



PROJECT REPORT 2016-2017

Team Number ECE - 18

The Effects of Distributed Energy Storage on a Power Distribution Grid

Team Members

<u>Name</u>	<u>Department</u>	<u>Email</u>
Christopher Fedor	ECE	caf92@drexel.edu
Elmer Turner	ECE	ert38@drexel.edu
Reynaldo Noel Jeune	ECE	rn363@drexel.edu
Jonathan Balsamo	ECE	jtb97@drexel.edu

Team Advisor(s)

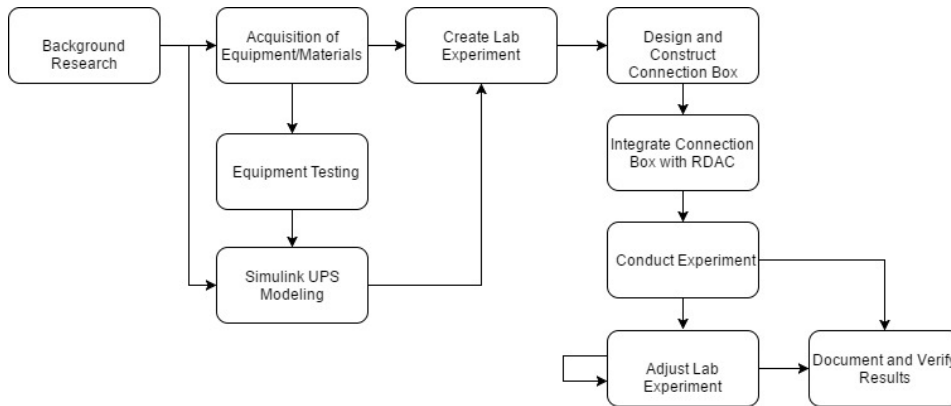
<u>Name</u>	<u>Department/Company</u>	<u>Email</u>
Dr. Karen Miu	ECE	karen.miu@drexel.edu

Group Leader's Signature : _____

Advisor's Signature : _____

1. Management Summary

With the interconnection of more distributed energy resources (DERs) into the power distribution grid, there are some technical issues that can arise from having multiple devices interconnected. Some issues that can potentially arise include over voltage problems, power quality concerns, and reverse power flow through sensitive equipment. In particular, this group is going to look at the connection of multiple battery energy storage systems (BESS) to a power distribution grid. First, the team will model a single BESS in Simulink and connect it to model of the Reconfigurable Distribution Automation and Control (RDAC) laboratory to see the effects caused by the BESS in a software environment. Then, the team will design a way to safely connect a UPS, which will be used as a hardware model of a BESS, to the RDAC laboratory and examine the results of this hardware testing.



For the results of this project, the team was able to successfully model a BESS in Simulink and study the results of having multiple BESS connected to a power distribution system. We noticed an increase in voltage magnitudes near where the BESS was connected and also noticed a increase in the neutral current of the system caused by the imbalance of the systems. For the hardware side, the team was able to successfully measure many key aspects of the UPS as well use a single UPS to power the RDAC laboratory. However, the team was not able to use both the UPS and Utility source at the same time because both phase and frequency control with the Utility source was not possible with the UPS.

Major Contributions to the Project:

- BESS Simulink model connected to the RDAC model
- Simulation results of multiple BESS connected to a power distribution system
- Update the existing Energy Management Software (EMS) in LabView to show the connection locations of the UPS
- Designed and tested procedures to measure key aspects of a UPS
- Designed, built, and tested a safe way to interconnect a UPS to the RDAC laboratory
- Designed and tested an Emergency Restoration plan using UPS

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2. Background

In recent years, distributed energy resources (DERs) such as battery storage and solar panels are becoming more integrated into power distribution grids because of improved cost/benefit ratios for customers. This relatively new paradigm in the electric power industry is gaining popularity because DERs are now easy to install and make the customers less dependent of the power from the grid [1]. Additionally, DERs help reduce harmful greenhouse gases that could potentially damage the environment since the majority of installed DERs are from renewable energy. Also, the chargers for plug in electric vehicles are typically unidirectional chargers, but in the future, the use and implementation of chargers that can consume power from the grid and deliver it back to the grid, will allow vehicle to grid interaction to happen [2]. Overall, DERs have the potential to make the grid more reliable.

This growing addition of DERs however comes with some challenges. Deploying DERs in a widespread, efficient, and cost effective manner requires complex integration with the existing electrical grid. Careful studies and research have been conducted recently, with no widely known solution, to determine the important problems arising from these new technologies. Some of these issues include the accurate modeling of DERs, the impact on power quality, the impact on reliability, and interconnection standards. Utilities are now facing these issues which add complexity in keeping their system balanced and stable. The variability of those resources has an impact on system operations, including voltage, current, frequency, and in general power quality. Institutions like the Electric Power Research Institute (EPRI) are already addressing these challenges by assessing feeder impacts; they are also developing strategies for future business impacts [2].

3. Problem Statement

Once DERs can be successfully integrated into the grid, a profusion of cleaner energy options can be deployed throughout the electrical grid as well. However, the growing usage of DERs comes with some challenges. Deploying DERs in a widespread, efficient, and cost-effective manner requires complex integration with the existing electrical grid. Careful studies and research have been conducted recently, with no widely known solution, to determine the important problems arising from these new technologies. Some of these issues include the accurate modeling of DERs, the impact on power quality, the impact on reliability, and interconnection standards.

Utilities are now facing these issues which add complexity in keeping their system balanced and stable. Some utilities will not permit their customers to use photovoltaic panels in areas in extreme cases when there is a high enough saturation of DERs in a particular area. The variability of those resources has an impact on system operations, including voltage, current, frequency, and in general power quality. Institutions like the Electric Power Research Institute (EPRI) are already addressing these challenges by assessing feeder impacts; they are also developing strategies for future business impacts [2].

In order to continually study the impacts of DERs on a electrical grid, both software modeling and hardware emulation systems are required. This project development will utilize both of these emulation methods to further study these effects. By using an Uninterruptible Power Supply (UPS), this project will focus specifically on the interconnection of battery energy storage systems (BESS) to an electrical distribution system.

4. Existing and Proposed Solution

The main reason our team decided to take on this problem of connecting multiple BESS to a power distribution system is because there is very little information known about their effects on a three phase distribution system. With the technology of Bi-Directional charging coming to electric vehicles, research into the effects that these chargers as well as multiple BESS onto a single distribution system is very valuable as the team will be able to see the effects these systems have as well as any problems that may arise. From our team's research and experimentation, we hope to have a better understanding of how these systems operate and any potential problems that may arise from connecting multiple BESS into a power distribution system.

These challenges give the opportunity for our team to study the effects of BESS connecting onto a power distribution grid. By emulating a power distribution grid in software and hardware, our team will analyze and document the impacts of multiple BESS in a system. In software, our team will create a working model of a BESS and connect that model into a model of the Reconfigurable Distribution Automation and Control (RDAC) laboratory using Simulink. Then for a hardware experiment, our team will connect an Uninterruptible Power Supply (UPS), which we will use to mimic a BESS, to the RDAC laboratory. Our team wants to study the effects of connecting these BESS to a power distribution system in both a software and hardware platform. Our team will then design a repeatable laboratory experiment for future ECE power students to learn more about these devices through experimentation.

The deliverables for the successful completion of this project will be as followed:

- A working Simulink model composed of one RDAC station with multiple UPS connected.
- Statistical analysis of the optimal configuration for the Simulink model with regards to power quality and system stability.
- A repeatable software laboratory experiment where DERs impacts can be studied.
- A connection box that will safely connect multiple UPS to the RDAC station.
- LabVIEW interface modules that represent UPS (batteries), loads and capacitors being attached to the RDAC station, and also a sub-visual interface of the Distribution Energy Management Software (DEMS) that show the voltage, current and power waveforms at the measurement points.
- A laboratory manual procedure for testing the properties of a UPS including input/output voltage and current
- A repeatable hardware laboratory experiment where multiple UPS can be connected to an RDAC station and the effects on a power distribution grid can be measured.

5. Justification for Solution Methodology

For the software simulation portion of this project, our team decided to use MATLAB's Simulink simulation software to create a model of a BESS. Simulink was chosen as the simulation software because of its continuous power flow solver that allows us to easily analyze the effects of a BESS onto a power distribution grid as well as its usability and availability to us. Also, all of the existing software simulations for the RDAC laboratory use Simulink, so the software laboratory that is being designed will easily line up with the existing software laboratory experiments.

For the hardware experimentation, our team decided to use a commercially available uninterruptible power supply (UPS) to mimic a BESS. A UPS was chosen because it is a self-contained battery, charger, and inverter which comprises the main aspects of a BESS. One shortfall our group may run into is that a UPS is not intended to be used in this fashion although we believe it will work for our purposes.

6. Major Technical Steps

6.1 Background Research

6.1.1 UPS Research

The UPS is the device that was decided on by the group to mimic a BESS and in order to use it in testing, research was performed to decide which types of UPS would be the best to study. The first UPS type that is being studied is the Standby UPS. A standby uninterruptible power supply when powered, takes the input power and use it to feed the load on the output end of the supply while simultaneously always charging the battery [3]. A transfer switch is able to detects loss of power. if this occurs the switch engages an inverter connected to the recharge battery. The load is then supplied by battery power. A circuit diagram for the topology of the Standby UPS can be found in Figure 10.

The second type of UPS selected is the Line-Interactive UPS, which operates slightly differently than the Standby UPS. Unlike in the Standby UPS, The inverter is always connected to the battery and to the load in a Line-Interactive UPS [3]. When the input power fails in a Line-Interactive UPS, the transfer switch opens and the power flows from the battery to the UPS output. Figure 11 shows the circuit topology for a Line-Interactive UPS.

6.1.2 Electrical Vehicle Research

Electric vehicles (EV) have been growing in popularity and as the power infrastructure improves to be able to support more EV saturation, they will continue to be manufactured and used. Interestingly enough, these EV charging stations provide some general system knowledge of incorporating DERs into the distribution grid. One extremely relevant application of EVs is using the charge from their battery to deliver power to the grid, which is also referred to as vehicle-to-grid (V2G) [4]. The concept of using electrical vehicles as DERs has been very useful in gaining a broader perspective of different applications of DERs in the distribution grid.

6.1.3 Standards Research

As part of the background research, any relevant standards and safety procedures needed to be identified and strictly followed. When conducting any kind of hardware testing it is very important to follow the safety guidelines developed by the Center for Electrical Power Engineering (CEPE). There are standards regarding the parts used in the experiment along with their interconnection that need to be adhered to which can be described in more detail in section 10 (Standards) of this report.

6.2 Simulink Modeling

When designing the software model for this project, there are two main objectives that need to be met: The UPS model that is being created needs to be able to work independently from the Simulink RDAC model and the UPS model needs to be able to work when integrated into the Simulink RDAC model. Independence is required to be able to confirm that the UPS

model is working correctly. Once an acceptable model has been created, it will then need to be integrated into the RDAC model. Once this occurs, further testing can be conducted into best integration techniques of the UPS into distribution system so it can be integrated in a functional, energy-efficient and safely in a physical setting.

6.3 LabVIEW Development

The Distributed Energy Management Software (DEMS) that was provided to us from the senior design team from 2015-2016 has some core features; however, there are additional tasks that we need the EMS to perform for our project. The 2015-2016 DEMS interface of the RDAC Laboratory as shown in Figure 1 does not provide a clear indication of where loads, batteries or capacitors are attached in the RDAC laboratory station.

Over the winter and spring terms, our group has included multiple selection functionalities as shown in Figure 2. The user can select at which of the eight system buses and at which of the three phases electrical components such as loads, batteries, capacitors and inductors are being connected to the RDAC station. Multiple drop-down menus for each bus and each phase as shown in Figure 2, were also implemented so that the user can select the type of the loads (R, RL, RC, or RLC) being added to the system.

The selection checkboxes are implemented with Boolean logic block diagrams that output a specific result based on the user selection. For example, in Figure 3, the Boolean block diagram that labels the type of the load being added to the system based on the user selection is shown. Once checkboxes are selected, small green indicators at the exact locations of the attached electrical components will light up, and small images and labels will become visible at the respective buses to make the locations of the attached components more apparent. A snapshot of the DEMS interface running with random components added is shown in Figure 4.

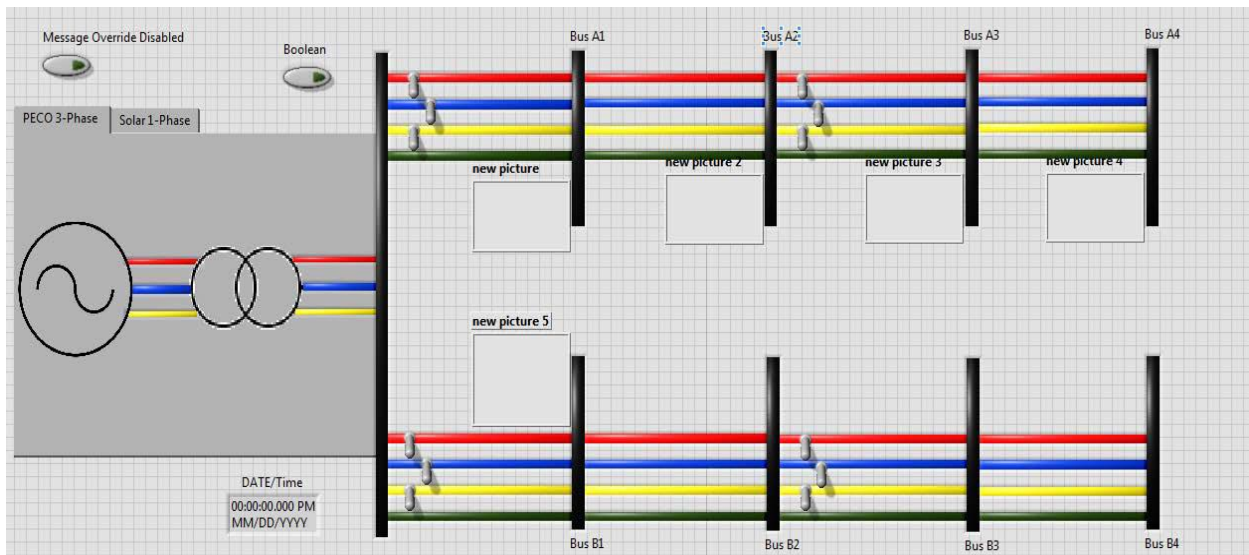


Figure 1: Initial LabVIEW model (2015-2016 version)

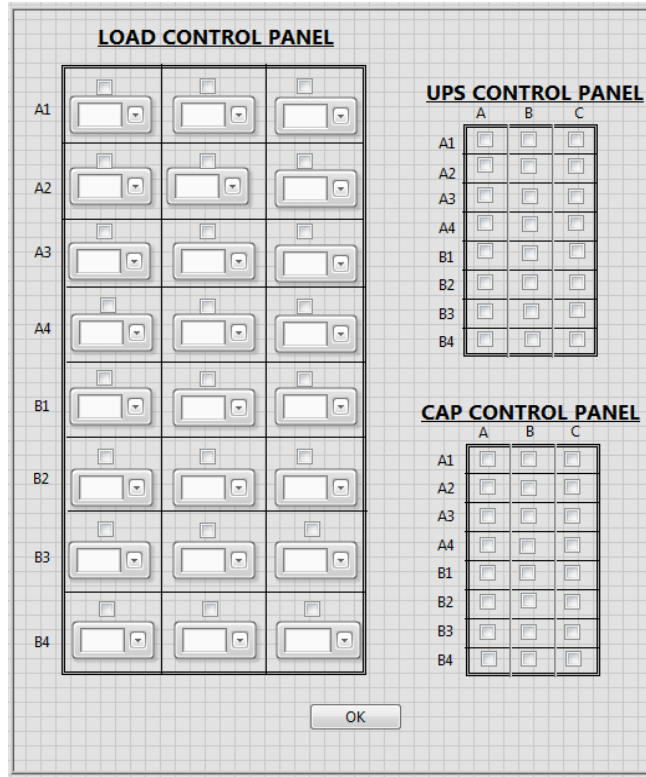


Figure 2: Functionalities added to the DEMS to select added loads, UPS and capacitors

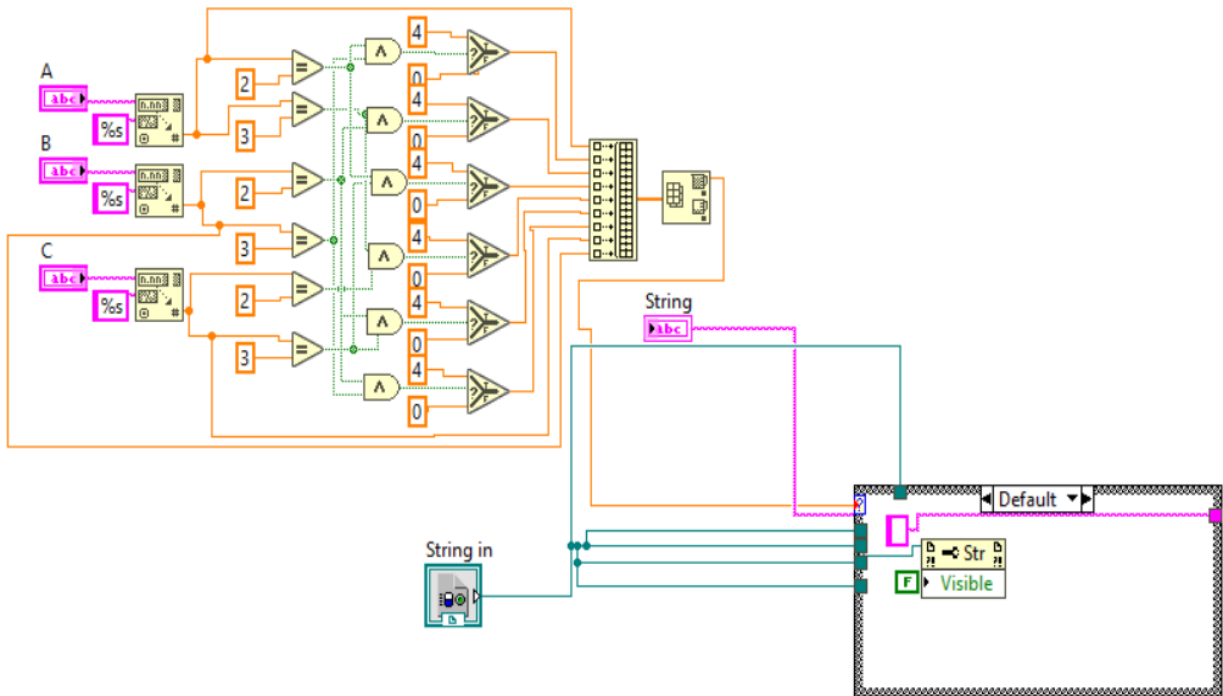


Figure 3: Boolean block diagram for the load type drop down menus

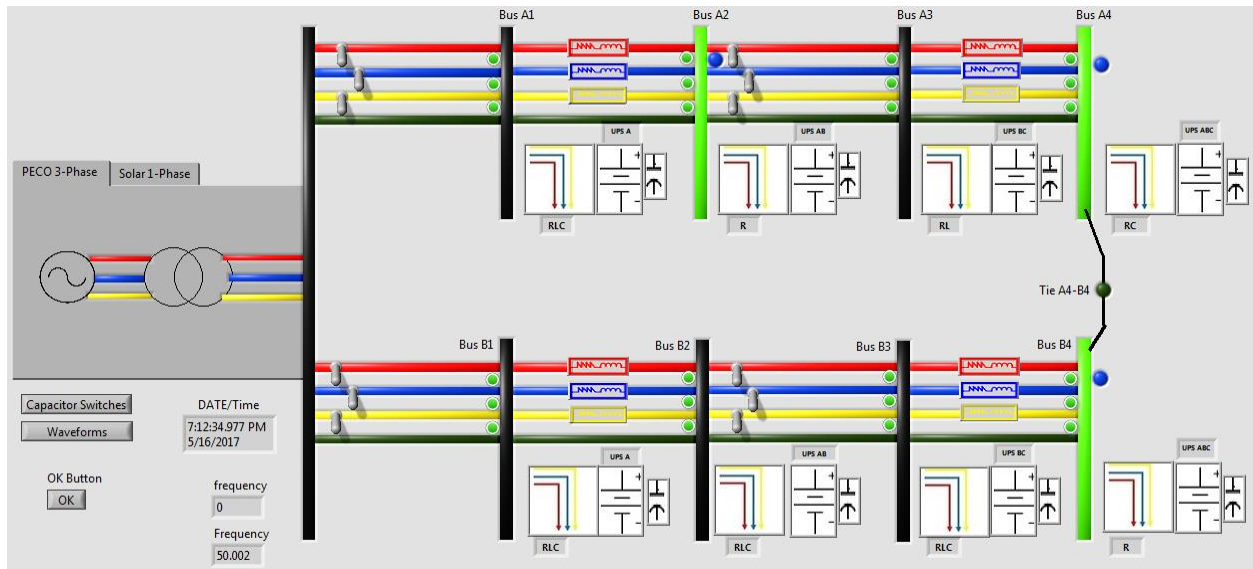


Figure 4: Snapshot of the DEMS interface with random electric components added

Our group also worked toward adding a subVI interface named “Waveforms” where voltage, current, and power for each phase are plotted over time at the measuring points of the RDAC station. Up to four measurement points can be taken at a time with one being always at the Feeder bus. A snapshot of the waveform subVI is shown in Figure 5. The waveform interface also provides phasor diagrams for the voltage and current.

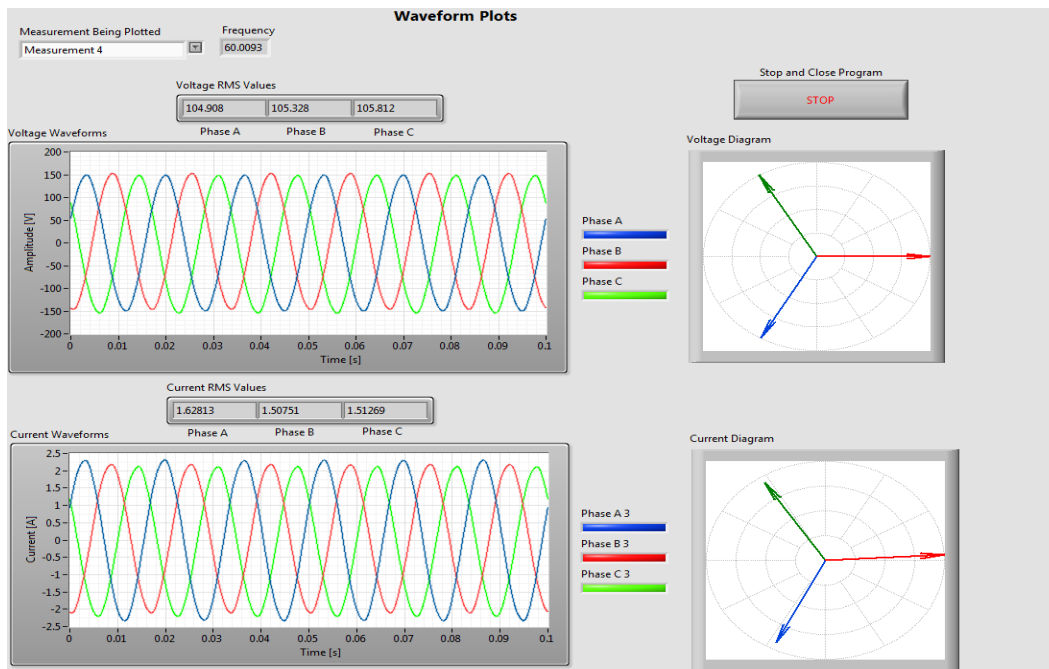


Figure 5: Waveform sub-visual interface added to the DEMS

6.4 Hardware Testing and Connector Box Construction

6.4.1 - UPS Acquisition

Both a 750 VA Standby UPS and a 1500 VA Line-Interactive UPS were selected and acquired for usage in the final experiment. The two will be used to represent a small and large BESS. Standby UPS are typically used for small residential applications and tend to have less control circuitry compared to the Line-interactive UPS [3]. These two UPS sizes and types should capture a wide range of studies. Table 1 below shows the relevant specifications for the 2 UPS that were selected. Four of each type of UPS was acquired. This allows for the possibility of connecting up to 3 UPS of a single type to the RDAC laboratory station (as a 3-Phase balanced load), while also maintaining a spare.

Table 1: UPS Specifications

<i>UPS</i>	<i>Maximum Apparent Power (VA)</i>	<i>Maximum Real Power (W)</i>	<i>UPS Type</i>	<i>Physical Dimensions (w x h x d) (in.)</i>	<i>Battery Capacity (Vah)</i>	<i>Typical Recharge Time (hrs.)</i>	<i>Run Time with 100 Watt Load (min)</i>
<i>APC Back-UPS 750</i>	750	450	Standby	7.09 x 3.54 x 14.29	104	16	38
<i>APC Power Saving Back-UPS Pro 1500</i>	1500	865	Line-Interactive	4.41 x 11.85 x 15.04	187	8	69

6.4.2 - UPS Hardware Testing

To confirm the validity of the initial software model, a laboratory experiment to determine the input and output properties of the different UPS at full battery charge was drafted and executed. This full procedure can be found in Appendix F below. The results from this experiment were critical for adjusting the Simulink UPS models and provided the first indication of how the UPS could behave when connected to the RDAC laboratory. See section 9.1 for the summarized results and Appendix G for the full results from this experiment.

The next phase of testing that was performed on both of the purchased UPS was to test their discharge rates on a certain load and then to look at the charging curve of each UPS. For each of the UPS, a single 80 W, carbon filament light bulb like that which is used in the RDAC laboratory was attached to the battery output stage of each UPS. The UPS were allowed to fully discharge and the amount of time it took each UPS to fully discharge was recorded. The full procedure for this experiment can be seen in Appendix H below. This experiment was repeated a total of 3 times and the results can be seen below in Section 9.3.

Also part of this experiment, while each UPS was recharging, we measured both the input voltage and current to come up with the charging waveform characteristics for each device. The

full procedure for this experiment can be found in Appendix H below and the results from this experiment can be seen below in Section 9.3

6.4.3 - 3-Phase Connector Box Construction

A 3-Phase Connector Box was designed as part of the scope of this project to connect up to 3 UPS to the RDAC lab. Two of these boxes were constructed in order to be able to connect up to 6 UPS to a single station of the RDAC laboratory. Each box has to be capable of accommodating up to three UPS and be able to switch them all individually between three different states: State 0: Disconnected from the station, State 1: Charging via the RDAC Station, State 2: Discharging back into the RDAC station. The boxes needed to have protective fusing of 10 amps to prevent any potential damage to the RDAC equipment or to the UPS. Figure 8 in the system diagram section demonstrates how a connector box interfaces between the RDAC Station and the UPS.

The critical features of the box are the three-stage toggle switch (Double Pole Double Throw switch), the 10 amp fusing, and the male NEMA (National Electrical Manufacturers Association Standard) 5-15 (Standard three prong Edison plug) inlet. These parts have all been specifically selected for operational safety. The three-stage toggle switch allows for all the requisite switching states, while preventing the possibility of connecting the UPS in a way that both the input and output are shorted together. There is 10 amp fusing on both poles of three stage toggle switch to prevent either the charging phase or discharging phase from drawing or sending too much current into a single bus connector into the lab. The NEMA 5-15 inlet is important as the output terminals from the UPS are all standard NEMA 5-15 outlets. If a NEMA 5-15 outlet was used in place of the inlet, a potentially hazardous male NEMA 5-15 to male NEMA 5-15 cable would be required. The inlet allows for the usage of safer standard extension cords.

All three phases of the box share a common ground and neutral. The boxes are contained within a 10in x 10in x 6in steel junction box. Figure 12 shows the circuit diagram for a connector box. The full component list for a single box can be found in Appendix E.

6.4.4 - Interconnect UPS to RDAC Laboratory

After completing the 3-Phase Connector boxes, the team needed to verify that they were functioning properly. A procedure (found in Appendix I) was drafted to both verify that boxes operated correctly and to record some preliminary results of what occurs with the UPS interconnected. These preliminary results were going to be used to formulate the final laboratory experiment.

After attempting to execute the box testing procedure, it was determined that the connector box is able to successfully switch a UPS between being disconnected, charging and discharging into the RDAC lab. During this preliminary testing it was discovered that while the UPS can successfully discharge into the system and power loads connected to other buses in on the RDAC station, this only worked with PECO AC power disconnected. When the UPS was

switched to discharging with PECO AC power, it consistently tripped the 10 Amp safety fusing in the connector box and well as trigger an battery overload shutoffs on the UPS.

This tripping of the fuse due to high current implied either a higher voltage difference than expected between the UPS and the AC input or low impedance between the box and the RDAC station. In the next test an inductor was connected between the the RDAC bus and the connector box to act as current limiter with minimum voltage drop. In this configuration switching the UPS to discharging did not blow the fuse but still resulted in an battery overload on the UPS. Based on these results, with the current setup, the UPS cannot be set to discharge into the lab simultaneously with PECO AC power active.

Based on the discovered limitations, a new experiment was designed to mimic an emergency restoration scenario on single phase feeder line. Voltage probes were added at one of the RDAC buses and at the UPS output connection to provide a better understanding of the difficulty interconnecting the discharging UPS to the RDAC lab with active AC power. The experimental results, waveform results and the resulting conclusions that were made can be found in Section 9.4.

7. System Diagrams

Multi-Phase Radial Power Flow Experiment

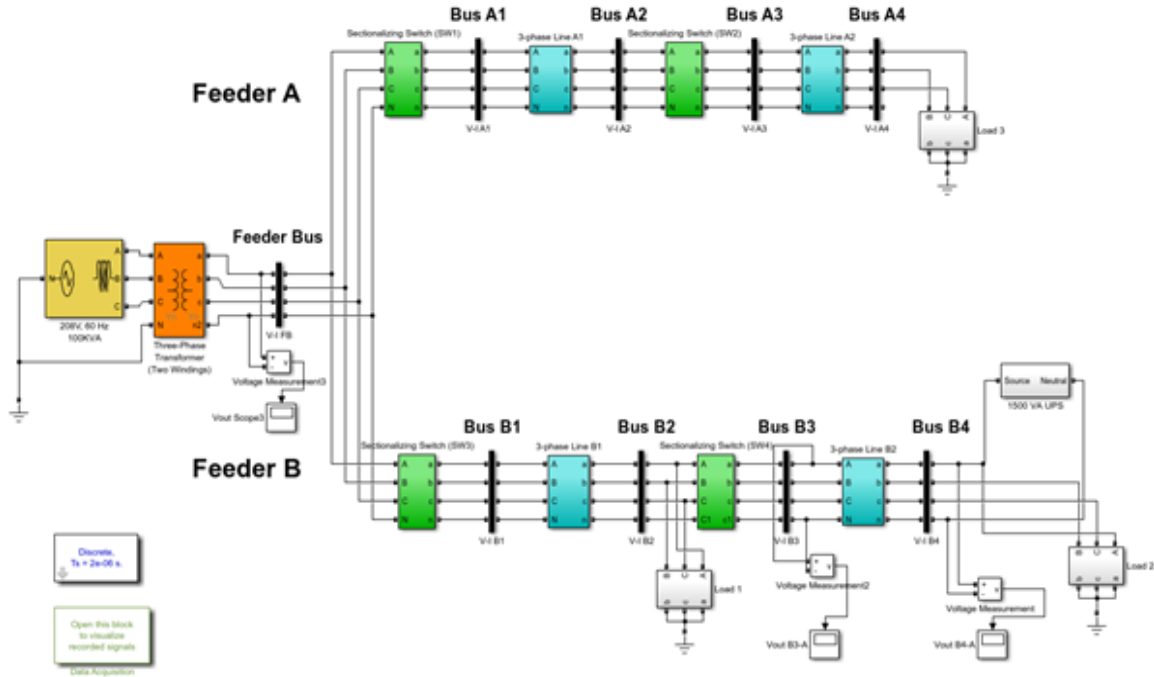


Figure 6: Simulink RDAC model with connected UPS at Bus B4

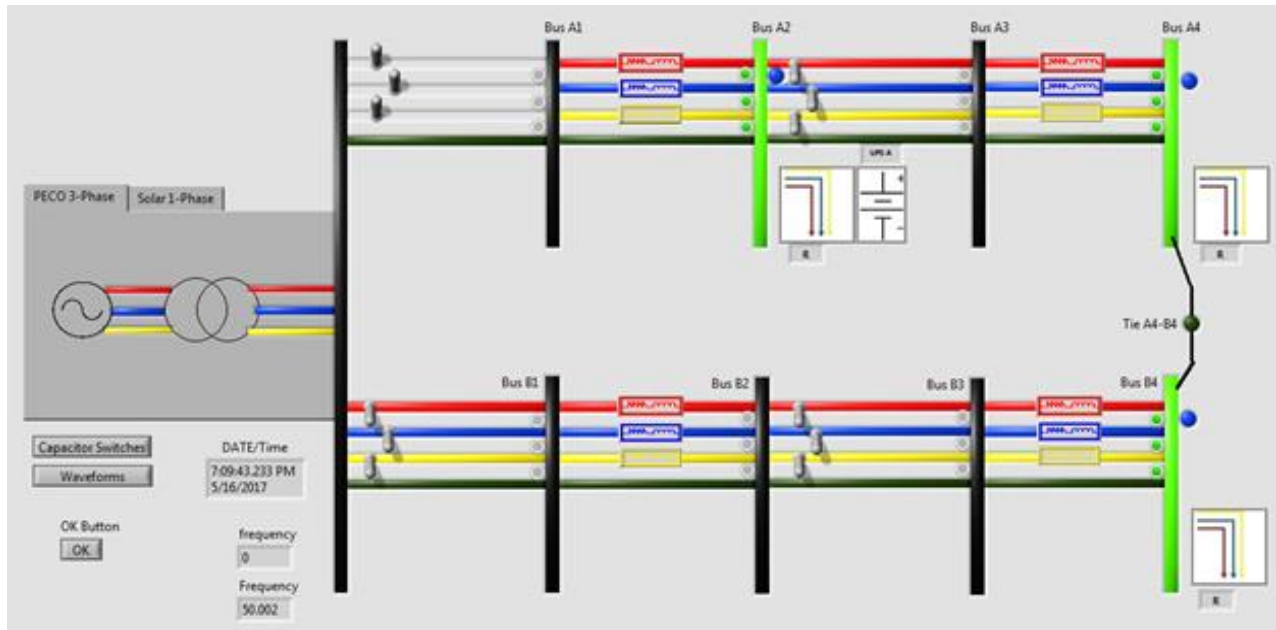


Figure 7: Updated LabView Model Showing Locations of the Connected Loads and UPS

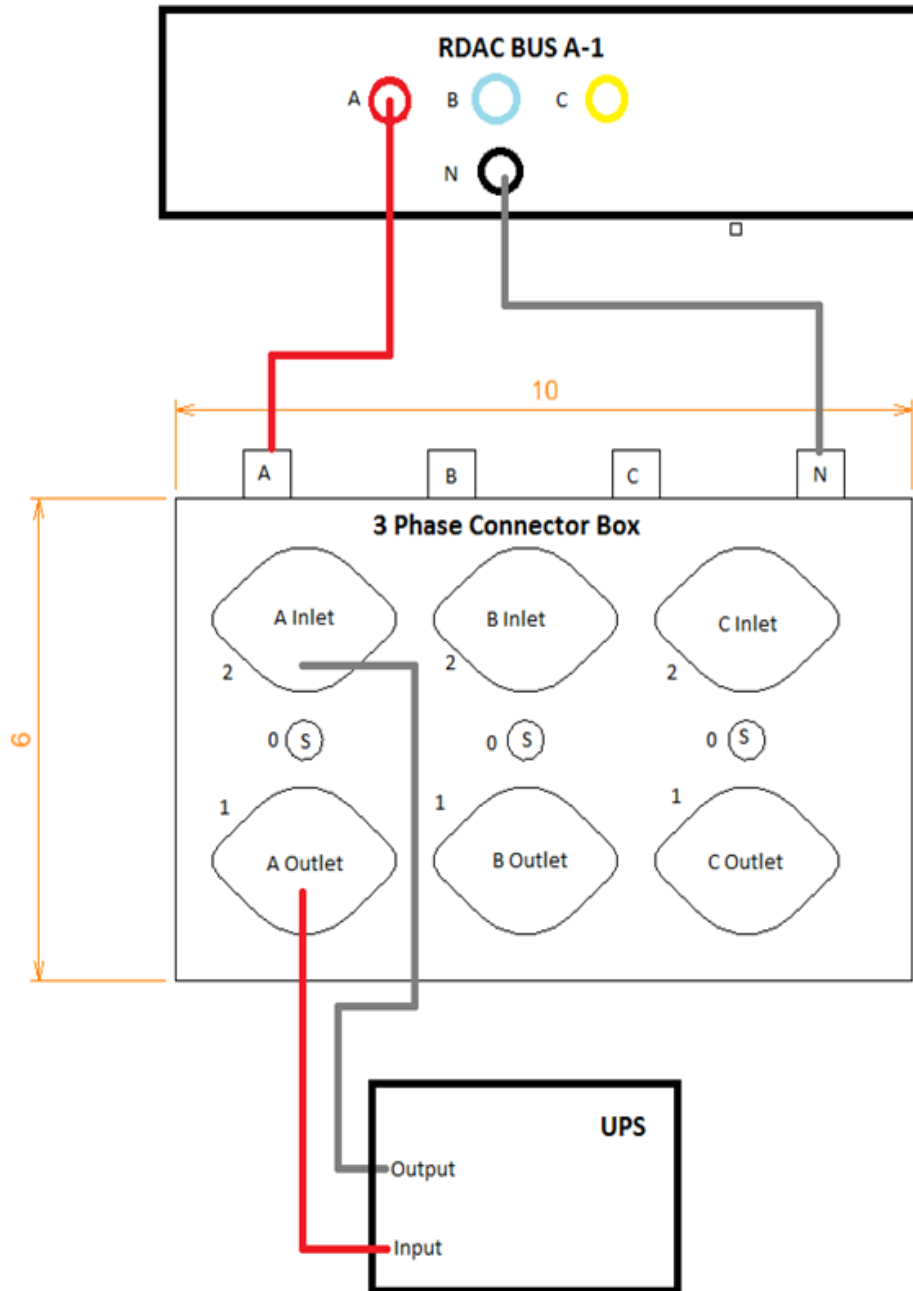


Figure 8: UPS to RDAC Connection Diagram

8. Circuit Diagrams

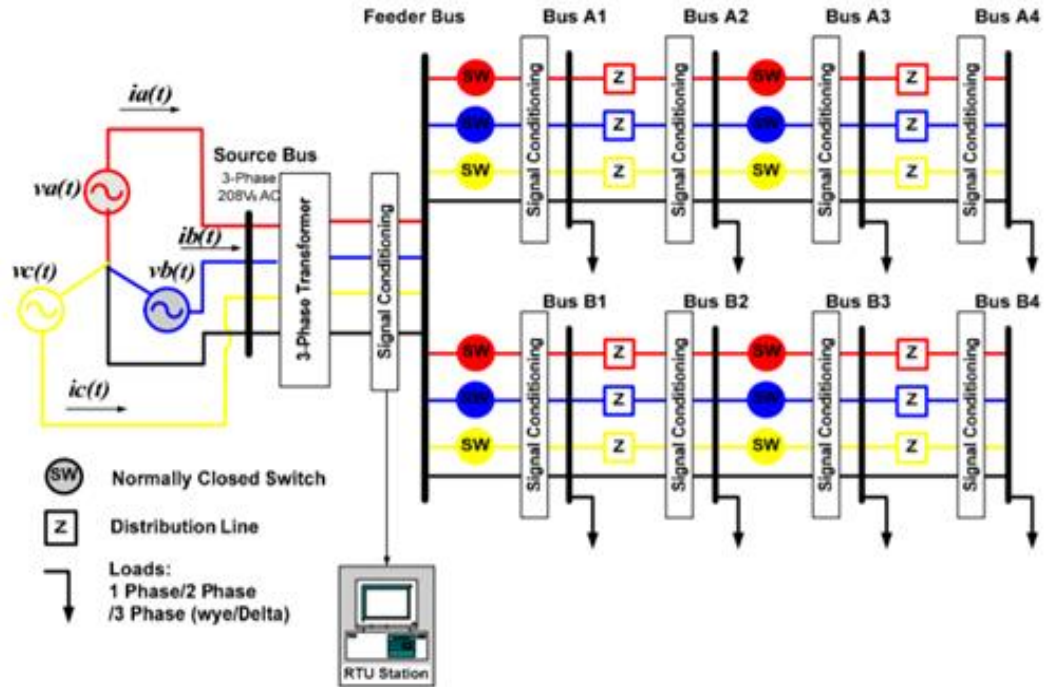


Figure 9: Three-Phase RDAC Schematic

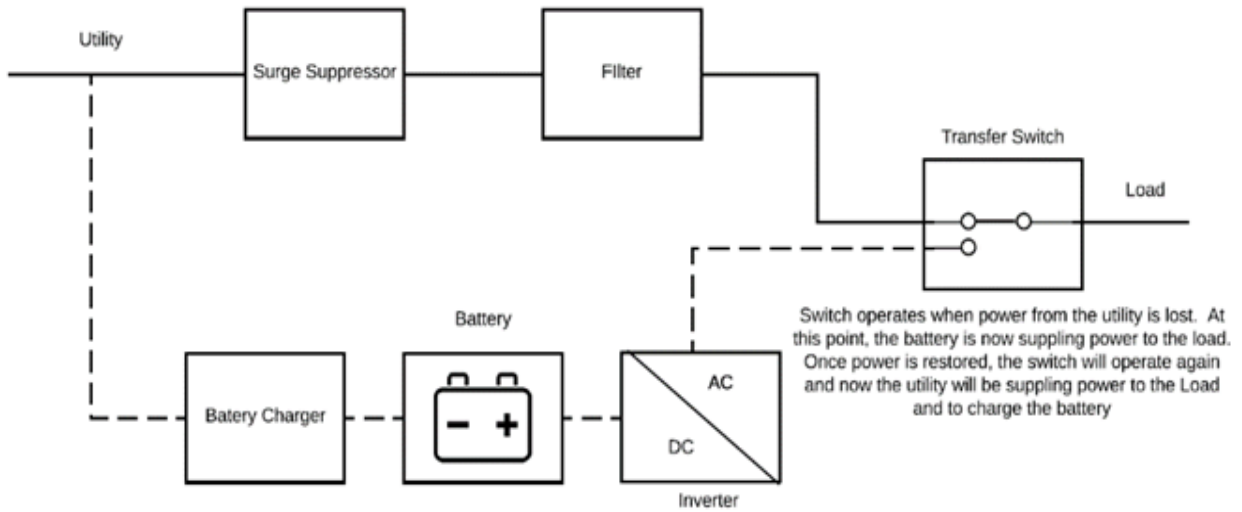


Figure 10: Standby UPS Schematic

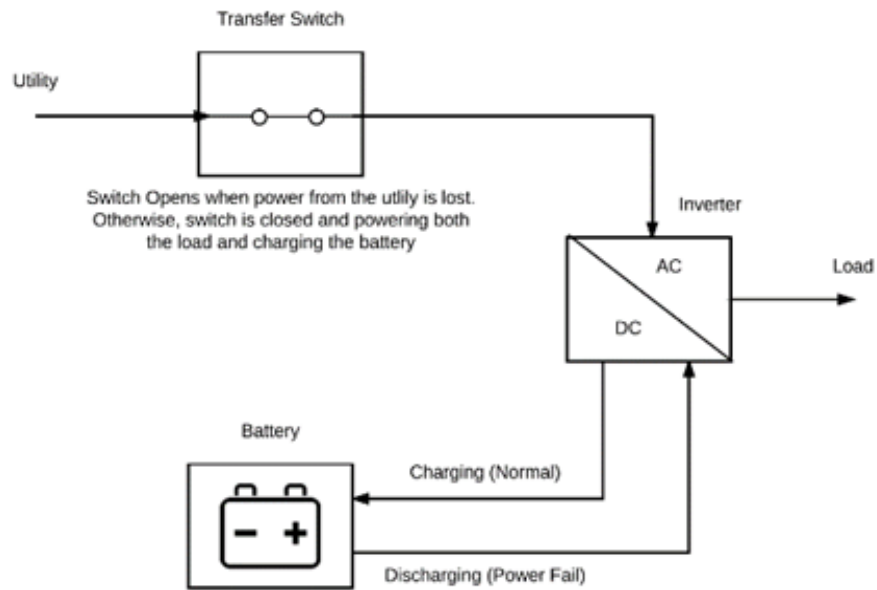


Figure 11: Line-Interactive UPS Schematic

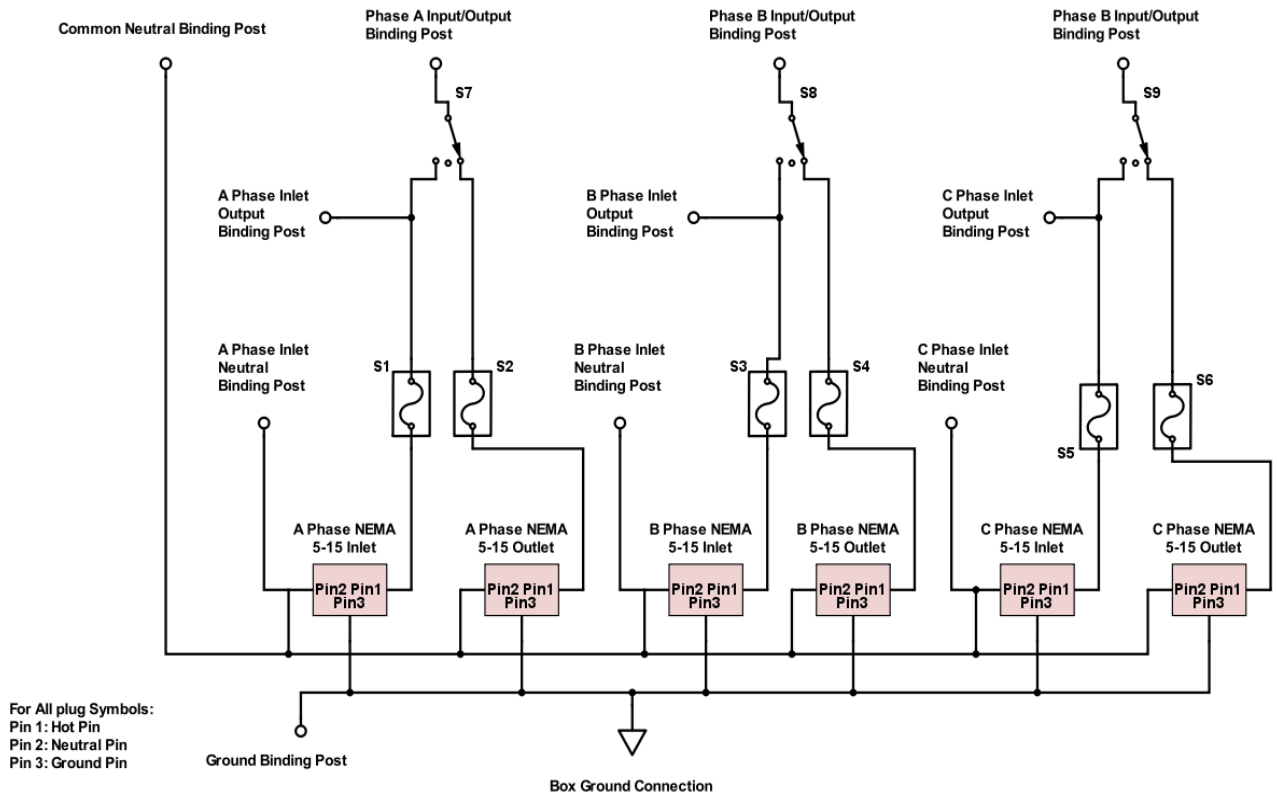


Figure 12: Connector Box Wiring Schematic

9. Experimental Results

9.1 UPS Input and Output Characterization Testing Results

When connected to AC power, both types of UPS output clean voltage and current AC sine waves. Both act as constant voltage sources which can be seen in Figures 13 and 14. While the output current waveforms are clean sine waves when AC power is supplied, the input currents are noticeably distorted. This distortion most likely results from the power electronics present in the UPS. Comparing Figures 15 and 16 it can be observed that the input current distortion differs between the two types of UPS. The standby UPS has an input current very reminiscent of a triangle wave. The line interactive UPS shows distortion that start to resemble a square wave. When the UPS are finally connected to the RDAC system the team will be paying close attention to how much this input distortion effect the full system.

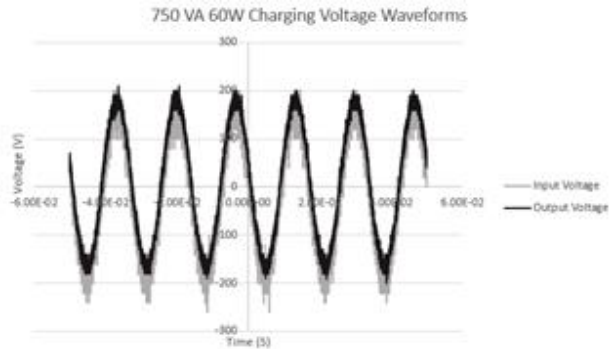


Figure 13: 750 VA UPS Charging Voltage

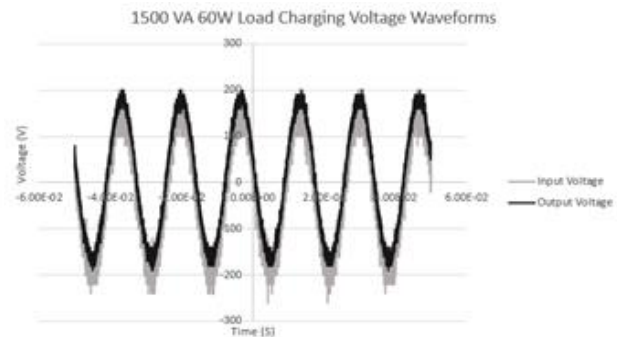


Figure 14: 1500 VA UPS Charging Voltage

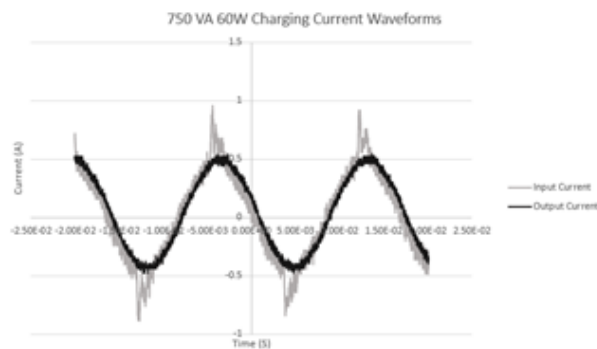


Figure 15: 750 VA Charging Current

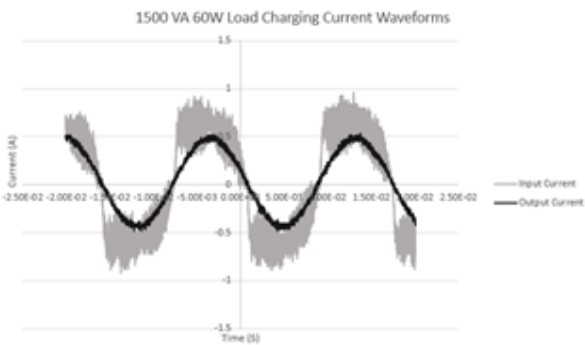


Figure 16: 1500 VA Charging Current

When the output is being supplied by strictly battery power the UPS output exhibits a very pronounced stepped output for both the voltage and current. While the UPS maintain output RMS and frequency values near identical to the RMS values of the AC power supplied output, the step output does not closely resemble a pure sine wave. Figures 17 and 18 show the measured stepped outputs from the 1500 VA line-interactive UPS. The degree of difference in this output waveform will be sure to have telling effect when connected to the full system. Any negative

effect on the system will illustrate a need for BESS to have more advanced inverter technology than what is present in these small UPS. See Appendix G for the full results of all tested loads.

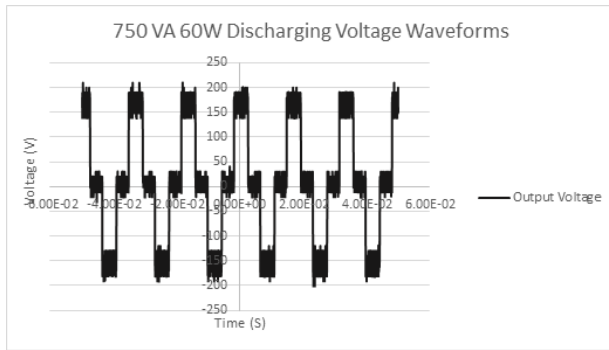


Figure 17: 750 VA UPS Output Voltage

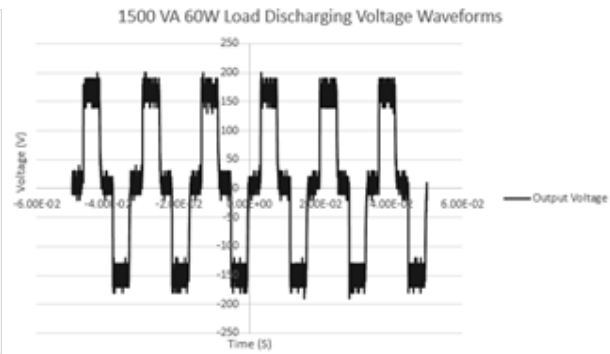


Figure 18: 1500 VA UPS Output Current

9.2 Simulink Simulation Testing Results:

After testing the two UPS units purchased, the Simulink model was created to represent the behavior seen in the hardware testing. Figure 19 below shows the Simulink Model for the 1500 VA UPS. The main components of this model include the “Source Voltage” which represents the outlet the UPS would be plugged into. The power then flows through the cable, modeled as a constant impedance, to the transfer switch. For this model, 2 switches in Simulink are used to model the transfer switch within the UPS. The power consumed to charge the battery is modeled as the “Battery Charger” load which is modeled as a constant power load.

Connected to SW 3 is a stepped AC voltage source which was used to model the battery and inverter. This produces a constant stepped sine wave voltage output which mimics the actual output of the inverter of the UPS as measured during the hardware testing. The output voltage from this model can be seen in figure 20 below. Also, a current limiting resistor was added to the schematic to limit the current output of the UPS to 10 amps based on the specifications on the data sheet. Finally, phase sensing technology was added to this model to be able to sense the voltage phase angle at the bus it is connected too. One drawback with Simulink is that it is unable to update this voltage phase angle while the simulation is running. The voltage phase angle for the stepped sine approximation can only be updated at the beginning and the end of the simulation.

1500 VA UPS Model

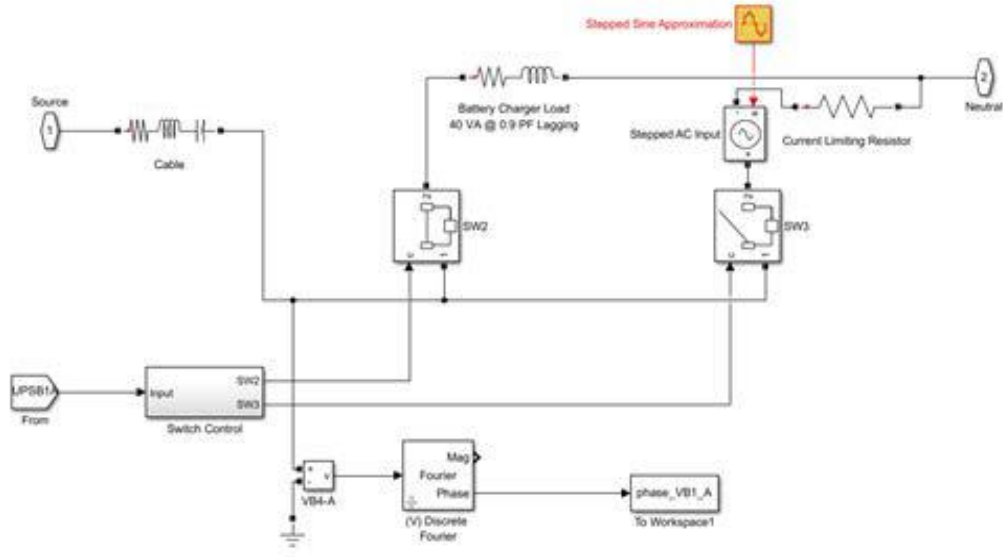


Figure 19: Updated Simulink UPS Model

Output Voltage from UPS

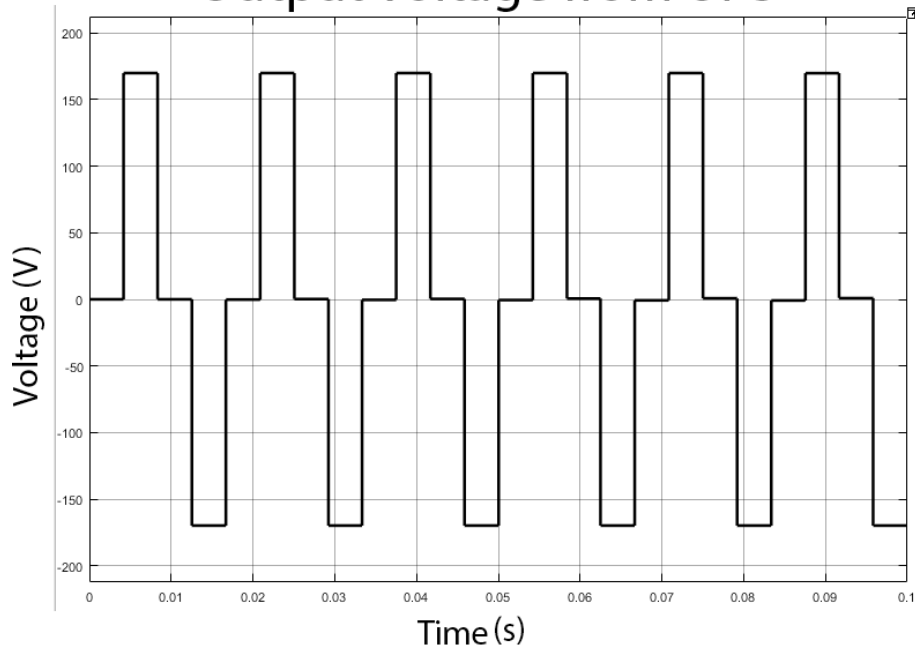


Figure 20: Simulink Output Voltage for our UPS model

Using this model, multiple simulations of a single station of the RDAC laboratory were run. Figure 21 below shows the configuration for one of the simulations that were run during the Winter term. For this simulation, a single UPS was connected at bus B4 on phase A with 3 balanced loads. Appendix D below shows the full results that were found from all of these simulations. Multiple configurations of the system were simulated varying both the location and value of the loads as well as the location of the UPS to see what effect they had on the system. Overall when the UPS was back feeding into the system, a lot of distortion on the voltage waveform at the buses closest to the UPS location was observed. At the buses further electrically away from the UPS location, less distortion for the voltage waveform was found. Figure 22 below shows some of the distortion we noticed at the bus location where the UPS was connected.

Multi-Phase Radial Power Flow Experiment

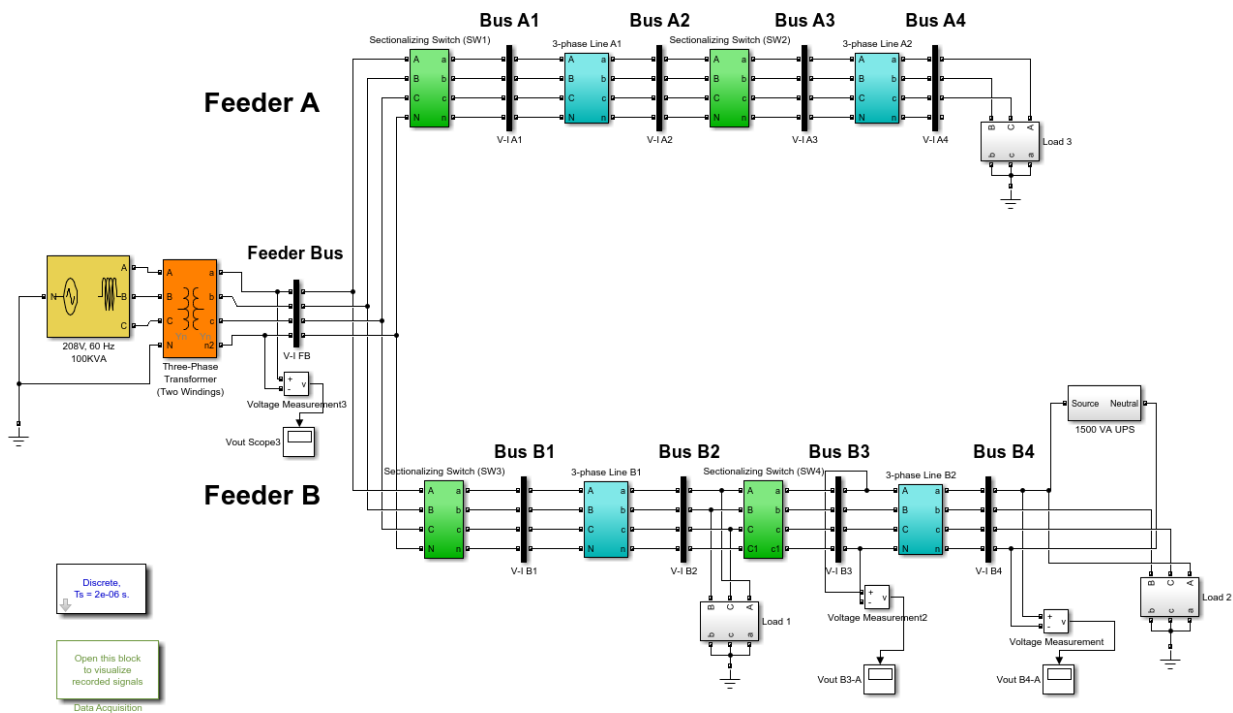


Figure 21: Simulink System Diagram for Case 1 Load 1

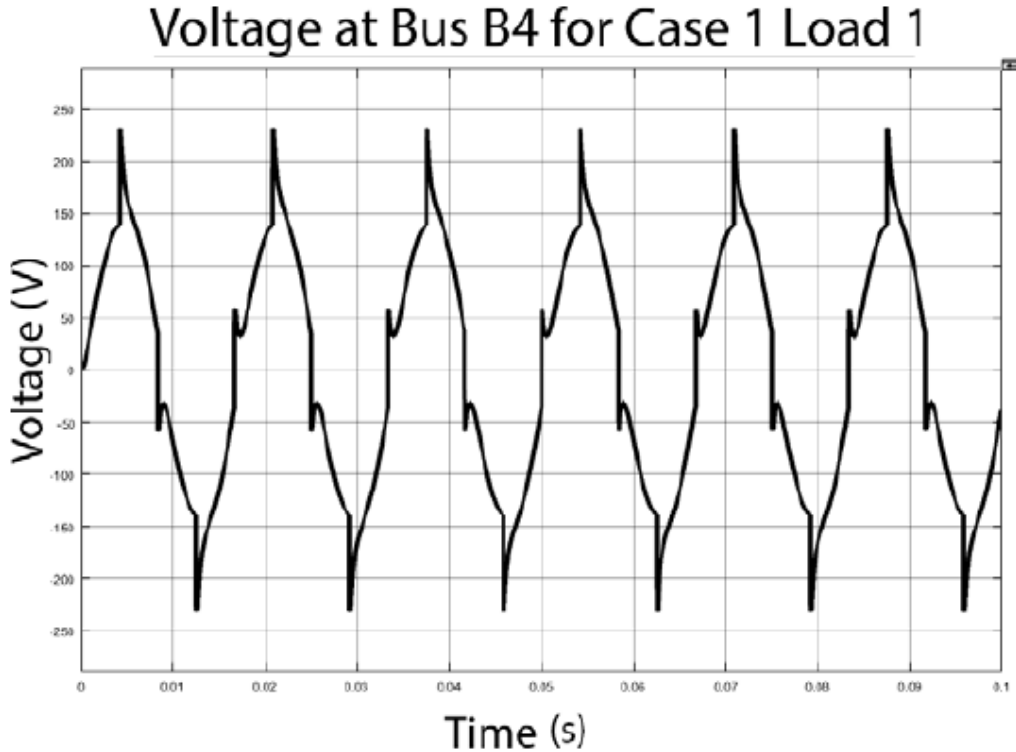


Figure 22: Simulink Simulated Voltage for at Bus B4 with the UPS at Bus B4 and Back Feeding (Case 1)

9.3 UPS Discharge Time and Recharge Current Testing Results:

Table 2 below shows the discharge time measured for each UPS when a single 80 W carbon filament light bulb (like the ones used in the RDAC lab) was connected to the output. The total run time for both UPS fell around the expected run time provided by the manufacturer. Over a period of three runs, the team found very similar results as to what was found by the manufacturer APC.

Table 2: UPS Discharge Time in Minutes

Discharge Time in Minutes						
UPS	From APC	1st Run	2nd Run	3rd Run	Average	Percentage Error
750 VA	50.8	45	57	48	50.00	5.51%
1500 VA	83.2	87	80	92	86.33	10.58%

Table 3 below shows the charging characteristics we measured for both UPS over time. We started charging both of the UPS from completely empty when we were finished with the discharging part of this experiment. Figure 23 below shows the charging curves measured for both UPS. The power draw when charging remained near constant for the 750 VA UPS. The 1500 VA UPS drew input power in a fashion that exhibited minor exponential decay over time.

Table 3: Charging Characteristics Observed for both UPS

	750 VA			1500 VA		
Time (hrs)	Voltage (V)	Current (mA)	Power (W)	Voltage (V)	Current (mA)	Power (W)
0	119	191	22.729	119	724	86.156
1	119	189	22.491	119	620	73.78
2	119	183	21.777	119	577	68.663
3	119	185	22.015	119	561	66.759
4	119	185	22.015	119	554	65.926
5	117	188	21.996	116	533	61.828
6	116	188	21.808	116	533	61.828
7	116	188	21.808	116	536	62.176

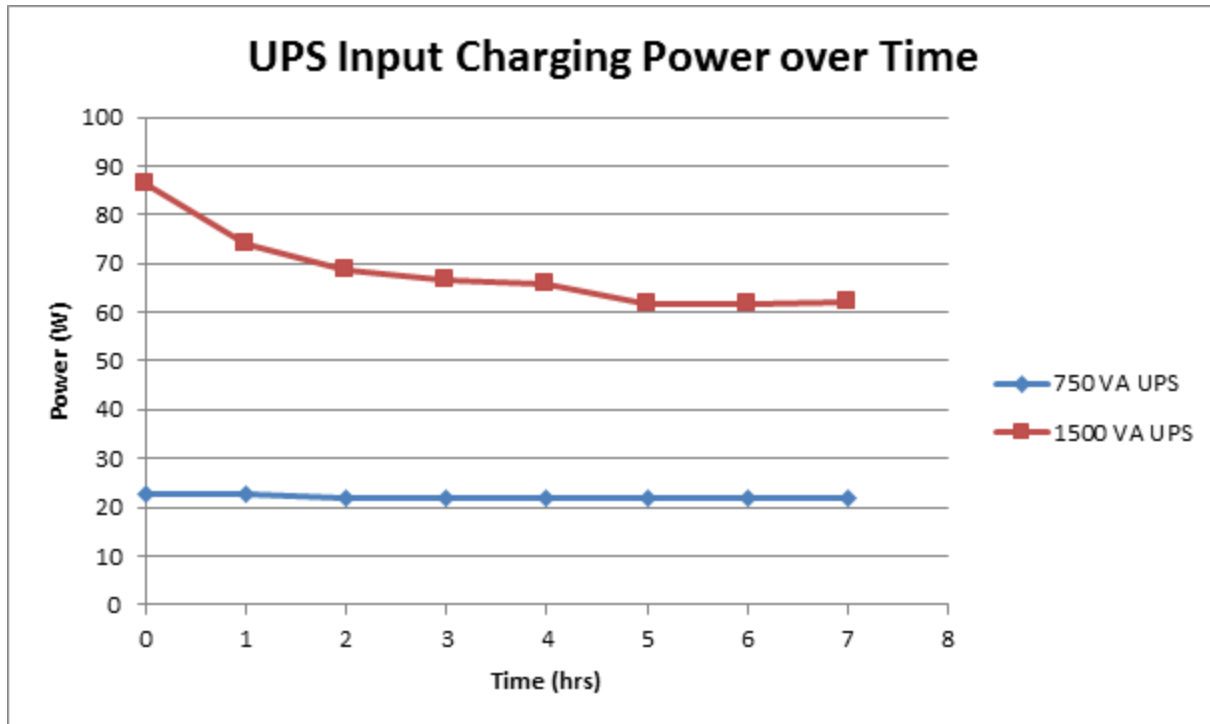


Figure 23: Charging Waveforms for both UPS

9.4 UPS Interconnection to RDAC Experiment Results

The team was successfully able to connect a single UPS to a station of RDAC and have the UPS power that station by itself. However, when the team tried to incorporate to the UPS and the Utility to power RDAC, we blew the protective fusing and triggered an overload error on the UPS. The team then decided to set up an oscilloscope in order to be able to understand what exactly is happening.

Figure 24 below depicts the voltage waveforms of an RDAC bus under PECO AC power compared to the voltage output of a 750 VA UPS that is connect to a different RDAC bus and is charging. In this configuration it can be seen that the voltage phase of lab and the voltage phase the UPS output are in near perfect sync. In Figure 25 the waveform comparison of the of the RDAC voltage and the UPS discharging voltage (ups was not connected to discharge into an active RDAC bus) shows the battery supplied output voltage is near exactly 180 degrees out of phase with the AC supplied voltage present in the active RDAC buses. This is the worst case scenario possible for interconnecting the UPS with currently running AC power. If the UPS would be connected to an active bus with this phase difference it would exhibit a max voltage difference of around 330V certain to overload the fuses. If the equipment was unprotected the resulting currents would have resulted in damaged. Not all trials of switching the UPS from charging to disconnected and comparing the voltage phase resulted a complete 180 degree phase difference from the bus voltage. The difference was still of margin that is cause for concern and prevent multi-source interconnection for the remaining experiments.

The other main observation from this testing showed that the Utility and UPS voltage were not actually at the same frequency. With the oscilloscope set to trigger on the voltage measured at the bus powered by the Utility, the team saw the voltage of the UPS start to creep across the screen. This means that the two waveforms are not operating at the same frequency. Unfortunately, the oscilloscope was not sensitive enough to measure a difference between the two waveforms, but it was clearly visible by the team.

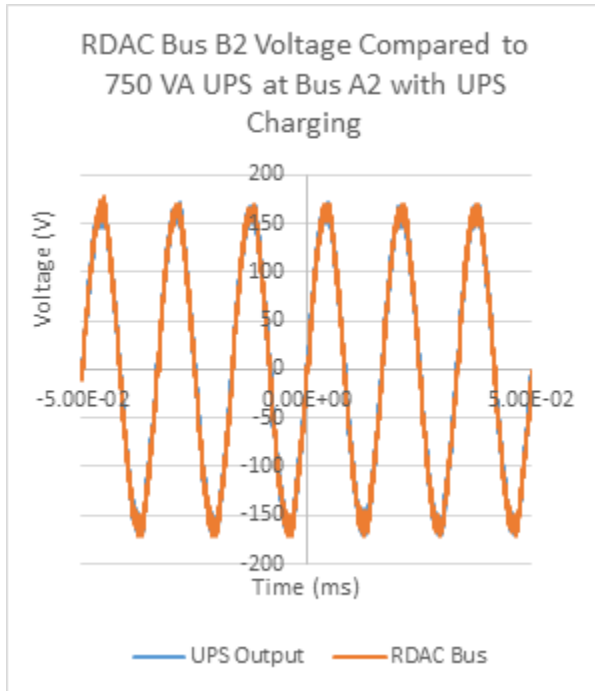


Figure 24: UPS Charging Comparison

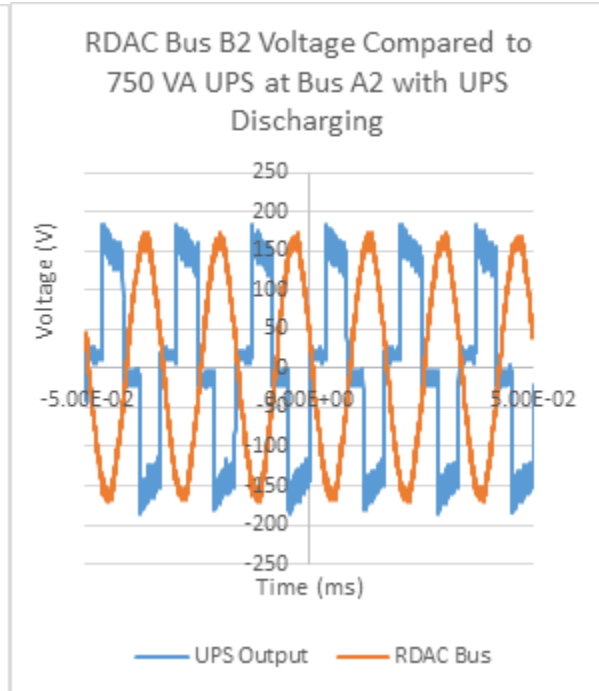


Figure 25: UPS Discharging Comparison

The next test the team performed was to see if it was possible to get two UPS in the same phase to see if we could use multiple UPS to power the RDAC station on the same phase. Figure 26 below shows a waveform captured by the oscilloscope of the input voltage as well as the voltage from two different UPS located on different buses. Unfortunately none of the three waveforms are in phase so this scenario was also deemed unsafe. Full results from this testing can be seen below in Appendix J. From our experimentation, the team determined that it was impossible to have more than one source power any bus of an RDAC station.

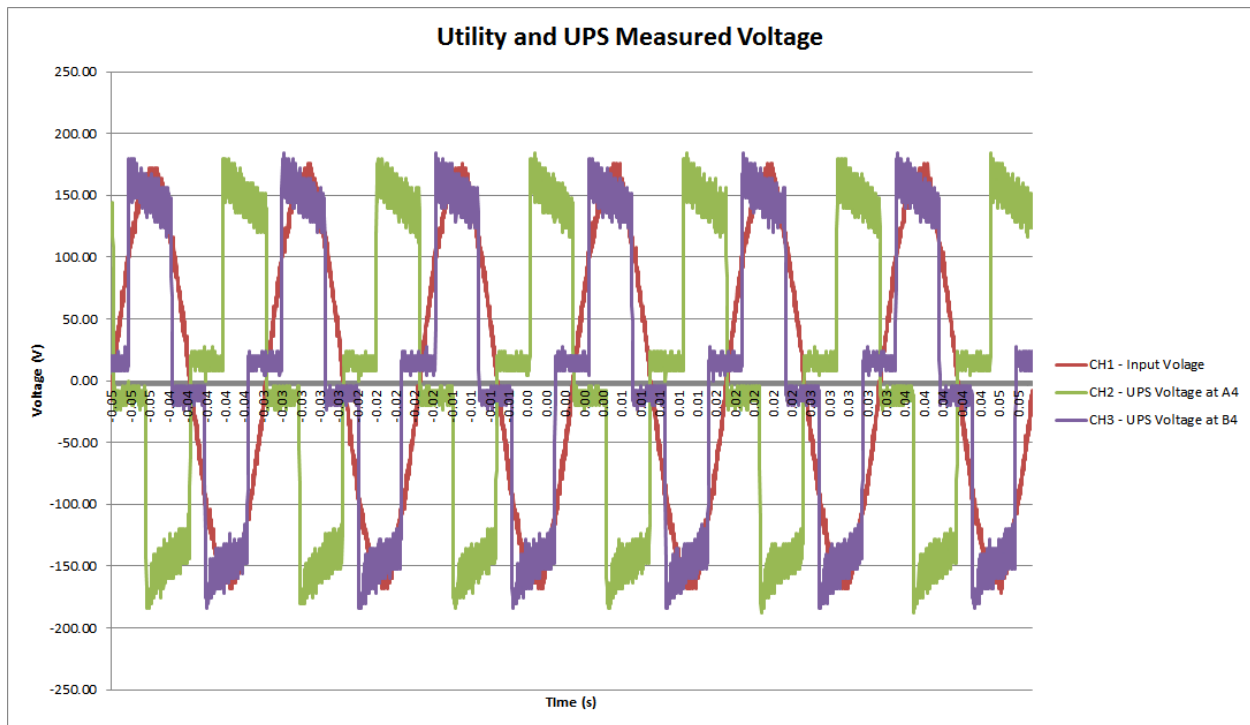


Figure 26: Utility and Measured UPS Voltage with 2 UPS Connected

9.5 Emergency Restoration with UPS Experiment Results

Since our team was not able to successfully have both a UPS and Utility power connected at the same time, the team decided for our final experiment to come up with an emergency restoration experiment where the user can power a section of the RDAC station with a UPS that has lost power from the utility source. The full experiment can be seen below in Appendix C. Currently, this is just a draft as we have yet to fully implement our new EMS into running this experiment. The team plans on running this experiment at least twice before the final presentation with the new software. Once this happens, we will be able to better finalize our final emergency restoration experiment.

The raw data captured from the first run of this experiment with the existing software can be seen below in Appendix K. Some initial observations the team saw include the large phase angle difference between the Utility source and the buses that were being powered by the UPS. We again also noticed that the UPS output is not perfectly 60 hertz as we saw the phase angle constantly changing. Finally we also notice an increase as well as a changing neutral current in the three-phase part of the experiment due to the frequency difference between the two sources. We will have more finalized observations from this experiment in the final presentation.

10. Standards and Regulations Relevant to the Project

Our team also researched the different standards related to our senior design project. Our team researched the IEEE 1547 standard which dictates the interconnection standards between distributed energy resources and the utility grid. This standard is important to understand in the scope of our project because any distributed battery energy storage system will have to adhere to these standards [5]. Our team also researched the IEEE 1184 standard which describes the selection, installation, maintenance, and testing of a UPS. This standard is important to understand for this project because we will be using different UPS in the power laboratory and we should have a firm understanding of how they operate [6].

When it came to constructing the 3-Phase connector boxes, the National Electrical Manufacturers Association (NEMA) connection standards were used for the receptacles and cables used to connect the UPS to the connector box. The standard that had the most impact on the 3-Phase connector boxes' final layout was that National Fire Protection Association (NFPA) code 70: National Electric Code. In NFPA 70, section 409 outlines standards for industrial control panels. The minimum spacing between bare metal component of opposite polarity as defined by this code were followed in the construction of the box.

11. Group Member Contributions

Christopher Fedor - Team Leader & Simulink Designer

- Performed project management tasks such as lead weekly meetings and communications
- Primary designer for the Simulink model of the BESS and implementing it into the RDAC model
- Assisted in the UPS selection and hardware testing
- Assisted in the design and construction of the UPS connection box

Elmer Turner- Primary Hardware Designer:

- Performed UPS Research and Selection
- Designed all aspects of the 3-Phase Connector Box
- Contributed in most stages of construction of the 3-Phase Connector Box
- Drafted Hardware testing procedures and conducted the relevant experiments

Reynaldo Noel Jeune- Primary Distributed Energy Management Software Developer

- Integrated indicators to the DEMS interface to represent electrical components being added to the RDAC station
- Developed an event case structure in LabView to represent loads, batteries, and RLC components being added to any of the 8 buses and any of the 3 phases to the RDAC station.
- Implemented logics to coordinate the placement of picture boxes and labels within the DEMS interface and assisted with adding a metric display subVI.
- Ran and analyzed simulations to see the effect of BESS on RDAC system

Jonathan Balsamo-Software Developer & Hardware Tester

- Assisted DEMS interface development in LabVIEW
- Assisted in hardware testing
- Contributed to construction of 3-Phase Connector Box
- Performed background research of electrical vehicles.

12. Societal Impacts of Project

According to the United States Energy Information Administration, in 2015 just 7% of the 4 trillion kilowatt-hours of energy was produced from renewable resources including wind and solar power [7]. The percentage of renewable energy in the US has been on the rise steadily in recent years. While the rise in the amount of renewable generation in the US is a big step forward and is helping to reduce our carbon footprint, there are some power quality issues that are starting to arise. Most of these issues are due to the inherent intermittent nature and the placement of these resources within the distribution system.

A promising way to fix these issues is the strategic placement of distributed battery energy storage systems (BESS) throughout the distribution system. With the installation of these devices, we will be able to fix some of the current issues within our power system that will then allow for the installation of more renewable sources of energy. The United States Department of Energy has a current target set of 20% renewable energy by the year 2030 and without the installation of these battery systems, we feel that we will not be able to reach this goal [8]. But first, we need to better understand the effects of these devices in a distribution system so that we can implement them so that more renewable energy can be installed.

Through our project of mimicking these distributed battery energy storage devices with a UPS in the RDAC laboratory, we are able to gain a greater understanding of how they work within a distribution system and be able to pass along this knowledge to future students. With this knowledge, more renewable generation can be evaluated in a systematic manner. This should help increase the adoptions rates of renewable energy subsequently, and will reduce our dependency on fossil fuels and help reduce our carbon footprint which will help to reduce global warming. Right now, climate change is one of the most heavily debated issues facing our society with major implications in both the social and political realms. The decisions we make now involving reducing our carbon footprint will have lasting impacts over the next couple of generations, and through this project we hope to understand how the implementation distributed battery energy storage systems can allow for the installation of more renewable energy on the distribution grid.

13. Project Timeline

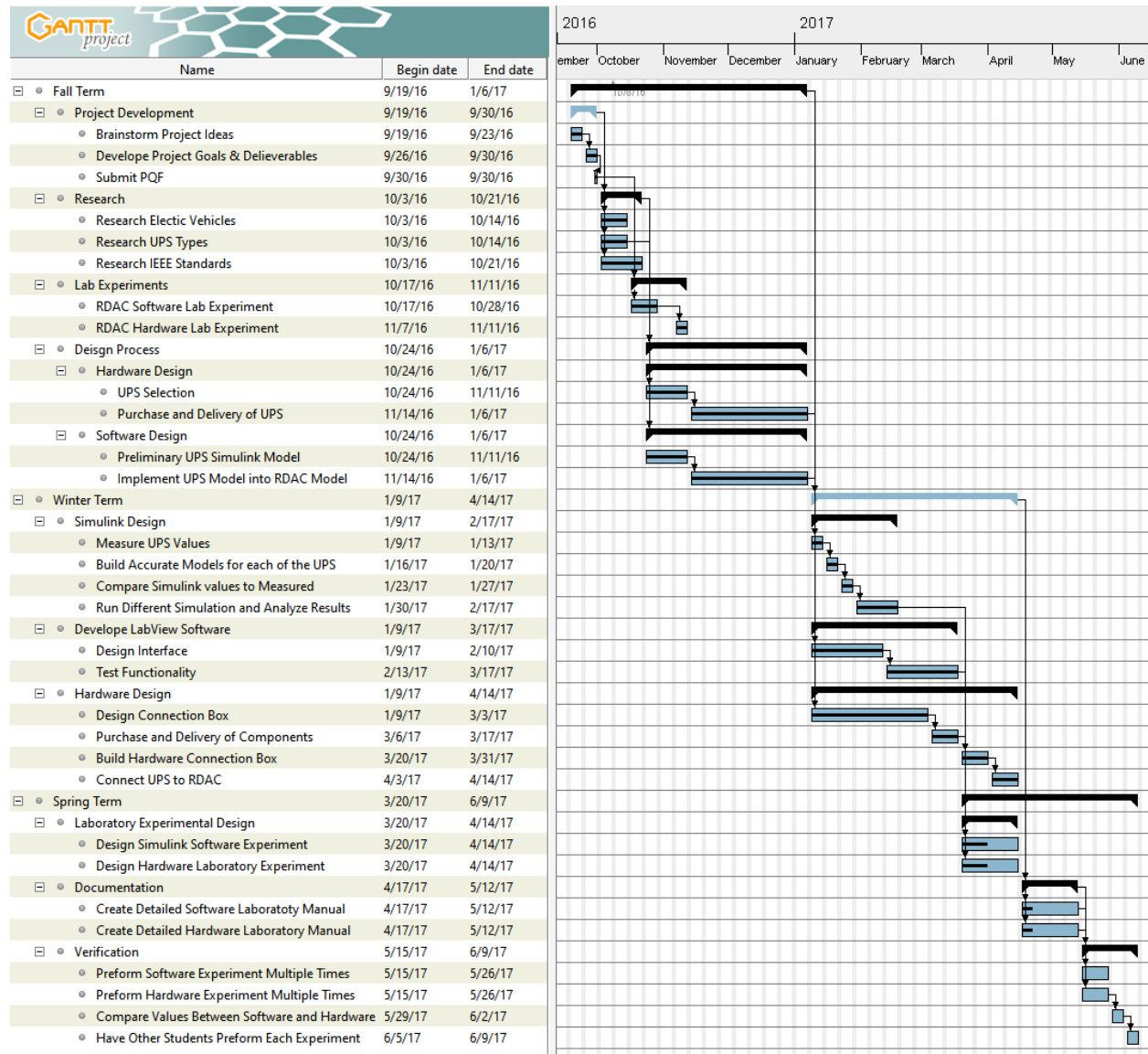


Figure 27: Timeline for the Entire Senior Design Project

Figure 27 above shows the entire timeline for the senior design project. In the fall term, the team focused mainly on background research and UPS acquisition. In the winter term, the team focused more on Simulink modeling, the connection box design, and hardware testing. Finally in the spring term, the team focused on the connection box construction and testing, the LabView EMS, as well as the final experiment designs.

14. Project Budget

Table 4: Industrial Budget [9][10][11][12]

	Expense Description	Total
Personnel Expenses	Entry Level Electrical Engineer Yearly Salary	\$69,299.00
	Entry Level Electrical Engineer Yearly Salary	\$69,299.00
	Entry Level Electrical Engineer Yearly Salary	\$69,299.00
	Entry Level Electrical Engineer Yearly Salary	\$69,299.00
	University Consultation fee (per year)*	\$39,000.00
	Overhead (30% total salary per person)	\$83,158.80
	Total Yearly Cost	\$399,354.80
	9 Month Weighted Cost	\$299,516.10
Office and Lab Space Expenses	Office rental rate (per sq ft per year)	\$30.00
	Space needed (sq ft)	1000
	Total office rental Price (per year)	\$30,000.00
	Utility cost (per year)	\$5,000.00
	RDAC Usage Fee** (per Year)	\$12,000.00

	Maintenance (5% of yearly rental cost)	\$1,500.00
	Total Yearly Cost	\$48,530.00
	9 Month Weighted Cost	\$36,397.50
Hardware Costs	Employee PC (4)	\$4,000.00
	APC Back-UPS 750 (4)	\$372.32
	APC Power Saving Back-UPS Pro 1500 (4)	\$737.96
	Connector Box Component Cost (2)	\$890.00
	Total Equipment Cost	\$6,000.28
Software Costs	Microsoft Office Home & Business (4)	\$920.00
	MATLAB license (4)	\$8,600.00
	LabVIEW License (4)	\$4,000.00
	Total Software Cost	\$13,520.00
	Overall Total	\$355,433.88

*Based on \$150 an hour/4 hours a week

**Estimated based on membership rates to public manufacturing labs

Table 5: Out-of-Pocket Budget

Expense Description	Unit Cost	Count	Total Cost
APC Back-UPS 750	\$93.08	4	\$372.32
APC Power Saving Back-UPS Pro 1500	\$184.49	4	\$737.96
Connector Box Parts	\$445.00	2	\$890.00
			Subtotal
			\$2,162.78
			Risk (20%)
			\$432.56
			Total
			\$2,595.34

*Risk includes possible charges such as shipping or other miscellaneous small replacement parts

15. Project Funding and Acknowledgements

The Team would like to acknowledge the help of our advisor Dr. Karen Miu as well as help from Nick Coleman with hardware testing in RDAC, Ed Schrubba for help with the construction of the connection boxes, and Tom Halpin with help updating the LabView DMS. The team would also like to thank the Center for Electrical Power Engineering (CEPE) for complete funding for this project.

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