

Incoming Power Grid Monitoring

Michigan State University
Senior Design – ECE 480 – Team 3

Sponsors

Great Lakes Controls & Engineering

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Executive Summary

The purpose of this project is to develop a three-phase four-wire AC power monitoring system capable of data logging voltage phase-phase, voltage phase-ground, current, and power. The system will alert a user at the occurrence of any transient event, as well as permit the user the ability to change the sampling rate, and possess enough memory to log data for a week with a sampling rate of 100 milliseconds. The system will also have a user interface to allow data viewing, changes for monitoring purposes, and the ability to export the logged data with a USB memory stick.

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Introduction

Great Lakes Control & Engineering were recently contracted with the task of developing a power monitoring system that would provide solutions to the shortcomings of their current device, the EXTECH 3-Phase Power Analyzer/Datalogger. The current device lacks Ethernet connect ability, samples the signal every 2 seconds and cannot send notifications warning about voltage or current transients.

Team 3 of the senior design capstone course at Michigan State University, ECE 480, has been tasked with developing a portable power monitor with the capabilities of the EXTECH 3-Phase Power & Harmonic Analyzer and more, to be installed and used in monitoring the power conditions of factories.

Background



Figure 1. Extech 3-Phase Power Analyzer/Datalogger

The Extech 3-Phase Power Analyzer/Datalogger was assigned by our sponsor, Great Lakes Control & Engineering, as a case study for this project. We are expected to create a new power monitoring device which would replicate the primary functions of the Extech device, with additional support features solving some of its shortcomings.

The first major shortcoming of the Extech device is its huge minimum sampling rate of 2 seconds and inability to detect transient data. Our sponsor desires a sampling rate of 100 milliseconds to enable more efficient detection of transients. The other main shortcoming of the Extech device are its lack of internet connectivity; the sponsor desires internet connectivity to enable the device send out email alerts at the occurrence of transient data.

Design Specification

The main objective of this project according to the team's sponsor is stated as:

“The purpose of this project is to develop a three-phase four-wire AC power monitoring system capable of data logging voltage phase-phase, voltage phase-ground, current, and power. The system will alert a user at the occurrence of any transient event, as well as permit the user the ability to change the sampling rate, and possess enough memory to log data for 1 week with a sampling rate of 100 milliseconds.”

The product design specifications, according to the sponsor:

1. *System must run off 120 VAC wall outlet*
2. *Ability to measure voltages up to 600 VAC*
 - a. *Voltage clamps must be used to clamp onto system being monitored*
 - i. *Quick disconnects into the system must be used.*
 - b. *Voltage resolution: $\pm 1\%$*
3. *Ability to measure current up to 100 Amps*
 - a. *Current loops must be used to loop around system being monitored*
 - i. *Quick disconnects into the system must be used.*
 - b. *Current resolution: $\pm 1\%$*
4. *Memory to log data for 1 week with a sampling rate of 100 milliseconds*
5. *User interface for control of system, data viewing*
 - a. *Control of;*
 - i. *Sampling rate*
 - ii. *Time clock*
 - iii. *Voltage transient reference*
 - iv. *Voltage $\pm$ % for transient*
 - v. *Clear all data function*
 - vi. *Copy data to external memory device*
 - vii. *Enter location of system (zip code)*
 - b. *Monitor;*
 - i. *Current voltage, amperage, and power*
 1. *Line voltage, phase voltage, line current, true power.*
 - ii. *Voltage, amperage, and power versus time graph*
 - iii. *Transient events that occur, along with time stamp of when occurrence took place*
 1. *Voltage swell, dip or outage*
 2. *Elapsed time event occurred*
6. *USB memory stick port for removal of data*
7. *Internet capabilities to alert user via email if any transient event occurs*
 - a. *Voltage swell, dip or outage*
 - b. *Elapsed time event occurred*
 - c. *Time stamp of occurrence of event*
 - d. *A current weather condition of area in zip code system is placed.*

Finally, the deliverables according to the sponsor:

1. *Power monitoring system*
2. *Wire clamps for voltage x4*
3. *Wire loops for current x3*
4. *Bill of material for all parts used*
5. *Electrical Schematics*
6. *Operator manual*
7. *Software code utilized for data collection.*

FAST Diagram

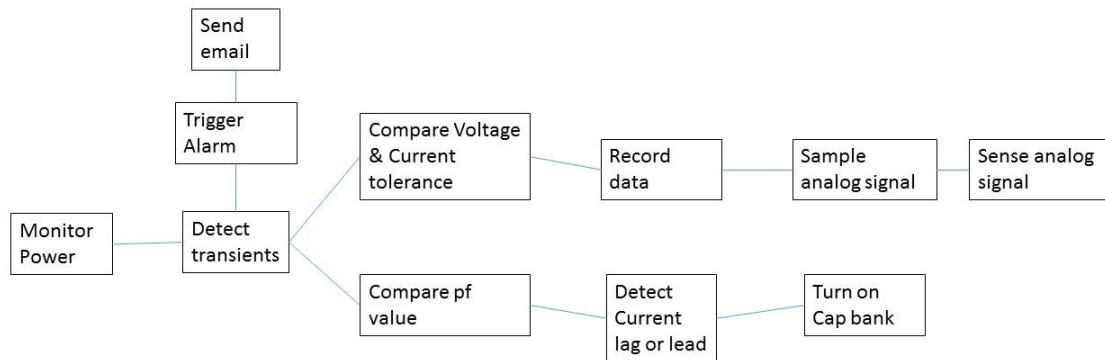


Figure 2. Proposed FAST diagram

Conceptual Design Descriptions

One of our initial concerns dealt with how to go about packaging the unit. Our foremost idea was to have all components, from the transformers to microcontroller, backup battery, etc., packaged within the same box. This raised some safety concerns as the 480 V coming into the box could create an arc flash hazard. After discussing these concerns with our sponsor, Great Lakes Controls & Engineering, we came up with a solution of sectioning off the transformers with plexiglass to resolve the concern. The reason for packaging all the components in one box is to allow for easy movement of the device. Keeping mobility, safety, and expanded functionality in mind, a new packaging solution was devised. It consists of a dual module interlocking system. One module consists of the transformers while the other consists of the battery backup, microcontroller, any other hardware under 12 V. The transformer module will sit on top of the controller module, latched into place. A connector will be used to take the output from the transformer, 2.5 V peak to peak, into the controller module so that power can be monitored. This design satisfies all our criteria. It has the same mobility as a standalone unit because the two modules lock into place, essentially acting as one unit. It is safer than the original design because the controller module is completely isolated from the 480V in the transformer module. This is important because the controller module will have to be opened in order to access the memory device that is storing the logged power data. Finally, this design meets the goal of expanded functionality. It does so by allowing the transformer module to be removed. What this means is that the same controller module can be used to monitor three phase power with different voltages. For example, one transformer module could be designed for 480 V input, while another could be designed for 240 V. As long as the transformers stepdown the voltage to 2.5 V peak to peak, contain the same latching hardware specified by the controller module, and have

the same connector to interface with the controller module, the exact same controller module can be used across a vast platform of power systems.

Apart from the ability to detect voltage or current transients, the device is also required to send an email notification whenever a transient is detected. This raises concerns regarding how the email address will be entered into the system. The initial idea was to design the device with three buttons to enable the email address to be input into the system. One button would scroll down through the alphabet, another would scroll up through the alphabet, and the last would be used to select the current character. This idea comes with the benefit of the ability to input the email address at any point in time, but the disadvantage of being slow, as it would be time-consuming scrolling through the alphabets for each letter. We then had the idea to pre-store the email address on a MicroSD card and program the device to read the email address off it. This method would be quicker for initial setup, however, a computer would be required to preset the email address on the MicroSD card. This method also comes with an additional security benefit, as a random person would not be able to change the destination email address without taking out the MicroSD card and having to go edit the programming on a computer.

Proposed Design Solution

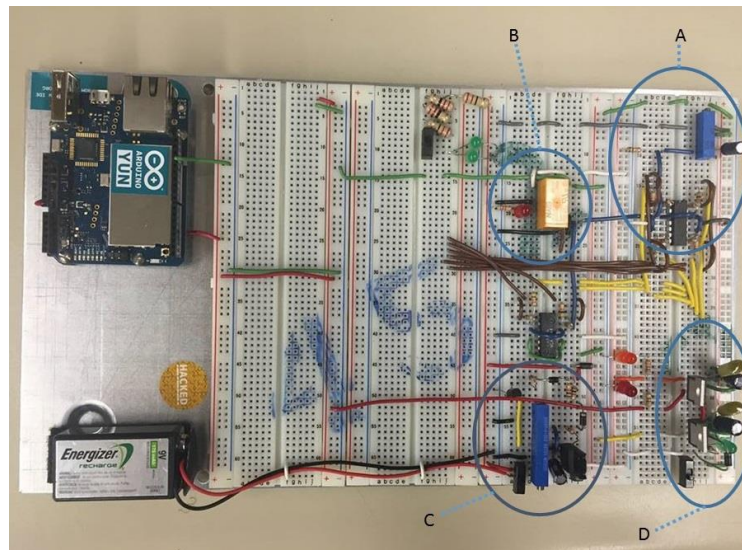


Figure 3. Top view of the overall circuit highlighting different parts.

The most vital part of our design is the circuit's ability to take an input voltage or current signal and convert it to a format our microcontroller can sample. Our microcontroller can only read voltages ranging from 0 to 5 V. To solve this issue, we designed a summing amplifier that would scale down the input signal and also add a 2.5

V DC offset, which would enable us to properly see the sine wave of the voltage or current input signal.

We plan to use transformers that will step down the signals to a 5 Vrms voltage; therefore, we will have an input of roughly 15 Vpp. If we build an inverting summer, the signal will be inverted which would not distort any information as long as each signal was inverted. We can also choose resistors such that the input signal is scaled down by a value of 4.7. If we are able to get a 5 Vpp input to the microcontroller, it would mean our input to the signal conversion circuit would be, $4.7 \times 5 = 23.5$ Vpp, well suited to handle the expected 15 Vpp signal. We used to quad operational amplifiers to realize this design as can be seen in part A of Figure 3.

To create the DC offset, we used a voltage divider with a variable pot to grant us the ability to control the output offset through calibration. The input terminals of the operational amplifier have a high impedance so there is little concern of loading effects while using a voltage divider and to create a stiff voltage, we used capacitors tied to ground. The signal conversion circuit schematic can be found in Figure 4 below:

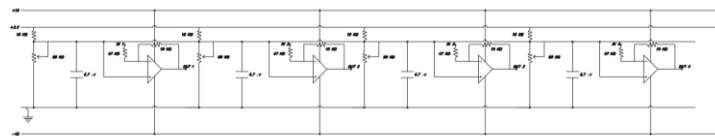


Figure 4. Signal conversion unit

To power our circuit, we plan to use a 120AC/12VDC converter. However, our micro controller does not have an on board regulator and requires a regulated 5 VDC power supply. To accommodate this requirement, we built a circuit to provide a regulated 5 V and 3.3 V source incase if needed. The design comes from research and availability of parts from the ECE 480 class lab at Michigan State University. We added LEDs with current limiting resistors to give an indication of a voltage presence at the output of each voltage regulator. The circuit can be seen in part D of Figure 3 and the schematic for the circuit can be found in Figure 5 below:

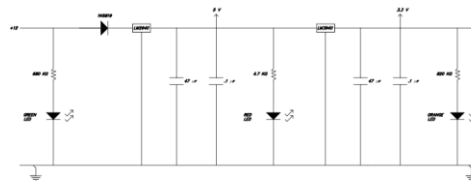


Figure 5. Input voltage circuit

Another major issue we wanted to overcome, not included in the design specifications, was the concern for a loss of power. The product is intended for use in a factory setting, where after it is installed, there could possibly be no human interaction

other than when an alarm rings out. Therefore, if the unit undetectably loses power, any voltage or current transients would go unnoticed and no email notification will be sent. If no transients are suspected, no one will think to have any interaction with the product. As a resolution, we designed a back up battery with a charging circuit.

To build a battery charging circuit that would have an overcharge protection, we referred to a conceptual design in Dr. Wierzba's ECE 402 class notes ^[2]. The circuit can be seen in Figure 6 below. We used an LM317 voltage regulator so that we could vary the output voltage using a potentiometer. If the voltage charging the battery gets too high, the zener diode will conduct and forward bias the transistor. When the transistor is forward biased, the output of the voltage regulator will drop and the diode at the top of the circuit will prevent the battery from backfeeding the regulator. We chose a 9 V rechargeable battery that has a nominal voltage of 8.4 V. The components and settings of the circuit were chosen such that the battery will charge to 8.6 V with a maximum current of 20 mA. These parameters came from research of the specifications of the battery charger designed for this battery.

We also included a discharge design in this circuit, which utilizes a switch to add a load to the battery for testing purposes. This is made of a series of four 22- Ω resistors.

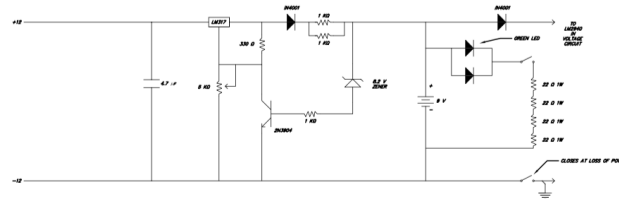


Figure 6. Battery charger circuit

In order for the battery charger to work, a 24 V supply was needed. However, when the battery is required to power the circuit, the negative terminal must be connected to the circuit ground. To solve this issue, we used an undervoltage relay to close a contact that shorts the negative 12 V supply to ground when there is a loss of power. We also used a contact on the relay to turn on a red LED to signal the loss of input power. We plan to use inverted logic as an input to the micro controller to signal a loss of power. If the input is shorted to ground, external power is present, and if it is floating, there is a loss of power. The schematic for the circuit can be found in Figure 7 below and a picture can be seen in part B of Figure 3.

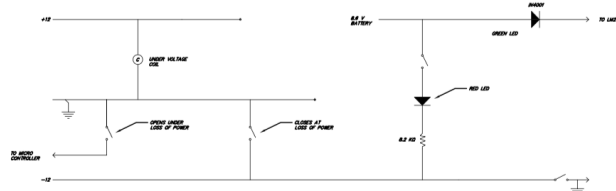


Figure 7. Loss of AC switchover circuit

The microcontroller we selected for the project is the Arduino Yun. Although Arduino is seen as more of a hobbyist controller, given our short timeframe for the project and the inexperience of the team in terms of computer programming, this microcontroller serves as the best choice for multiple reasons. There are many open source codes and information on the internet pertaining to our project like for sending emails, writing to LCD displays, writing to USB, to name a few. This selected microcontroller also has 6 analog inputs for our signal sampling, an Ethernet port, microSD port, a USB port, and enough digital input/output ports to write to the LCD screens and our pushbutton inputs. With this controller, we can sample the signals, program any settings with the pushbuttons, save data to the microSD, send emails, and export data to a USB drive.

A limiting factor of our selected microcontroller was the number of inputs/outputs, as we would need a total of nine digital pins on the microcontroller in order to control the four LCD screens. Seeing as we would need pins for various applications, there was a need to reduce the number of pins used for the LCDs without reducing the number of LCD's. In order to do this we would have to use I²C communication, therefore, we would need to buy modules that allow the LCD's to use this form of communication by giving the LCD's an address, where no LCD shares the same address.

The major parts of our conceptual design that remain unfinished are the programming of the microcontroller to process the input signals, send emails, write data to either a USB or a microSD, and a clipping circuit to protect our product from large voltage or current transients.

Risk Analysis

Due to nature of the project, the main risks associated with this project are all as a result of the high voltage and current involved with it. Firstly, the system should be able measure voltages and currents up to 600 VAC and 100 Amps respectively. Exposure to such could result in severe health defects and even death. To improve the safety of the unit, the team plans to have a section strictly for the transformers and the input of the voltage and current within the unit, secluded with plexiglass. The system would also have voltage and current clamps.

Secondly, some concerns regarding the internal components would be the possibility of voltage or current transients defecting the parts within the device and the possibility of the storage memory becoming corrupted. With regards to this voltage or current transient's risk, the team plans to set up clipping diodes within the circuits to protect against that fear.

Finally, other risk factors to consider would be heat dissipation of the components within the overall unit, as well as, possible power shortages into the device or the device being connected to a bad power outlet. To accommodate the possible heat dissipation of the components, the team currently plans to leave 25% free space inside the unit or install a cooling fan within the unit if possible. The loss of power switch-over circuit (Figure 7) and battery charger circuit (Figure 6) will serve as a precaution to have the device operational in the case of a bad power outlet or anything that would cause a power loss.

Project Management Plan

Personnel

In order to successfully meet the sponsor's requirements and in due time, the team divided the project tasks between its members. The duties for each team member are as follows:

McCormick, James - General Management

James, the General Manager of the team, is in charge of the overall coordination and supervision of the project. He will play a part in the supervision of every aspect of the project and work with all other coordinators in making sure all tasks are completed promptly and efficiently. Being the only member with prior experience with power, thanks to his time working with Consumers energy, he will be in charge of researching, developing and testing all the necessary circuits needed for proper functioning of the device. This includes, but is not limited to, designing power inputs for the circuit and microcontroller, developing the circuit which would sample the signal, designing the backup power and capacitor bank for the circuit.

He will also mainly be in charge of all hardware configuration and testing. He will work closely with the lab coordinator in the main programming of the project, as they both have the most experience in the related fields.

Lange, Alex - Lab Coordinator

Alex will primarily be in charge of the supervision of all laboratory equipment, experiments and procedures. He will be tasked with placing orders for any needed parts, as well as maintenance of all the equipment and the team's assigned locker. Being the only member of the team with prior experience with the team's chosen microcontroller, Arduino, he would also be in charge of all programming related tasks. These include researching, developing and testing all codes and programs to meet the deliverables as requested by the sponsor.

He will also work closely with the team's General Manager in the design, development and testing of the circuits; and work closely with the team's webmaster in maintaining the team's online platform. Apart from his main duties and tasks, he will also play a part in the preparation of the team's documents and presentations.

Ezenwoko, Victor Tobenna - Documentation Manager

Victor would primarily be in charge of coordinating all forms of documentation regarding the team. His main tasks would include taking notes during each team meeting, to the preparation, review and supervision of all needed documents for submission, and the final operator manual for the device; where he would prepare the skeleton and majority of the documentation, and assign other parts to the rest of the team members. Afterwards, he would review all documentation ensuring they meet all requirements and the team's quality standards. He will also work closely with the presentation manager in the preparation of written, visual and oral presentations.

Apart from the documentation responsibilities, Victor, in conjunction with the presentation manager and webmaster, will also be in charge of monitoring the logistics behind the project and providing additional research and physical assistance to the General Manager and Lab coordinator.

Jebb, Jacob - Presentation Manager

Jacob would primarily be in charge of coordinating all forms of representation regarding the project. This includes, but is not limited to, the preparation, review and supervision of all needed visual and oral presentations. He will also be in charge of capturing images and videos of all concepts, ideas, progress and prototypes. He will also be tasked with creating digital representation of all schematics, calculations and designs. He will also work closely with the documentation manager in the preparation of all necessary documentation.

Apart from the presentation responsibilities, Jacob, in conjunction with the documentation manager and webmaster, will also be in charge of monitoring the logistics behind the project and providing additional research and physical assistance to the General Manager and Lab coordinator.

Qian, Zhihoug - Webmaster

Zhihoug is primarily in charge of coordinating the team's online image and platform. This not only includes the creation, design and maintenance of the website, but also involves ensuring all the team's documents and media are available on the website, and creating a respectable brand for the team. He will also work closely with the lab coordinator in the programming of our device.

Apart from the website responsibilities, Zhihoug, in conjunction with the documentation and presentation managers, will also be in charge of monitoring the

logistics behind the project and providing additional research and physical assistance to the General manager and Lab coordinator.

Time Schedule

The team designed a time schedule for this project in the form of a GANTT chart. The GANTT chart can be found below broken down into Figure 8a, 8b, and 8c.

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessor	Resource Names
1		Project Definition	6 days	Wed 9/9/15	Wed 9/16/15		
2		group meet, outline questions of topic	2 days	Wed 9/9/15	Thu 9/10/15		Everyone
3		meet with sponsor, address questions,	2 days	Fri 9/11/15	Mon 9/14/15	2	Everyone
4		group meet, define project in words	1 day	Tue 9/15/15	Tue 9/15/15	3	Everyone
5		meet with facilitator, present topic	1 day	Wed 9/16/15	Wed 9/16/15	4	Everyone
6		Research Topic	3 days	Thu 9/17/15	Mon 9/21/15		
7		Research professional monitoring systems	2 days	Thu 9/17/15	Fri 9/18/15	5	Everyone
8		Research Hobby monitoring systems	2 days	Thu 9/17/15	Fri 9/18/15	5	Everyone
9		Brainstorm individual ideas	1 day	Mon 9/21/15	Mon 9/21/15	8	Everyone
10		Combine rough Ideas	1 day	Tue 9/22/15	Tue 9/22/15		
11		meet with group, discuss ideas	1 day	Tue 9/22/15	Tue 9/22/15	9	Everyone
12		define feasible ideas	1 day	Tue 9/22/15	Tue 9/22/15	9	Everyone
13		choose one direction to head in	1 day	Tue 9/22/15	Tue 9/22/15	9	Everyone
14		Ordering Parts	26 days	Thu 9/24/15	Thu 10/29/15		
15		Order microcontroller	7 days	Thu 9/24/15	Fri 10/2/15	29	Alex
16		Order ethernet shield	7 days	Thu 9/24/15	Fri 10/2/15	29	Alex
17		order USB shield	7 days	Thu 9/24/15	Fri 10/2/15	29	Alex
18		Order LCD screens	5 days	Mon 10/5/15	Fri 10/9/15	17	Alex
19		Order push buttons/knob	5 days	Mon 10/5/15	Fri 10/9/15	48	James
20		Order AC loss alarm relay	5 days	Mon 10/5/15	Fri 10/9/15	47	James
21		Order signal conversion supplies	5 days	Fri 10/9/15	Thu 10/15/15	51	James
22		Order AC current clamps	5 days	Fri 10/23/15	Thu 10/29/15	55	James
23		Order cap control relay	5 days	Thu 10/1/15	Wed 10/7/15	37	James
24		Order plexiglass	5 days	Fri 10/23/15	Thu 10/29/15	55	James
25		Order step down transformers	5 days	Fri 10/23/15	Thu 10/29/15	55	James
26		Order wire/terminals/rails	5 days	Fri 10/23/15	Thu 10/29/15	55	James
27		Order final box	5 days	Fri 10/23/15	Thu 10/29/15	55	James
28		Micro-controller	11 days	Wed 9/23/15	Wed 10/7/15		
29		Research microcontrollers to use	1 day	Wed 9/23/15	Wed 9/23/15	13	Jake/Alex
30		Develop code to write to LCD screen	1 day	Wed 9/23/15	Wed 9/23/15	13	Alex

Figure 8a.

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessor	Resource Names
31		Develop code to read RMS values	2 days	Wed 9/23/15	Thu 9/24/15	13	Alex
32		Develop sample values to test RMS code	1 day	Fri 9/25/15	Fri 9/25/15	31	Victor
33		Develop code to send emails	3 days	Wed 9/23/15	Fri 9/25/15	13	Jake
34		Develop code to read weather from	3 days	Wed 9/23/15	Fri 9/25/15	13	Victor
35		Develop code to write to USB	3 days	Wed 9/23/15	Fri 9/25/15	13	Alex
36		Develop code to calculate PF	2 days	Mon 9/28/15	Tue 9/29/15	32	Alex
37		Develop code for cap control output	1 day	Wed 9/30/15	Wed 9/30/15	36	Alex
38		develop code to calculate True power	1 day	Wed 9/30/15	Wed 9/30/15	36	Alex
39		Develop code for pushbutton/alarm inputs	1 day	Thu 10/1/15	Thu 10/1/15	38	Alex
40		Develop code for processing inputs	4 days	Fri 10/2/15	Wed 10/7/15	39	Alex/Jake/Victor
41		Hardware	12 days	Wed 9/23/15	Thu 10/8/15		
42		Research step down transformers	3 days	Wed 9/23/15	Fri 9/25/15	13	James
43		research push buttons	3 days	Wed 9/23/15	Fri 9/25/15	13	James
44		research battery packs	3 days	Wed 9/23/15	Fri 9/25/15	13	James
45		research power supplies	2 days	Mon 9/28/15	Tue 9/29/15	44	James
46		design power circuit	2 days	Wed 9/30/15	Thu 10/1/15	45	James
47		design loops of AC circuit	1 day	Fri 10/2/15	Fri 10/2/15	39	James
48		design knob/push button inputs	1 day	Fri 10/2/15	Fri 10/2/15	39	James
49		design USB port interface	3 days	Mon 9/28/15	Wed 9/30/15	35	Victor
50		research current clamps	3 days	Thu 9/24/15	Mon 9/28/15	29	James
51		design signal conversion to	10 days	Fri 9/25/15	Thu 10/8/15	31	James/Jake/Victor
52		Prototype 1	6 days	Thu 10/15/15	Thu 10/22/15		
53		Build sample enclosure	1 day	Thu 10/15/15	Thu 10/15/15	73	James
54		brainstorm layout	1 day	Fri 10/16/15	Fri 10/16/15	53	Everyone
55		assemble parts	4 days	Mon 10/19/15	Thu 10/22/15	54	Everyone
56		Final design	12 days	Fri 10/23/15	Mon 11/9/15		
57		Brainstorm layout	2 days	Fri 10/23/15	Mon 10/26/15	55	Everyone
58		Assemble parts	7 days	Fri 10/30/15	Mon 11/9/15	27	Everyone
59		Web Design	33 days	Wed 9/23/15	Fri 11/6/15		
60		research old websites for ideas	2 days	Wed 9/23/15	Thu 9/24/15	13	Everyone

Figure 8b

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessor	Resource Names
61		meet with group, create outline	1 day	Fri 9/25/15	Fri 9/25/15	60	Everyone
62		start skeleton of website	5 days	Mon 9/28/15	Fri 10/2/15	61	Zhihong
63		fill in body	10 days	Mon 10/5/15	Fri 10/16/15	62	Everyone
64		update	10 days	Mon 10/19/15	Fri 10/30/15	63	Zhihong
65		finish website	5 days	Mon 11/2/15	Fri 11/6/15	64	Zhihong
66		Testing	36 days	Mon 9/28/15	Mon 11/16/15		
67		Complete ethernet interface	3 days	Mon 10/5/15	Wed 10/7/15	16	Everyone
68		Complete sending emails	3 days	Mon 10/5/15	Wed 10/7/15	16	Everyone
69		Complete writing to USB	3 days	Mon 10/5/15	Wed 10/7/15	17	Everyone
70		Complete reading sample RMS values	3 days	Mon 9/28/15	Wed 9/30/15	32	Everyone
71		Complete Reading analog RMS values	3 days	Mon 10/5/15	Wed 10/7/15	15	Everyone
72		Complete display on LCDs	3 days	Mon 10/12/15	Wed 10/14/15	18	Everyone
73		Complete pushbutton/alarm inputs	3 days	Mon 10/12/15	Wed 10/14/15	20	Everyone
74		Complete Cap control	3 days	Thu 10/8/15	Mon 10/12/15	23	Everyone
75		Complete prototype	5 days	Fri 10/23/15	Thu 10/29/15	55	Everyone
76		Complete final design	5 days	Tue 11/10/15	Mon 11/16/15	58	Everyone
77							

Figure 8c

Cost

The team was assigned a budget of \$500 by the University, however, after meeting and discussing with our sponsor, Great Lakes Controls & Engineering, we were instructed not to lay much emphasis on the budget as they would provide any needed necessary components they had or would order any component which would affect the University given budget. Such components include the step-down transformers, enclosure

for the unit, and the current/voltage clamps. Based on this knowledge, the sponsor provided components have been kept out of the budget. Components used in the circuit which were free and provided by the ECE shop were also excluded from the budget.

The budget breakdown for the project can be seen in Table 1 and Figure 9.

Quantity	Item	Cost
2	Arduino YÚN Microcontroller	\$138.54
4	Basic 16x2 Character LCD - White on Black 5V	\$39.80
4	I2C Serial Interface Board Module LCD	\$8.36
1	64GB MicroSD Card	\$35.99
	Total:	\$222.69

Table 1. Budget breakdown list

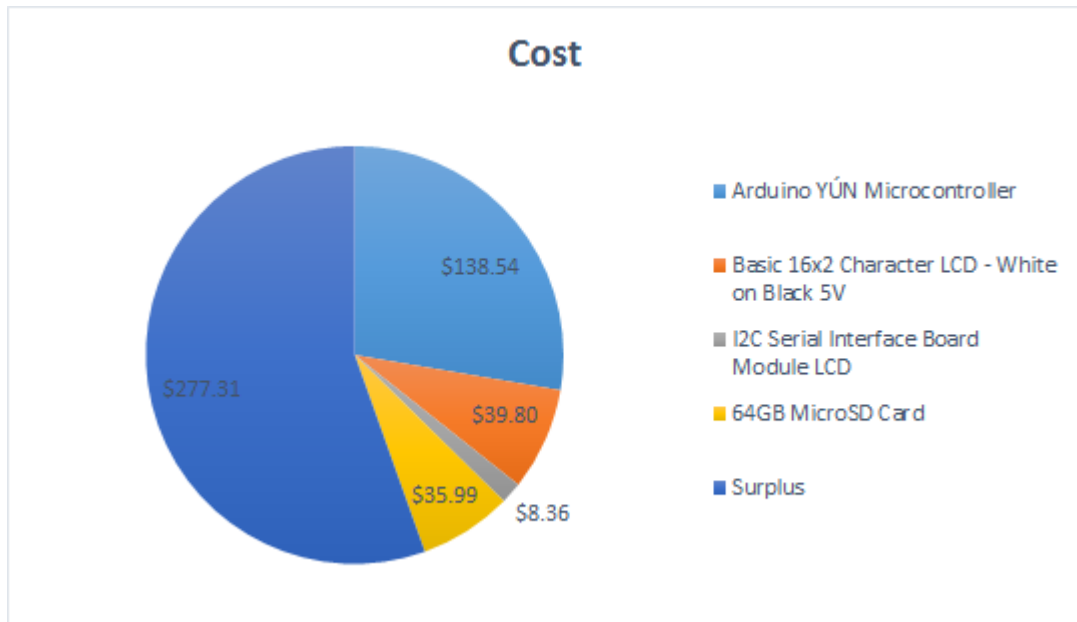


Figure 9. Budget breakdown chart

References

[1] 1200A 3-Phase Power Analyzer/Datalogger, Extech Instruments Product Datasheet, 2009. Authorship by Extech Instruments Corporation.

[2] ECE 402 Applications of Analog Integrated Circuits Course e-Notes, 2015. Authorship by Gregory M. Wierzba.