total Power (W)
10:00	360	3.0	1.58	361.6
10:15	360	3.0	1.58	361.6
10:30	372	3.1	1.69	373.7
10:45	1092	9.1	14.57	1106.6
11:00	288	2.4	1.01	289.0
11:15	288	2.4	1.01	289.0
11:30	288	2.4	1.01	289.0
11:45	792	6.6	7.67	799.7
12:00	468	3.9	2.68	470.7
12:15	468	3.9	2.68	470.7
12:30	468	3.9	2.68	470.7
12:45	792	6.6	7.67	799.7
13:00	504	4.2	3.10	507.1
13:15	504	4.2	3.10	507.1
13:30	504	4.2	3.10	507.1
13:45	792	6.6	7.67	799.7
14:00	504	4.2	3.10	507.1
14:15	504	4.2	3.10	507.1

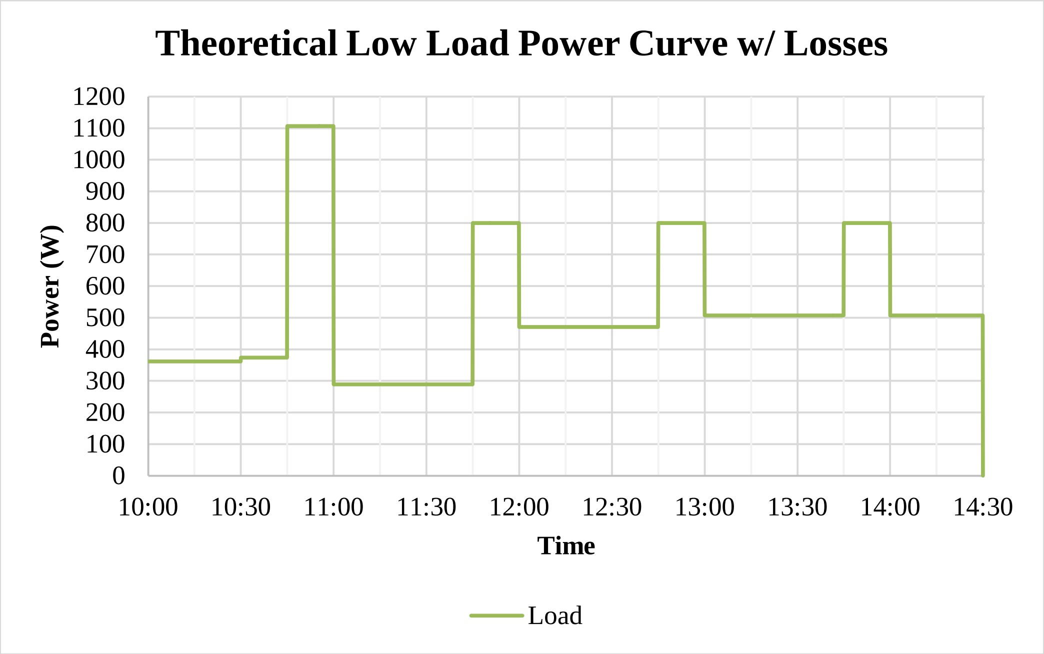


Figure 14: Low Load Curve Profile Theoretical

For the calculation of the Amp-hours, or charge, that will be required for each interval, it is based on the following formulas

E_load(Wh) = P_load (W) *(t/60)h

Where *t* is 15 minutes from the set intervals because the load settings change after this much time.

Charge (Ah) = E_load (Wh) / V_battery (V)

Where V, is the operating voltage of the battery at 24V. An example computation for a whole hour is provided

@ 10:00am P_load = 372 W, P_losses = 1.69 W, t = 0.25 h, V = 24 V

E_load = 373.69 *.25 = 93.42284 Wh

Ah_load = 93.42284 Wh / 24V = 3.89 Ah

@10:15am P_load = 372 W, P_losses = 1.69 W, t = 0.25 h, V = 24 V

E_load = 373.69 *.25 = 93.42284 Wh

Ah_load = 93.42284 Wh / 24V = 3.89 Ah

@10:30am P_load = 720 W, P_losses = 6.34 W, t = 0.25 h, V = 24 V

E_load = 726.3 *.25 = 181.575 Wh

Ah_load = 181.575 Wh / 24V = 7.57 Ah

@10:45am P_load = 720 W, P_losses = 6.34 W, t = 0.25 h, V = 24 V

E_load = 726.3 *.25 = 181.575 Wh

Ah_load = 181.575 Wh / 24V = 7.57 Ah

For 10am-11am: Ah_total = 3.89 + 3.89 + 7.57 + 7.57 = 22.92 Ah

The rest of the of the hours are calculated for the actual amount of charge that the Lithium Ion Battery may need for future tests, if solar power was not provided at each interval.

Table 18: Large Load Amp-hour and Watt-hour Use per Hour

	10am	11am	12pm	1pm	2pm	Total
Ah	22.92	37.53	33.32	32.57	10.56	136.91
Wh	550.0	900.8	799.7	781.7	253.6	3285.87

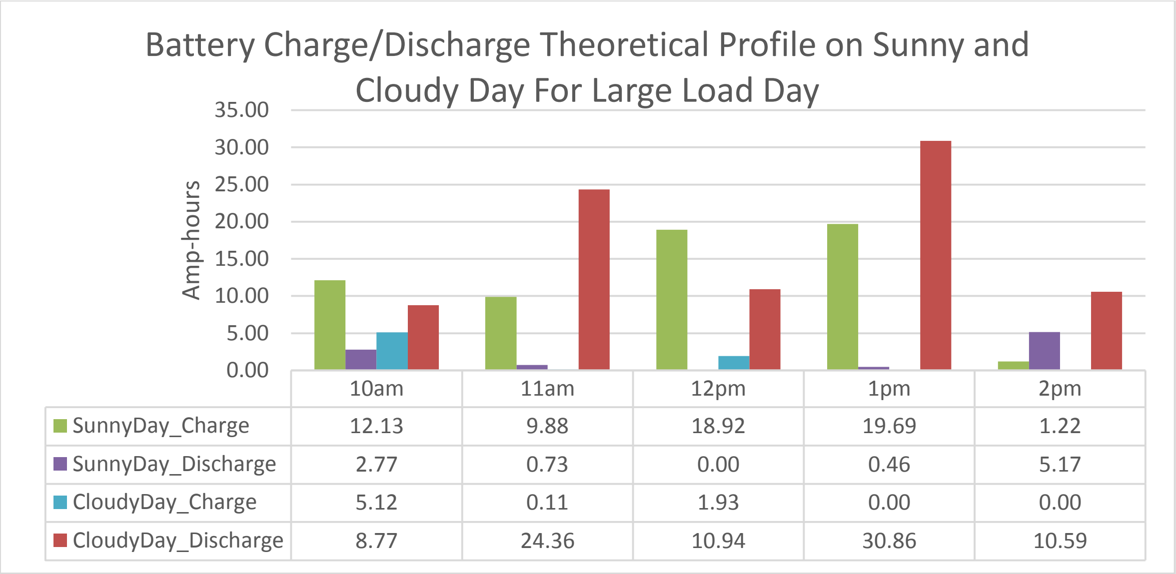
In order to calculate the charging/discharging profile that the Battery Management System may experience during either a sunny day or on a cloudy day, the data from the SPOP tests in February and April were taken and compared to the load that will be in demand by a difference in energies. Because the intervals between each sample of data is roughly 5 seconds, this will be our time, *t*, that will be multiplied to the power values to get the energy. The ΔE is then calculated from the load energy and the cloudy or sunny day data. Afterwards, the charge is calculated by dividing by the operating voltage of the battery, 24V. The charge is observed, if it is positive then it is charging the battery and if it is negative then it is discharging. Charging values are added up altogether for the time period and similar steps are taken for the discharging values.

Energy (Wh) = Power (W)*t(h), where t = 5/3600 hours

ΔE = E_Sunny – E_Load, or ΔE = E_Cloudy – E_ Load

Charge (Ah) = ΔE / V, where V = 24V.

The following data has been compiled and placed together on a chart for comparison between both load profiles.



	10am	11am	12pm	1pm	2pm
🟩 SunnyDay_Charge	12.13	9.88	18.92	19.69	1.22
🟪 SunnyDay_Discharge	2.77	0.73	0.00	0.46	5.17
🟦 CloudyDay_Charge	5.12	0.11	1.93	0.00	0.00
🟥 CloudyDay_Discharge	8.77	24.36	10.94	30.86	10.59

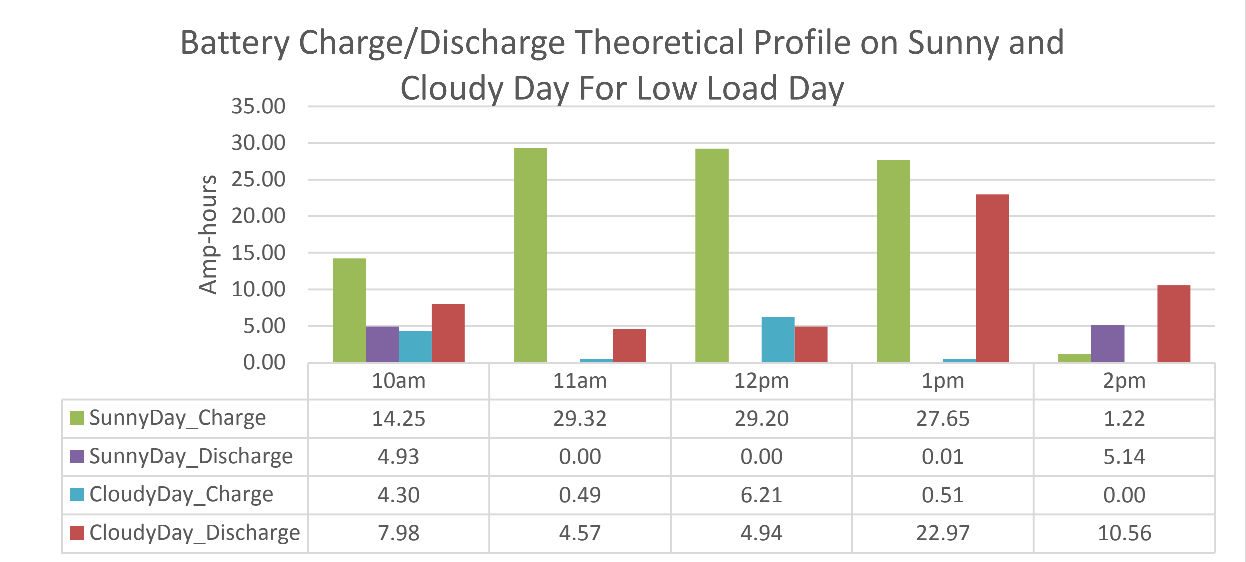
Figure 15: High Load Profile, SOC for battery set at 75%

Table 19: Total Amp-hour Charge/Discharge for Sunny and Cloudy Day Data for a Large Load Day

	Total (Ah)
SunnyDay_Charge	61.84
SunnyDay_Discharge	9.13
CloudyDay_Charge	7.16
CloudyDay_Discharge	85.53

Table 20: Low Load Amp-hour and Watt-hour Use per Hour

	10am	11am	12pm	1pm	2pm	Total
Ah	22.95	17.36	19.61	27.22	10.56	97.71
Wh	550.9	416.7	470.7	653.4	253.6	2345.15



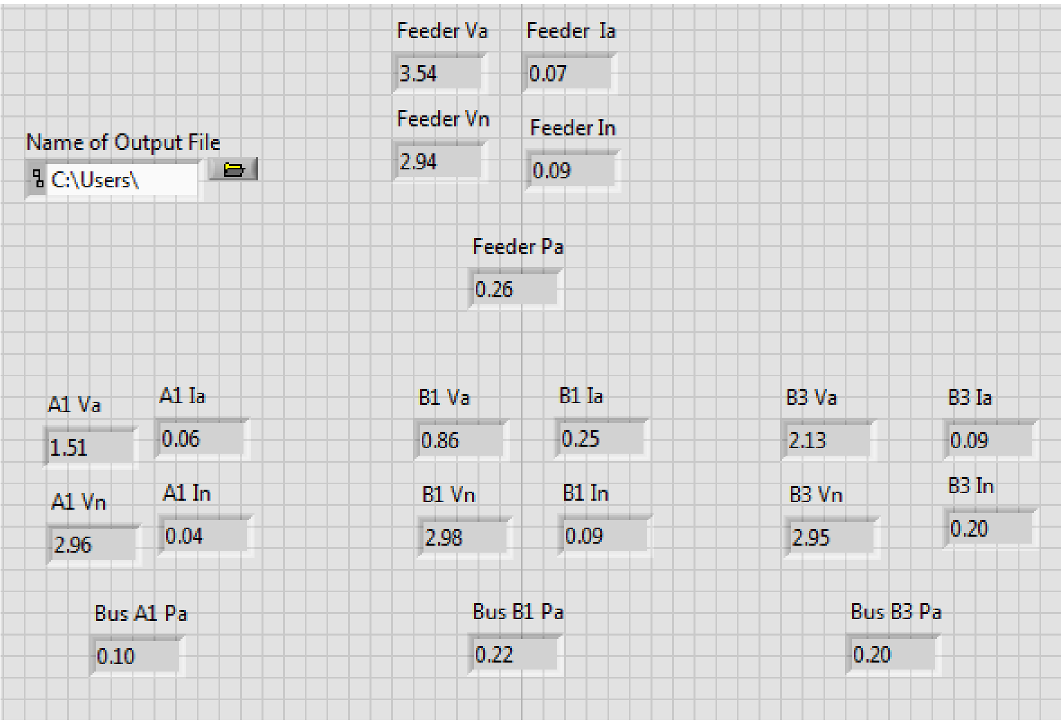
	10am	11am	12pm	1pm	2pm
🟩 SunnyDay_Charge	14.25	29.32	29.20	27.65	1.22
🟪 SunnyDay_Discharge	4.93	0.00	0.00	0.01	5.14
🟦 CloudyDay_Charge	4.30	0.49	6.21	0.51	0.00
🟥 CloudyDay_Discharge	7.98	4.57	4.94	22.97	10.56

Figure 16: Low Load Profile, SOC for battery set at 60%

Table 21: Total Amp-hour Charge/Discharge for Sunny and Cloudy Day Data for a Low Load Day

	Total (Ah)
SunnyDay_Charge	101.64
SunnyDay_Discharge	10.09
CloudyDay_Charge	11.51
CloudyDay_Discharge	51.03

Appendix E: LabVIEW Interface Screenshots



Name of Output File
C:\Users\

Feeder Va 3.54
Feeder Ia 0.07
Feeder Vn 2.94
Feeder In 0.09
Feeder Pa 0.26

A1 Va 1.51
A1 Ia 0.06
A1 Vn 2.96
A1 In 0.04
Bus A1 Pa 0.10

B1 Va 0.86
B1 Ia 0.25
B1 Vn 2.98
B1 In 0.09
Bus B1 Pa 0.22

B3 Va 2.13
B3 Ia 0.09
B3 Vn 2.95
B3 In 0.20
Bus B3 Pa 0.20

Figure 17: LabVIEW Interface Front Panel

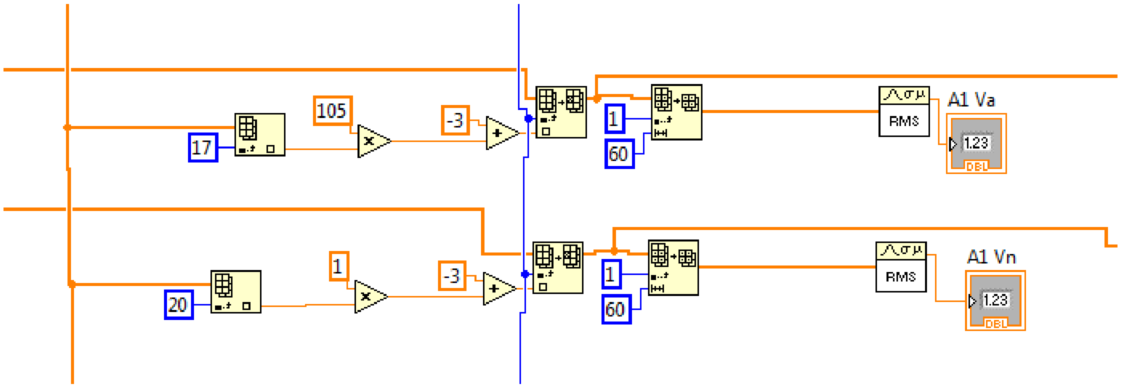


Figure 18: LabVIEW Interface V_a Voltage Block

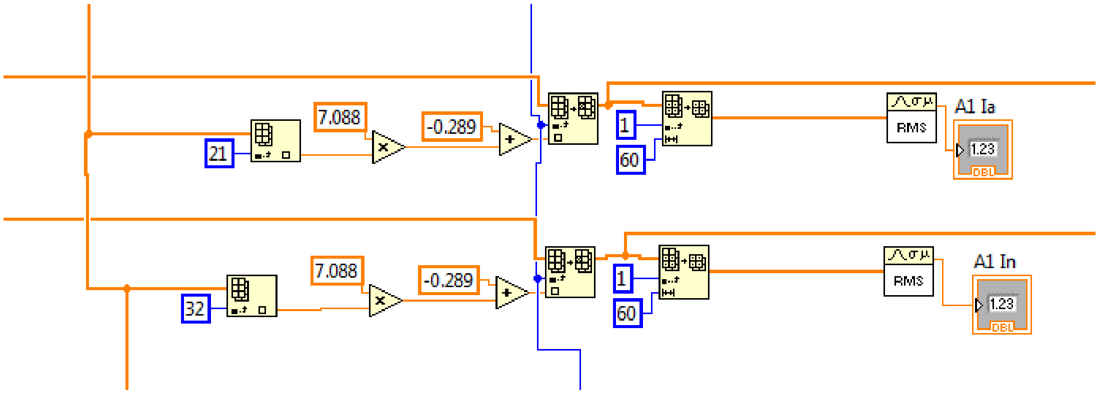


Figure 19: LabVIEW Interface I_a Current Block

Appendix F: Solar Panel Output Power Test Procedure

Single Phase Solar Powered Distribution, Single Home Model Test

Purpose:

This document describes the general procedure for setting up a solar powered distribution system that will be connected to a single home. The outlines in this procedure will direct the reader as to what connections need to be made in order to ensure that the solar energy being produced by the solar panels on the roof of the Drexel Main Building reaches the Reconfigurable Distribution and Automation Control Laboratory (RDAC) safely.

System Description and General Test Setup:

Located on the roof of the Drexel Main Building, the 1.6kW solar panel array provides Drexel students with the unique chance to test the effects of an isolated solar powered microgrid in a laboratory environment. Figure 1 shows these panels:

Figure 20: Solar Panels on Main Building

These solar panels are connected to the CEPE via an inverter and charge controller located next to the main transfer panel in IPSL. It is also at this point in the circuit that the battery will be connected to the system.

Installed in the Fall Quarter of 2014, the IPSL/RDAC Interconnection is a 4-wire cable running from the Main Transfer Panel in IPSL (Figure 21) to a dedicated connection box in RDAC (Figure 22).

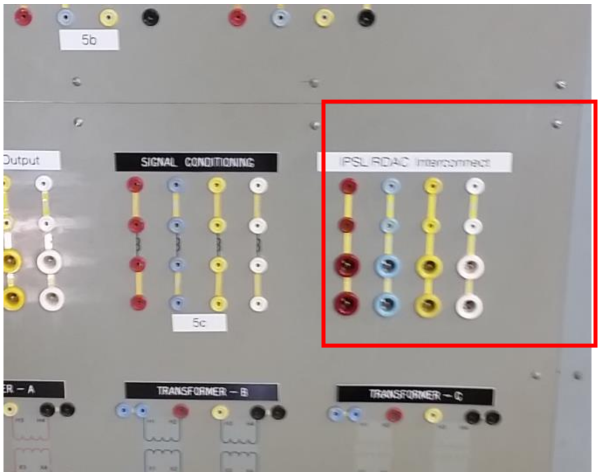


Figure 21: New connection points on the IPSL main transfer panel for the IPSL RDAC Interconnect

Figure 22: RDAC-side connections for the new IPSL RDAC Interconnect located in the back corner of RDAC

This connection can be used as a single or three phase AC link or DC link between the two laboratories. This test procedure will use a single phase AC setup in order to transfer the solar power produced by the solar panels into the RDAC to the RDAC Interconnect shown in Figure 2.

<u>Required Equipment</u>:

Computer with LabVIEW and required LabVIEW VIs installed
Actual Home Loads from Load Profile
Junction Box with Outlet Connections
Various cables as needed

Circuit Layout:

The following diagram shows the one line diagram for the entire experiment connection:

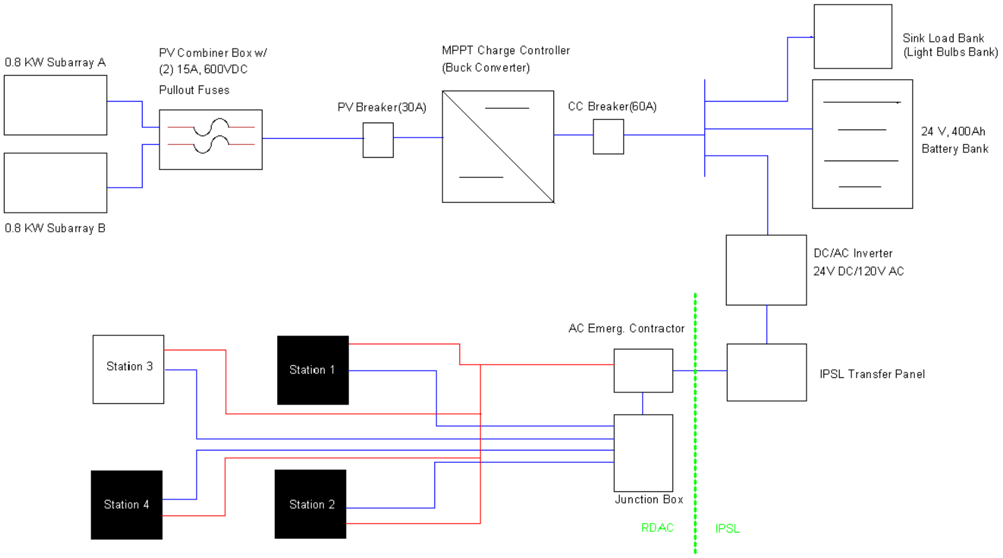


Figure 23: One Line Diagram for Single Home Load Test (Station 3 is in use)

Test Preparation:

Step 1:

Make sure the battery for the experiment is discharged at the necessary level for the experiment. (Additional calculation needed: Pbatterymax = Psolarmax – Ploadmin)

Step 2:

Connect a light bulb bank with the solar output. This step is for the case that the power goes into the battery would exceed the battery capacity. The light bulb bank is used to dump the extra power from the solar panel.

Step 3:

Set up the IPSL to RDAC connection. Use Phase A and Neutral Phase for Single phase load experiment. Connect the solar power to the Phase A and Neutral Phase on the IPSL transfer panel. In Figure 2, the Red node is for Phase A, the white node is for Neutral Phase.

Step 4:

Make sure the RDAC measurements connection is in the right position. The following table is the measurements set up:

Table 22: Measurements Card Connection Set up

Measurement Card Number	Bus Number
Measurement I	Source Bus
Measurement II	Bus A1
Measurement III	Bus B1
Measurement IV	Bus B3

Step 5:

Set up the connection between buses and light bulb banks for the experiment. Use the following table as the guide.

Table 23: Buses and Light Bulb Bank Connections.

Bus Number	Light Bulb Bank
A1	3-I(Yellow) + 3-II(Yellow)
A3	3-I(Red) + 3-II(Red)
B1	2-I(Red) + 2-II(Red)
B3	1-I + 1-II

Step 6:

1. Connect the RDAC side IPSL power with the transformer.
2. Connect the transformer with the Station and also connect the power to the Feeder Bus A and Feeder Bus B of the station.
3. Connect power from the Feeder Bus A and B to the buses that will be used during the lab. (Bus A1, A3, B1 and B3)

Test:

Step 1:

Turn on one bulb on each bank used in the experiment. (Purpose: to check the light bulb bank at the beginning of the test)

Step 2:

Close the switch on the RDAC side IPSL panel showed in Figure 2. Turn the transformer wheel to adjust the power source voltage to 120V. If each bank has one light ON successfully, turn off the bulb on each bank.

Step 3:

Sep up the light bulb bank set-up for 10:00am in the load profile. Turn on bulbs one by one, wait 1 second between each.

Step 4:

Run the LabVIEW software and make sure the software is taking measurements correctly.

Step 5:

Change the light bulb banks set-up every 15 minutes according to the load profile. (The power reading will not be exactly matched with the set power shown in the load profile due to the losses power.)

Step 6:

When the test is done, save the recorded test data for further analysis.

Concluding Activities:

1. Plot
    a) Measured Feeder Bus Voltage vs. Time.
    b) Measured Feeder Bus Current vs. Time.
    c) Measured Feeder Bus Power vs. Time.

Appendix G: WIT Reviewed Draft

The confirmation email from the Drexel Writing Center is attached. Additionally, the part of the report that was reviewed by the Drexel Writing Center is also attached.