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MODELING POWER GRID WITH BATTERY STORAGE FOR BELD. DATA ACQUISITION.

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MODELO DE LA RED ELÉCTRICA CON ALMACENAMIENTO EN BATERÍAS PARA BELD. ADQUISICIÓN DE DATOS.

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RESUMEN DEL PROYECTO

El objetivo principal de este proyecto es crear una herramienta que pueda ser utilizada para analizar baterías en el contexto de almacenamiento de energía eléctrica. Con este proyecto se da una recomendación a Braintree Electric Light Department, compañía eléctrica, sobre qué tipo batería es la óptima para su red eléctrica.

1. Introducción

Braintree Electric Light Department (BELD) tiene centrales eléctricas tanto renovables como no renovables que generan electricidad para la zona de Massachusetts. Cuando la demanda de electricidad es alta, generadores complementarios se encienden, incrementando el coste y por tanto el precio de la electricidad. El objetivo de este proyecto es proporcionar a BELD una herramienta con la cual baterías puedan ser analizadas. Como consecuencia de esto, se podrá determinar qué tipo de batería es la idónea para esta compañía eléctrica. Este proyecto mostrará a su vez los beneficios del almacenamiento de energía en baterías tales como dar estabilidad a la red.

2. Definición del proyecto

El proyecto consiste en un modelo físico de la red eléctrica. Este modelo incluye un sistema de almacenamiento de energía con baterías que será utilizado para analizar las distintas clases de baterías tales como la de ión-litio. Las instalaciones de almacenamiento de energía son caras por lo que un análisis de qué batería es la adecuada puede ser de gran utilidad para BELD. El resultado final del trabajo es un modelo físico a pequeña escala con una adquisición de datos automática que ayudará al análisis de las baterías.

El producto final está colocado en un contenedor de cristal acrílico para que sea seguro y que pueda ser movido con facilidad. Dicho producto contiene cuatro partes principales: la generación y distribución, el sistema de baterías, la simulación de la curva de demanda y la adquisición de datos.

3. Descripción del proyecto

El proyecto puede ser divido en cuatro partes cuyo esquema se muestra en la siguiente ilustración.
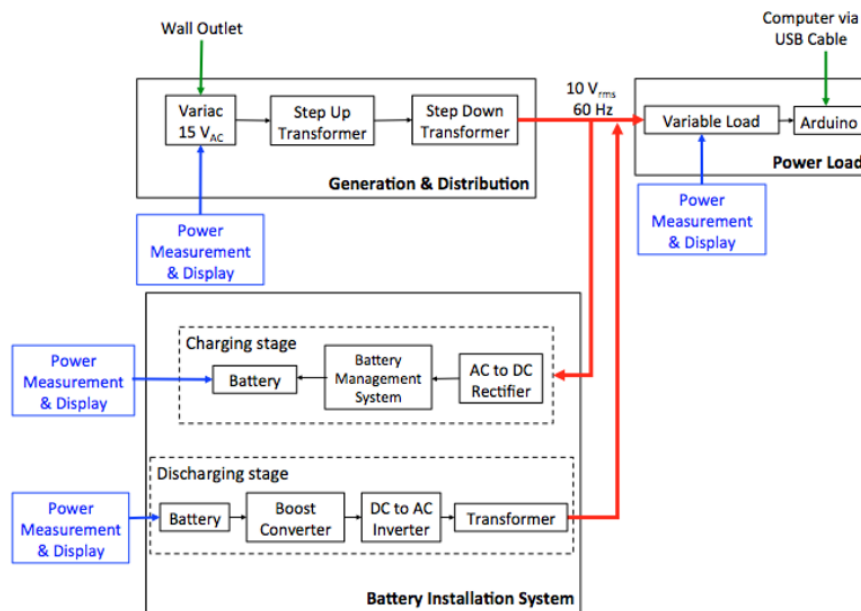

Ilustración 1. Esquema general del proyecto.

Para la generación y distribución se han usado tres transformadores: un variac para la generación y dos transformadores que simularán la red de distribución de BELD. La curva de demanda será simulada mediante una resistencia variable. Se pueden representar por tanto distintos escenarios de demanda. El sistema de almacenamiento en baterías está dividido en una estación de carga y otra de descarga. Cada uno de estos subsistemas está conectado con circuitos capaces de medir la potencia eléctrica. Dichos datos se guardarán automáticamente para su análisis.

4. Resultados

El objetivo del proyecto no es solo analizar determinadas baterías sino dar la herramienta para que esto sea posible. Por tanto, el resultado del proyecto es el modelo físico en pequeña escala de la red que puede verse a continuación.
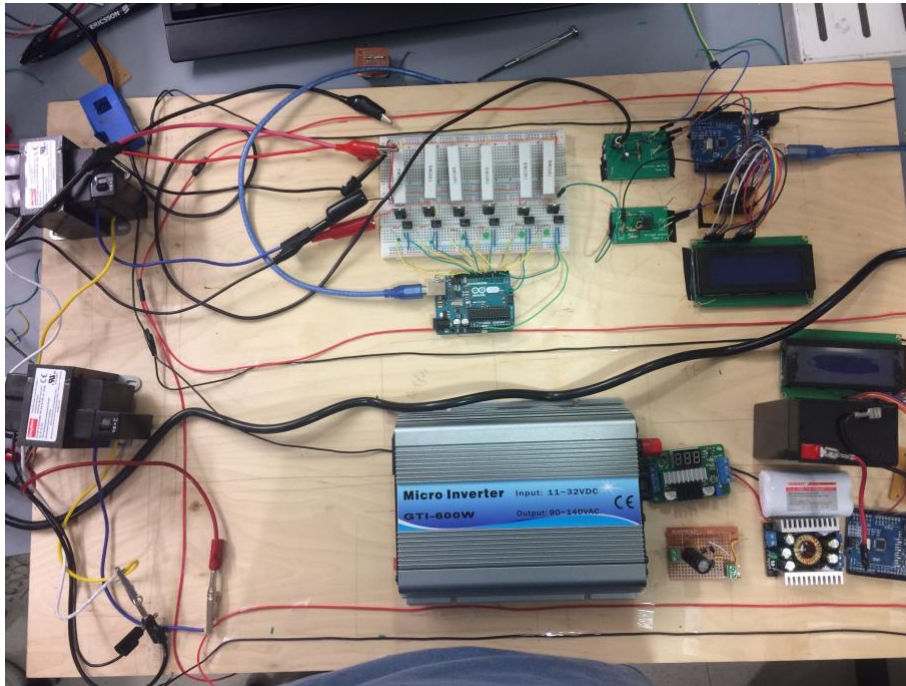

Ilustración 2. Simulación de la red a pequeña escala.

5. Conclusión

El almacenamiento de energía en baterías aún no se ha desarrollado sustancialmente como para poder competir con otras tecnologías similares. Sin embargo, en los últimos años ha habido un incremento de la utilización de esta tecnología en compañías eléctricas.

Este proyecto ha servido como fundamento para el análisis de baterías y proporcionará una herramienta de utilidad para poder estudiarlas y realizar pruebas con ellas.

MODELING POWER GRID WITH BATTERY STORAGE FOR BELD. DATA ACQUISITION

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ABSTRACT

The main objective of this project is to create a tool that can be used to analyze batteries in the context of electrical energy storage. With this project, a recommendation is given to Braintree Electric Light Department, a utility company, on what type of battery is optimal for their grid.

1. Introduction

Braintree Electric Light Department (BELD) has both renewable and non-renewable power plants that generate electricity for the Massachusetts area. When electricity demand is high, complementary generators are switched on, increasing the cost and therefore the price of electricity. The objective of this project is to provide BELD with a tool with which batteries can be analyzed. As a consequence of this, it will be possible to determine what type of battery is suitable for this electric company. In addition to this, the project will show the benefits of energy storage in batteries such as providing stability to the network.

2. Project overview

The project consists of a physical model of the electric grid. This model includes a battery energy storage system that will be used to analyze different types of batteries such as lithium-ion batteries. Energy storage facilities are expensive, so an analysis of which battery is preferable can be very useful for BELD. The final result of the work is a small-scale physical model with an automatic data acquisition that will help the analysis of the batteries.

The final product is placed in an acrylic glass container so that it is safe and can be moved easily. This product contains four main parts: the generation and distribution, the battery system, the simulation of the demand curve and the data acquisition.

3. Project description

The project can be divided into four parts whose outline is shown in the following figure.
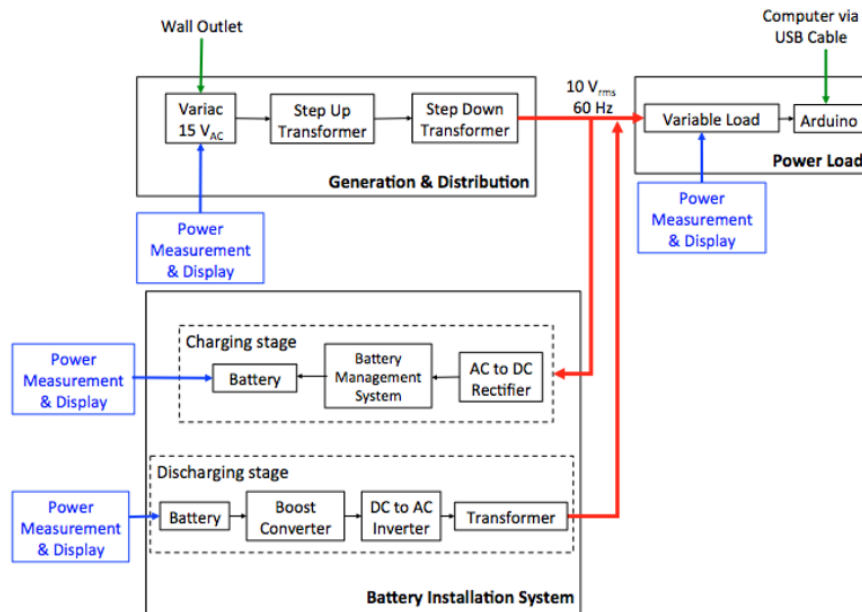

Figure 1. System overview.

For the generation and distribution, three transformers have been used: a variac for the generation and two transformers that will simulate BELD's distribution grid. The demand curve will be simulated by a variable resistance. Therefore, different demand scenarios can be represented. The battery storage system is divided into a charging station and a discharging station. Each of these subsystems is connected with circuits capable of measuring electrical power. These data will be automatically saved for its analysis.

4. Results

The objective of the project is not only to analyze certain batteries but also to provide the tool to make this possible. Therefore, the result of the project is the small-scale physical model of the network that can be seen below.
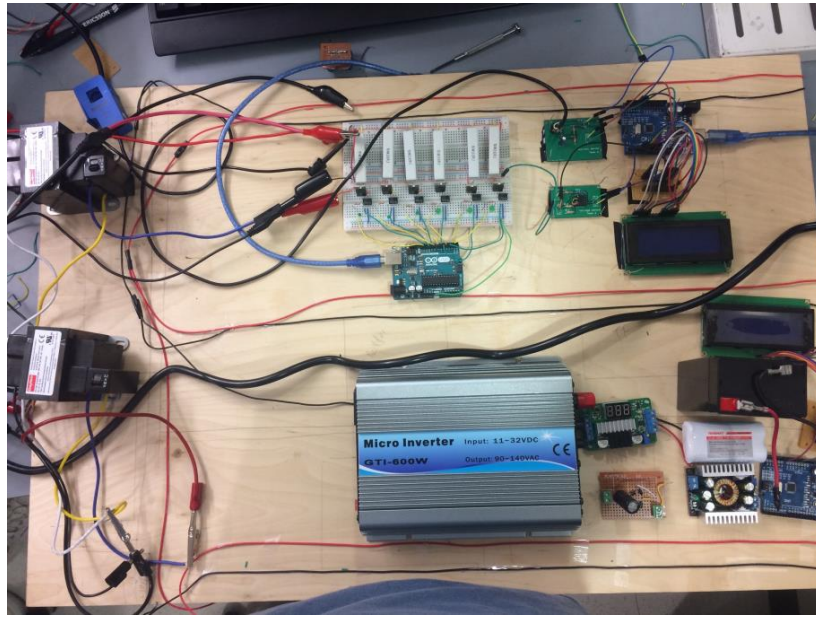
Figure 2. Small-scale physical mock grid.

5. Conclusion

The storage of power in batteries has not yet been developed substantially to be able to compete with other similar technologies. However, in recent years there has been an increase in the use of this technology in utilities.

This project has served as the basis for the analysis of batteries and will provide a useful tool to study and perform tests on them.

INDEX:

FIGURE INDEX:

TABLE INDEX:

EQUATION INDEX:

PART I: REPORT

Chapter 1: Introduction

1.1. Motivation

The motivation for this project as well as some background and an overview of the project will be given in this section.

1.1.1. Problem statement

Braintree Electric Light Department (BELD) is a local utility company based in Braintree. They are considering investing in battery storage for their utility. BELD wants our team to investigate different battery chemistries, in order to determine which battery installation is more efficient, cost effective and optimal for their utility.

BELD has multiple traditional and renewable power-plants that supply the state of Massachusetts. When the demand for electricity is high, it puts a significant pressure on the power-plants, especially if the renewable plants (i.e. solar and wind) do not produce enough to meet the demand. With this project several tests will be performed on batteries to show how they can contribute to peak-load-shaving and provide stability to the grid.

1.1.2. BELD's background. Battery storage in BELD

To this day BELD has four power plants: Potter II, two Thomas A. Watson and a diesel unit [1]. As BELD is a member of the New England Power Pool (NEPOOL) these four power plants have the duty of providing reliability to the grid as well as sustaining an open nondiscriminatory market [2]. NEPOOL GIS distributes certificates related to the power produced in the New England area. It also takes into account the power imported to New England from nearby power plants. Their certificates range from emission reports of the generators in the region to load management certificates. The fact that BELD is a

member of NEPOOL is relevant to the development of battery storage. This is because the integration of storage technologies can have a huge effect in the rest of the members of this organization in terms of the reliability and sustainability of the grid in the New England area.

The four power plants can be classified depending on their size. The first one, Potter II, is a combined-cycle plant with a maximum output of 96 MW. The second and third one called the Thomas A. Watson have a maximum output of approximately 58 MW. They are quick-start simple-cycle turbines. Lastly, the diesel unit has an output of 2 MW [3]. A figure of BELD's power mix is shown below.
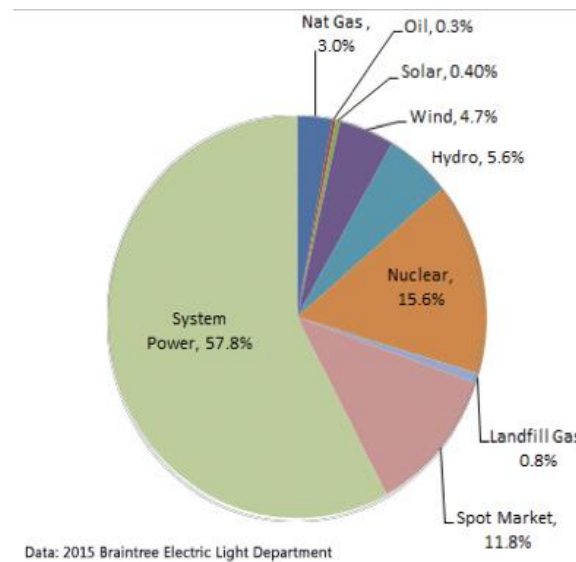
Figure 3.BELD's power mix. [4]

New laws have been implemented in the area that demand a certain amount of collaboration between utilities. This means that out of the maximum power output of the Thomas A. Watson power plants only 30% can be used by BELD while the rest is under contract to seven other public utilities. As for Potter II, BELD uses up to 88 MW and the remaining 8 MW are sold to other utilities and municipal light plants [5]. By retaining most of their produced power and selling the rest, BELD ensures that the customer has the lowest possible rates.

On December of 2017, Massachusetts Clean Energy Center (MassCEC) awarded a grant to Borrego Solar Systems. Borrego Solar Systems in collaboration with BELD will invest the grant of $700,000 in a 2 MW/4.2 MW lithium-ion battery storage unit [6]. The unit will be installed in one of BELD's substations. However, to this day, BELD does not have a significant amount of energy stored in a battery storage unit. Therefore, our project of modeling the power grid with battery storage is relevant to BELD as it tries to show the benefits of this technology in terms of reliability as well as the peak shaving that can be accomplished to reduce costs.

1.2. Project overview

The project consists of a physical model of the power grid. This power grid has a battery storage system that tests multiple battery chemistries such as lithium-ion, nickel-cadmium, and lead-acid to help analyze which battery is optimal for BELD's utility. Battery storage systems are very expensive, so a real in-depth analysis of various battery chemistries in a small scale and cost-effective way will help them make that decision. The final deliverable is a physical grid network with various battery installations and with real time data acquisition such that the user can experiment and analyze the data collected. The physical model will be put into a compact container such that it can be easily moved for further testing. There will be four main subsystems in our power grid which are the power generation and distribution system, the loads that will consume this power, the battery system to either charge, or discharge power to the loads, and the data acquisition. The power grid model will feature live characterization readings from the batteries, generation, and loads such that the user can run the model and analyze it.

Firstly, three transformers were used (a variac transformer, a step-up transformer, and a step-down transformer) to model the generators and distribution lines of BELD. Secondly, the power demand of Braintree is modelled using resistive loads. These loads are variable so that different states of the demand curve can be simulated. Thirdly, different batteries are integrated into the grid to model the batteries that BELD could potentially use. Furthermore, various microcontrollers are used to measure voltage, current and power consumption at every stage of the circuit. In addition to this, data of

the behavior of the batteries is gathered using the model grid. With this data a report is created stating the advantages and disadvantages of the various batteries and configurations. A summarized visual of the overall parts of the project is shown below.
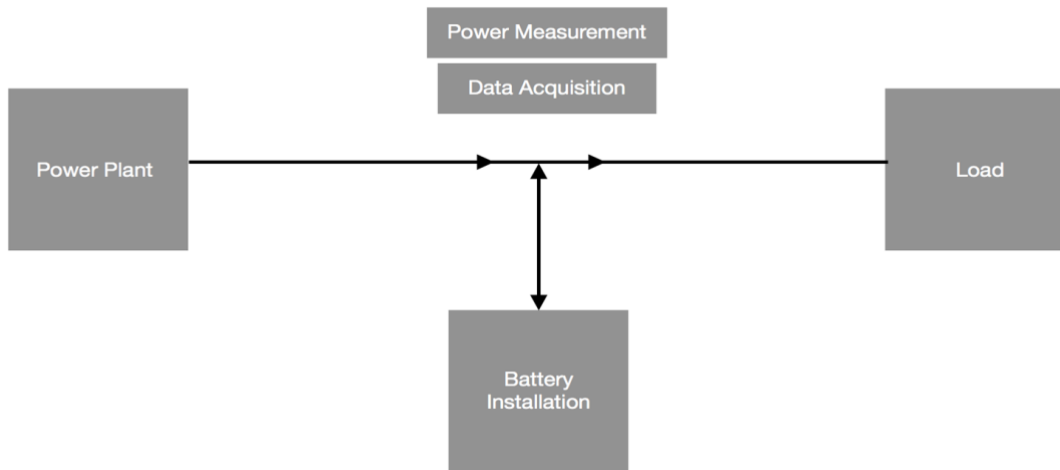
Figure 4. Technical overview

Chapter 2: State of the art

2.1. Current state of battery storage in US utilities

This project focuses on BELD, a utility company in the area of Braintree in Massachusetts, US. Therefore, the current state of battery storage will be described but only of the utilities within the US.

As seen in the figure below the power capacity of utility-scale battery installations has increased in the past years. In 2017, these battery storage units made up for 0.06% of the generating capacity, having installed a total of 700 MW. An increase of almost 100 MW can be expected for 2018 [7].
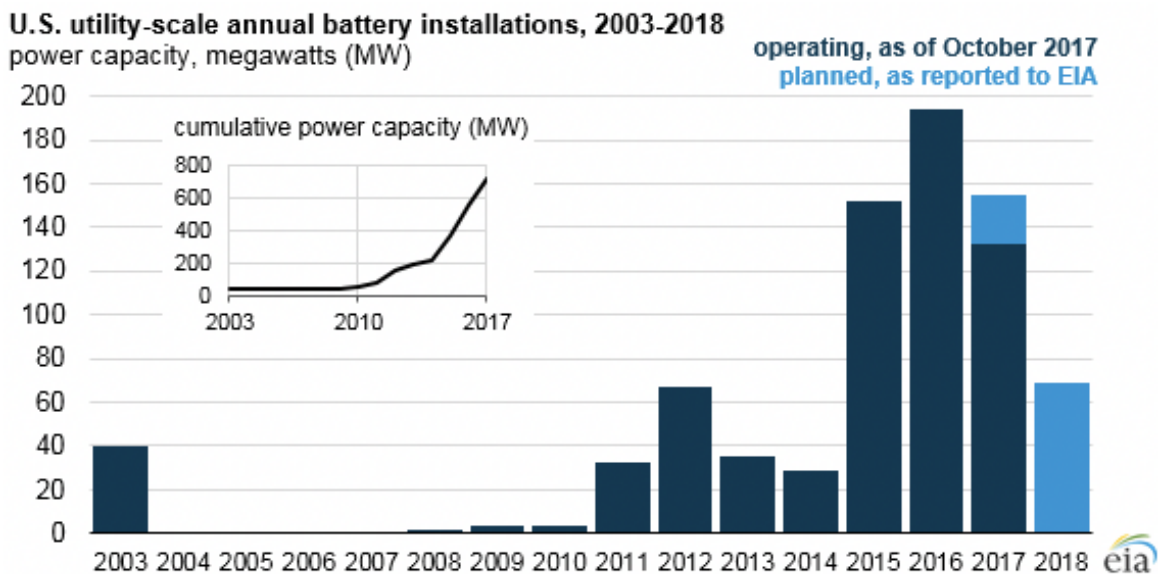
Figure 5. US utility-scale annual battery installations. 2018 [8]

Although there is a noticeable increase in battery storage, it is only due to two independent electric power transmission system operators: California Independent System Operator (CAISO) and PJM Interconnection. These two make up for 65% of the power capacity (*Figure 6*). As for the rest of the US, it could be argued that battery storage has not really kicked off yet although some measures have been taken.

The New England Independent System Operator (ISO-NE) does not currently have a significant amount of battery storage installations. However, states from within the ISO-NE such as Massachusetts, where Braintree is located, are on the verge of increasing the number of energy storage installations. On November 2016, the Federal Energy Regulatory Commission (FERC) noticed that certain rules created for traditional electric resources were obstructing the development and implementation of emerging technologies such as electricity storage. As a result, the Commission issued a rule in February 2018 that focused on removing certain barriers for electric storage resources.

The graph below shows the distribution of utility-scale battery storage capacity. In this figure we can distinguish between two different concepts: power capacity and energy capacity. On the one hand, power capacity is the maximum instantaneous amount of power that can be produced in a continuous basis. On the other hand, energy capacity is the amount of energy that can be stored or discharged from the batteries.
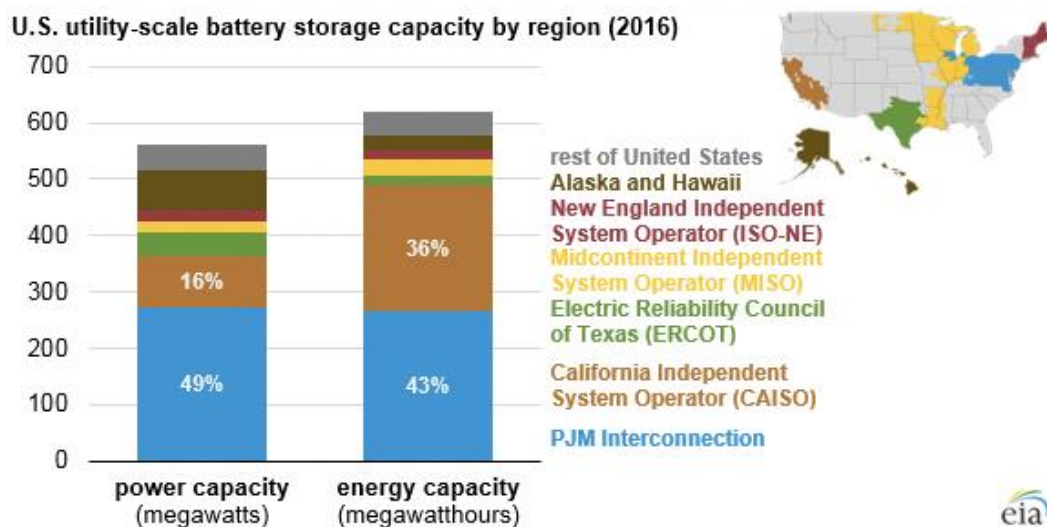
Figure 6. US utility-scale battery storage capacity. 2016 [9]

2.2. Battery chemistries

One of the objectives of the project is trying to compare different battery chemistries. There is a large number of them but only a few are used in utility-scale battery storage installations. These batteries are: lithium-ion, nickel-based, sodium-based, lead-acid and flow batteries.

Lithium-ion batteries, commonly known for being the batteries used in cars, are the current go-to batteries in utilities. In 2016, lithium-ion batteries represented more than 80% of the batteries used for storage in the US. They have fast response time as well as high energy density and efficiency [10].

Sodium-based batteries have never been widely used to store electricity although they underwent a huge increase in 2013. They are known for their: long-life cycle, high energy density, quick response and long-discharge duration. Heating may be necessary for its use.

Nickel-based batteries were the first batteries to be used as a utility-scale way to store electricity in 2003. However, since then, this chemistry has experienced a very low demand due to their small cycle life. They generally have high reliability and energy density.

Lead-acid batteries are also known for being used in vehicles, but they have not been in the spotlight of utility-scale energy storage. In 2016, only 3% of battery storage in utilities was due to lead-acid batteries. Lead-acid batteries are susceptible to high discharge rates and have low energy density. However, they are efficient compared to other batteries.

Flow batteries only represent a 1% of the battery storage capacity. They are quite different from the rest of chemistries as flow batteries involve the use of different chemistries that are put together in a fluid solution. The can be charged/discharged a large number of times. Although they possess a large capacity, they do not have high energy density.

The figure below shows the evolution of the different battery chemistries used in utility-scale storage.
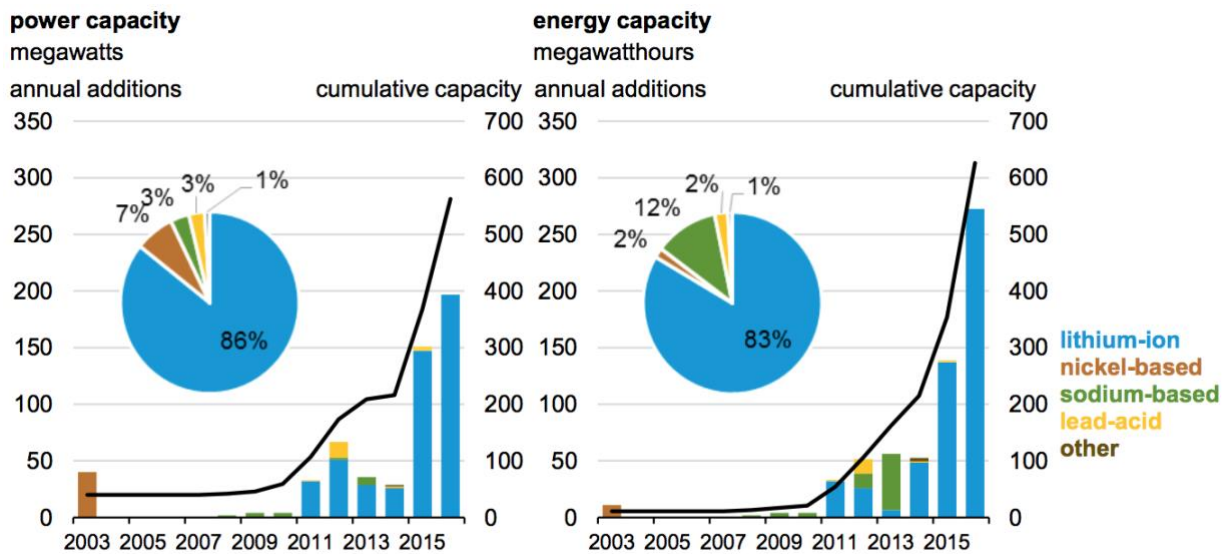
Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

Figure 7. US Large-scale Battery Storage Capacity by Chemistry. 2016 [11]

2.3. Competing technologies

In this section the various benefits of battery storage will be discussed as well as its relation to other forms of storing energy. To do this, a definition of other common storage technologies will first be given:

- Hydroelectric pumped storage produces energy by using water that has been previously stored in an upper reservoir. It is used during peak hours when the cost of generation is higher.

- Flywheels technologies are based on the principle of energy conservation. A rotor is rotated at very high speeds. By having the flywheel lose as little energy as possible from friction, when power is needed the kinetic rotational energy is transformed into electricity by slowing down the flywheel.

- Compressed air storage as the name indicates consists on compressing air to store the energy and releasing it when needed. This technology needs heat to release the air (natural gas is normally used for this purpose) and uses turbines to generate the electricity.

2.3.1. Benefits

As seen in the battery chemistries section, batteries are very different from each other and can be used in a number of ways. On the contrary, this does not happen with other technologies, that have more or less a concrete function.

Hydroelectric pumped storage is a very common storage technology due to the maturity of the technology and its high energy capacity. Their biggest flaw is that they are geographically constraint, so they cannot be installed where it would be preferable.

Compressed air technologies have a similar problem to hydroelectric pumped storage. They are as well geographically constraint unless expensive tanks are used. The cost of these pressurized tanks is a major drawback for this technology and this is the reason why some utilities opt for liquid air energy storage. Compressed air installations can be turned on fairly fast and have a high durability. [12]

Flywheels are widely used for energy storage due to their almost unlimited number of charge/discharge cycles. Although flywheels have a high initial cost, its maintenance is cheap. [13]

There are benefits to the implementation of electricity storage technologies. However, not all of these technologies serve the same purpose nor has the same cost. In a first classification we can distinguish between technologies for long timescales and short timescales.

Technologies that are being used for long timescales are pumped hydroelectric or compressed air for example. There function is energy management through these long periods of time. They try to moderate predictable extremes in demand when it increases or decreases significantly.

Other technologies such as battery storage, flywheels or super-capacitors are used for shorter periods of time. They serve the purpose of maintaining power quality. These technologies are used for these time frames due to their short response time.
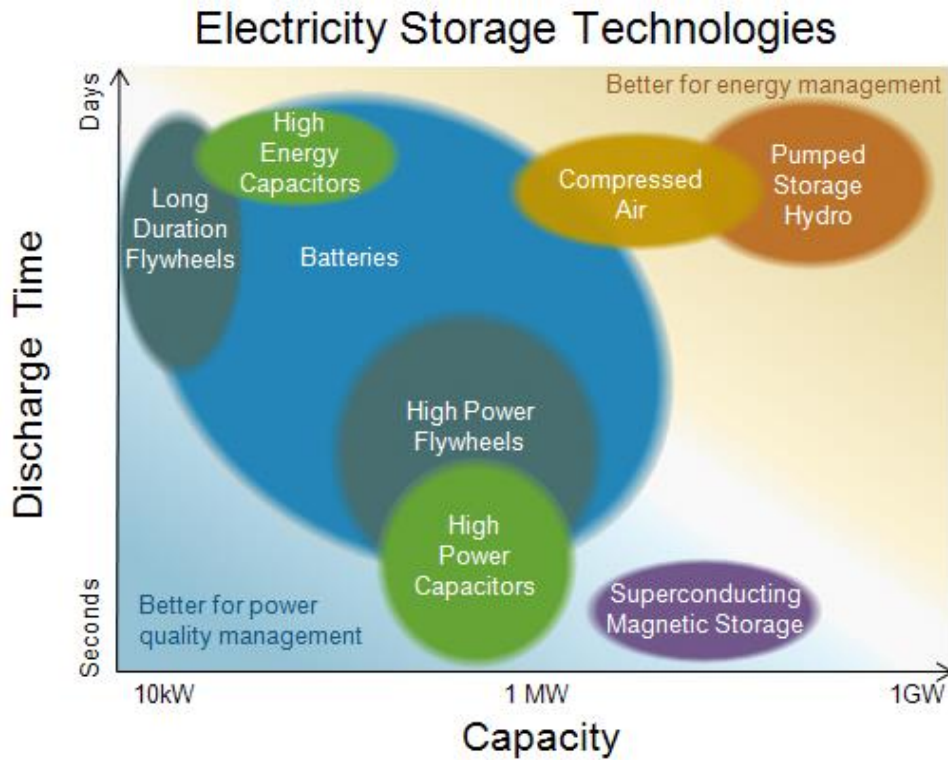
Figure 8. Electricity storage technology's characteristics. [14]

As shown in *Figure 8*, batteries can sometimes embed both functions (energy management and power quality management) depending on the installation, size, battery chemistry and characteristics. This is the reason why it is difficult to compare battery storage with other forms of electricity storage. Batteries have a wide range of sizes and characteristics and that results in very different costs and uses for them.

2.3.2. Costs

The use of batteries is oriented to one of two things: power capacity or energy capacity. Therefore, a separate classification in cost is necessary as companies that want to invest in battery storage for a concrete purpose may focus on one cost and overlook the other one. On the one hand, batteries oriented to power capacity are meant for shorter periods

of time as they are intended to discharge instantaneously large amounts of power. On the other hand, batteries oriented to energy capacity are meant for longer durations and as a result, for peak-shaving purposes. These systems have lower costs for kWh but higher for kW. In the figure below, we can see this difference in cost depending on the use and period of time.
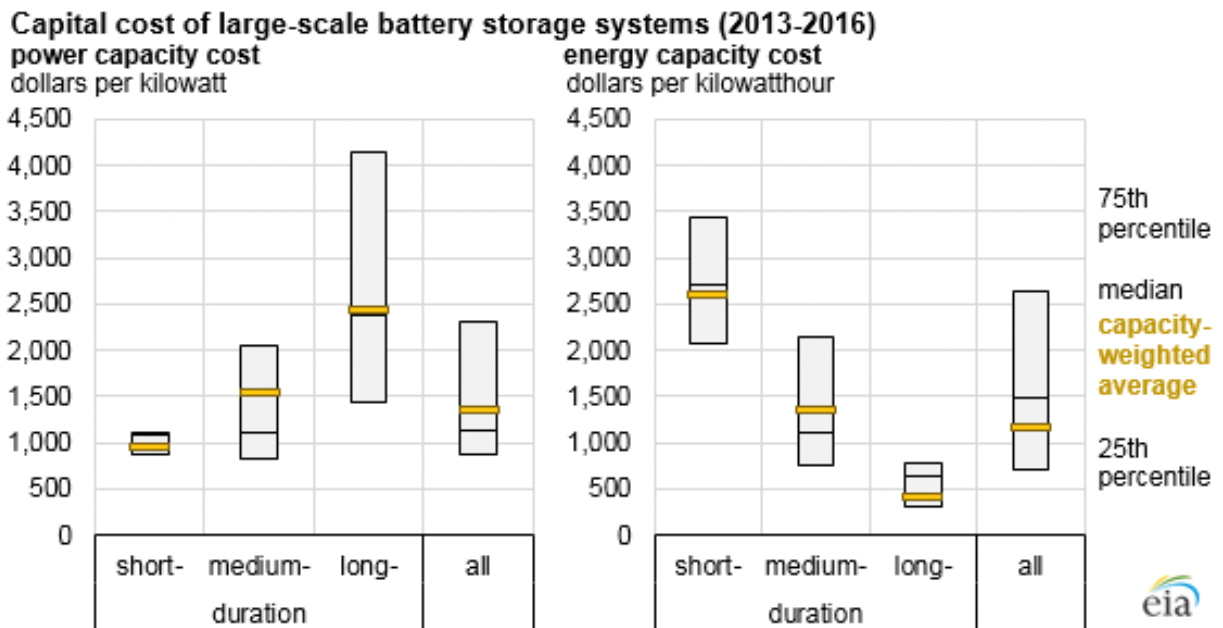
Figure 9. Capital cost of battery storage systems. [15]

While there are a lot of different sources that provide energy generation such as coal or natural gas, other technologies that provide additional power supply such as solar, wind, hydroelectric pumped storage, flywheels or batteries are starting to gain popularity among utilities. Of these last technologies, hydroelectric pumped storage is one of the oldest as shown in the figure below. Batteries, on the contrary, do not have a lot of history in utility-scale energy storage.

Figure 10. US utility-scale electric generating capacity by initial operating year. [16]

Chapter 3: Project development

3.1. Objectives and requirements

The general objectives of this project are:

- Show how the use of battery storage technologies can help with the reliability of the grid.
- Show how the use of battery storage technologies can reduce costs with the peak-shaving of the supply curve.
- Determine key characteristics of the batteries that are tested.
- Ultimately, this project or its future continuations will help determine the most optimal battery chemistry for BELD.

These objectives translate into various engineering requirements:

- The project will be a physical small-scale mock grid.
- The power demand will be modelled by a variable load.
- The variable load needs to be able to represent different demand curves to test the batteries in different scenarios.
- The mock grid will work in AC. This implies that all DC sources have to be converted to AC.
- The grid will have a step-up and a step-down transformer to simulate to an extent BELD's distribution grid.
- The voltage, current and power must be measured in at least four points of the grid.
- The user must be able to store the data obtained from a test.
- The interface needs to be user-friendly.
- The data will be automatically displayed after a test.
- The data needs to be visible during the test to ensure that the values are in range and check the overall development of the test.
- The mock grid frequency must be 60 Hz.

- For security, the voltage must range between 0 and 30V.

- For security, the current must be below 3A at all times.

- For security, the project will be enclosed in some type of box.

- This box has to fit through a standard door.

There are some comments to be made about these objectives. Initially, an engineering requirement was that the inverter had to be bidirectional. However, this proved to be more complex than initially thought. As this requirement did not serve a general objective and the results of the test could be accomplished with the use of two separate inverters the bidirectional inverter was not built as the other parts of the project were focused.

Initially, an objective was to determine the most optimal battery chemistry for BELD. Nevertheless, as the grid was built from scratch, there was not enough time to perform tests or to implement certain parts of the project to the grid. As a result, this objective was left for future continuations of the project.

3.2. Work methodology

Our group is composed by four people and therefore the work was distributed so that each member had one of the four parts of the project. This does not mean that a member does not work on other areas as, in the end, all of them are related and one of the parts needs of the correct functioning of the others. However, it is important to have a direct responsible for each part that can be held accountable for its success. If this was not the case, the responsibility could be deluded in the group. Therefore, at the beginning, each of us was in charge of a subsystem of the project. The responsibilities were distributed as follows:

- Javier Olavarria (myself): Data acquisition

- Teresa Jimenez-Castellanos: Variable load

- Agastya Bellad: Power generation

- Andres Vazquez: Battery charging/discharging system

3.3. Project development

In this section the project will be explained extensively. An overview of the subsystems will be given. This overview, however, will be shown with a more in-depth schematic than the one previously seen. Note that the demand curve modeling (variable load) will be explained thoroughly by Teresa Jimenez-Castellanos Vida in *Modeling Power Grid with Battery Storage. Demand curve modeling*.

3.3.1. Overview

As stated in the introduction section the overall objective of the project is to help BELD with their battery storage decisions such as the chemistry of the battery to be used. The conceptual approach to this problem is to build a physical mock grid where these different batteries can be tested. Characteristics such as rate of discharge, efficiency and cycle life should be determined.

The physical approach was not the first option using computer simulation programs such as PSS®E developed by Siemens to represent the mock grid was as well on the table. However, BELD's representative in this matter, Tim Leung, had a physical model in mind when he asked our team to carry out this project. From an engineering perspective this was optimal, as the theory does not always translate that easily in laboratory experiments. Problems that were not thought beforehand surfaced later in the lab. A theoretical approach would have been interesting but, to an extent, easier as important details may have been overlooked.

3.3.2. Subsystems

The project can be broken down into four parts: generation, battery installation, data acquisition and the demand curve modeling. In the figure below a more descriptive system overview can be seen.
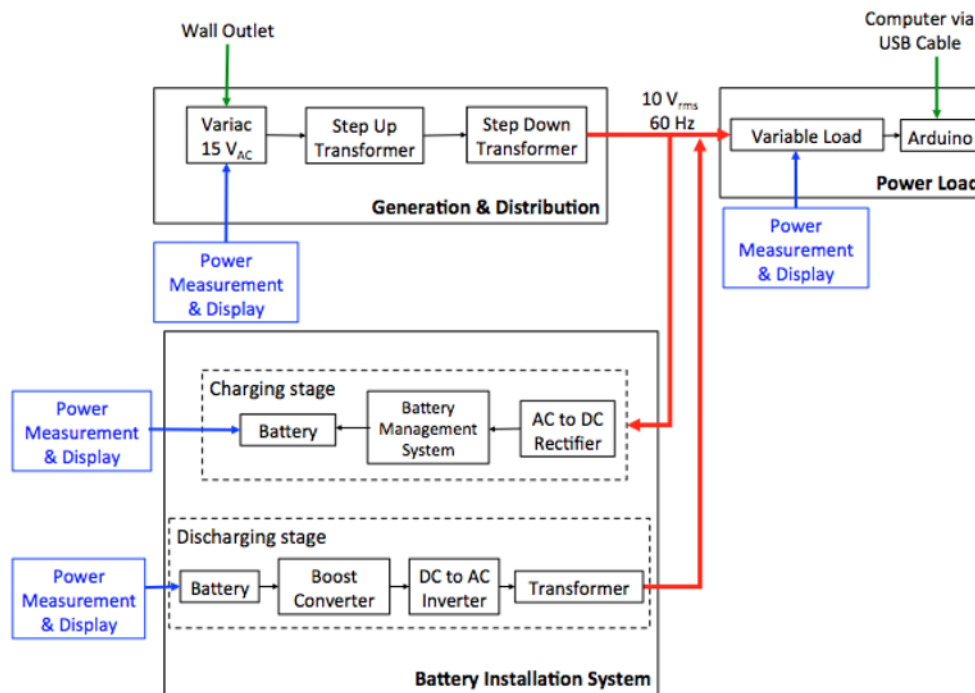
Figure 11. System overview.

It is important to note certain details of the system overview:

Firstly, how the battery installation has been separated in two smaller systems: the charging and discharging installation. This is due to the difficulty of building or finding a small-scale bidirectional inverter. The final decision was to divide it in two separate systems.

Secondly, the power measurement system is located in four different parts of the project. This ensures that the user can check at any moment if the system is performing the test as expected. By making a reading of each part we can achieve certain degree of security making sure that, for example, the current does not go beyond 3A at any moment.

3.3.2.1. Generation

BELD's distribution grid information is not open to public and therefore the exact distribution of the electric lines is unknown. However, it is known that BELD owns four power plants and, as any utility, the voltage is stepped up to high voltage transmission

lines to achieve fewer losses until the substations where the voltage is stepped-down. The voltage is stepped-down and distributed to houses, buildings, etc.

Therefore, to replicate this grid, the four power plants were simplified into one variac that is plugged to the wall. By having the variac plugged to the wall we could guarantee a 60 Hz output voltage. The voltage that was being outputted was also modified in case adjustments were necessary. The final 9.7V rms voltage was not the first option and had to be changed numerous times to adapt the voltage to the charging and discharging installations.

The step-up and step-down of the transmission lines is represented by two transformers. In an initial stage of the project where the voltage was 15V these transformers were tested. They increased the voltage from 15V to 74V and then decreased it to 15V again. The ratio of the transformers is 1:5.
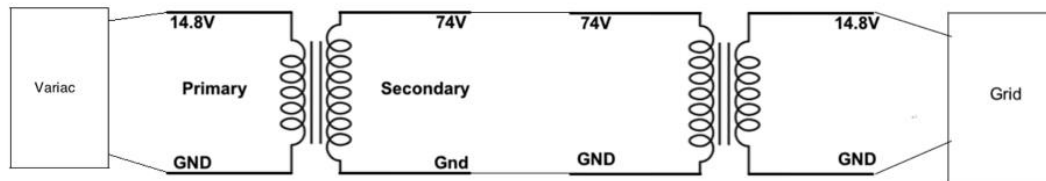
Figure 12. Schematic of the power generation system.

As seen in *Figure 13*, a sine wave of 15V and 60 Hz was obtained. It is not a perfect sinusoidal wave, but it was acceptable for the experiments.

Measure	P1:ampl(C1)	P2:max(C1)	P3:ampl(C2)	P4:max(C2)	P5:freq(C1)	P6:- -
value	14.981 V	7.62 V	343 mV	182 mV	59.95420 Hz	
mean	15.30259 V	7.7602 V	335.3 mV	194.1 mV	59.9952464 Hz	
min	1.501 V	853 mV	286 mV	146 mV	59.88952 Hz	
max	23.223 V	11.67 V	402 mV	253 mV	60.07740 Hz	
sdev	2.05573 V	1.0223 V	18.4 mV	17.7 mV	36.4062 mHz	
num	423	423	423	423	112	
status	✓	✓	✗	✓	✓	
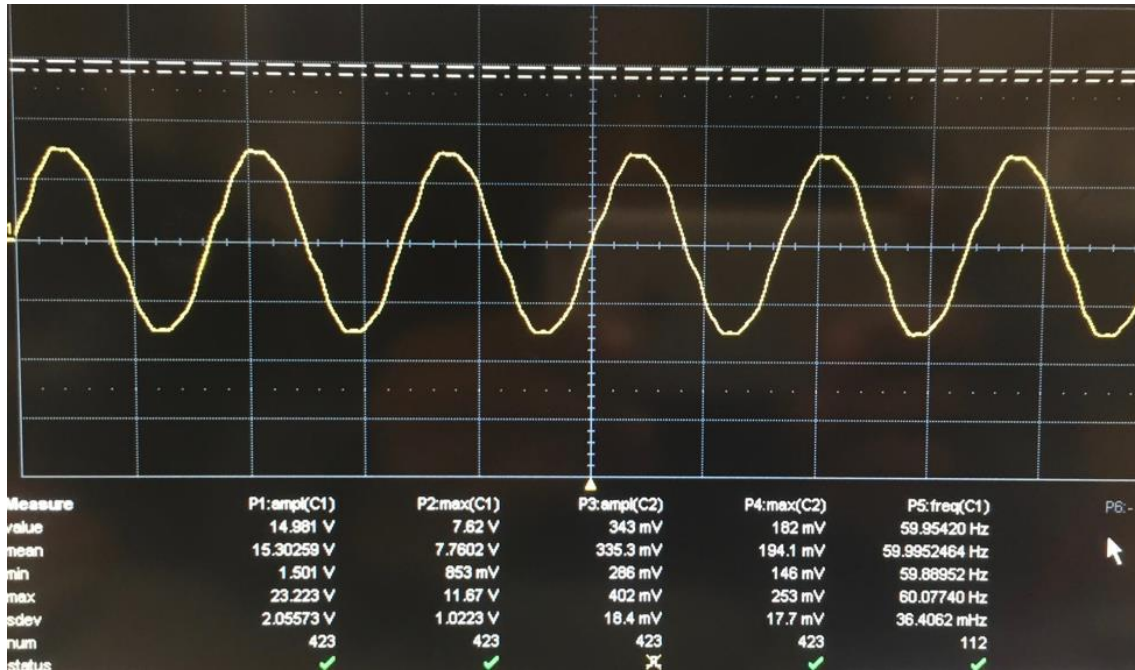
Figure 13. Output voltage to the batteries and loads.

The equipment used is: a Variac Variable AC Power Transformer 0-130V and two 4VZF5 Class 2 Transformer, Open, Foot. The wires of these transformers had to be cut, stripped and opened to connect them to the rest of the components.

3.3.2.2. Battery installation

The battery installation system's objective is to connect the batteries to the variable load and the grid so that they are able to drain or supply power. This part of the project had several issues and some of them will be described in this section.
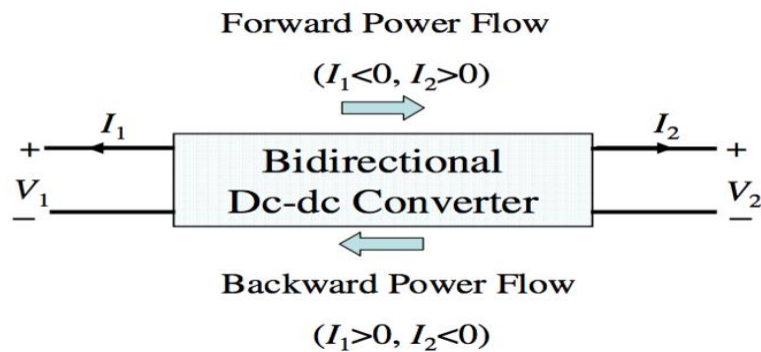
Figure 14. Bi-directional DC-DC simple schematic overview.

Originally, the battery installation was going to be composed by a bi-directional converter (*Figure 14*) such that the current would flow in either way. Being precise, the need of two bi-directional converters were necessary: an AC-DC converter and a DC-DC converter. With the use of a switch the user would be able to control if the power was supplied to the load or stored in the batteries. With this objective in mind a computer simulation of the DC-DC bidirectional converter was run (*Figure 15*). The problems of this converter were:

Firstly, the soldering process of the PCB (Printed Circuit Board) was really difficult as it implied the use of very small components which were difficult to solder by hand. Secondly, the pads of the PCB were made too small. Finally, the clearances were really narrow. As a result, continuing with this option would imply risking the creation of shorts to ground in certain parts of the PCB by accident.
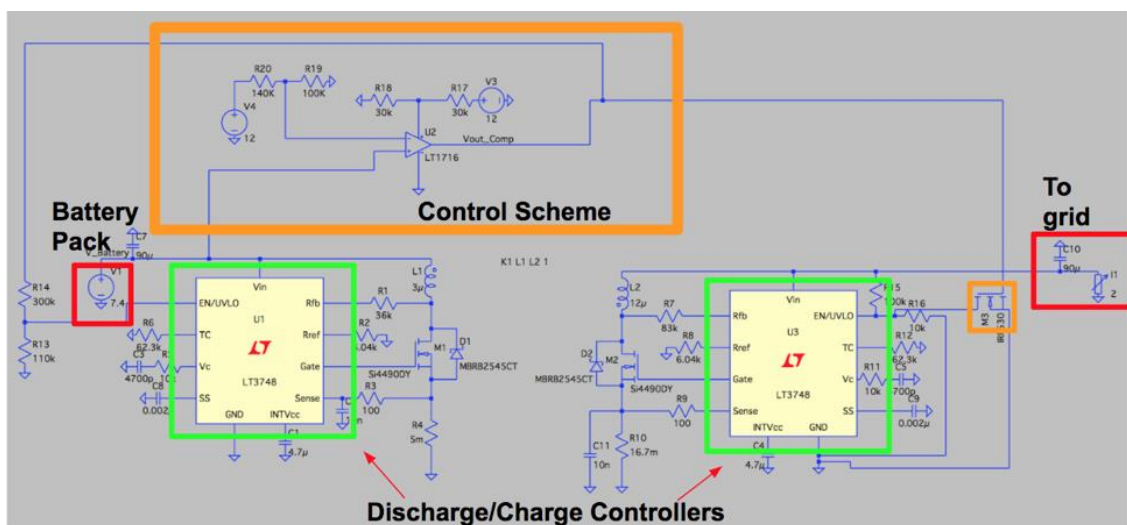
Figure 15. Bi-directional converter schematic.

In the schematic of the DC-DC bidirectional converter we can distinguish four parts:

- The battery pack, which is represented with a voltage supply of 7.4. In reality, this pack is composed by two batteries in series to achieve the 7.4V. An example of these batteries is the 18650 3.7V Lithium-ion battery.

- The grid, which is represented by a resistor and a capacitor.

- The charge and discharge controllers, which were the parts that posed the soldering problems of the PCB.

- The control scheme, which is shown in the orange box. The control system consists of a comparator circuit that would read the voltage of the batteries and determine if they needed to be charged or discharged. This is possible because there is a correlation between the voltage of the batteries and their state of charge. A reference voltage was established, under which the batteries would be charged. Therefore, when the measurement circuit detected the voltage below the threshold value the charging station would be turned on. This voltage was 5V and was decided based on the fact that below this value the battery's lifetime can decrease.

The results of the simulation of this DC-DC converter are shown below (*Table 1*). Note that the test was performed when the voltage of the grid was still 15V. The modes are D and C, that stand for Discharging and Charging respectively.

Bi-Directional Measurements (7.4V <-->14.8V) w/ Output Discharge current of 20A				
Mode	C	D	C	D
Output Current(A)	2	2	1	1
Vin(V)	14,8	7,4	14,8	7,4
Vout (V)	8.23 - 8.42	14.75 - 15.08		14.8 - 14.95
Vsense (mV) (1/2)	-48	(84/-140)		(40 / -60 to 40)
Error	2,02%	1,80%		
Gate frequency(KHz)(1/2)	(0/ 71KHz)	35/0	0/ 68	71/0
Rsense(mOhm)	16,7	5	16,7	5
R2	100k	300k	100k	300k
R1	10k	110k	10k	110k
L(uH)	5,5	23	5,5	23
Rfb	35k	85k	35k	85k
		Frequency must be higher than 42KHz		
Bi-Directional Measurements (8.4V <-->14.8V) w/ Output Discharge current of 20A				
Mode	Charge	Discharge	Charge	Discharge
Output Current(A)	2	20	2	20
Vin(V)	14,8	7,4	14,8	7,4
Vout (V)				
Vsense (mV) (1/2)				
Error				
Gate frequency(KHz)(1/2)				
Rsense(mOhm)	18,5	0,512		
R2	100k	300k		
R1	10k	110k		
L(uH)				
Rfb	82.9k	36.5k		

Table 1. Simulation results.

On the one hand, as previously stated, the DC-DC converter was simulated but not tested due to the problems with the PCB. On the other hand, problems surfaced far sooner with the AC-DC converter. AC-DC bi-directional converters are used with high powered systems and converters that could be adapted to our low voltage systems were impossible to find. Building an AC-DC bi-directional converter from scratch would have been really complex.

Finally, two separate systems were created so that the current only flowed in one direction. Therefore, we can distinguish between the charging and discharging station.

- Charging station:

The charging station is composed by a full wave AC-DC rectifier and a buck converter. The batteries are located in the DC side of the charging station while the rest of the mock grid (variable load and the power generation system) is placed on the AC side of the circuit.
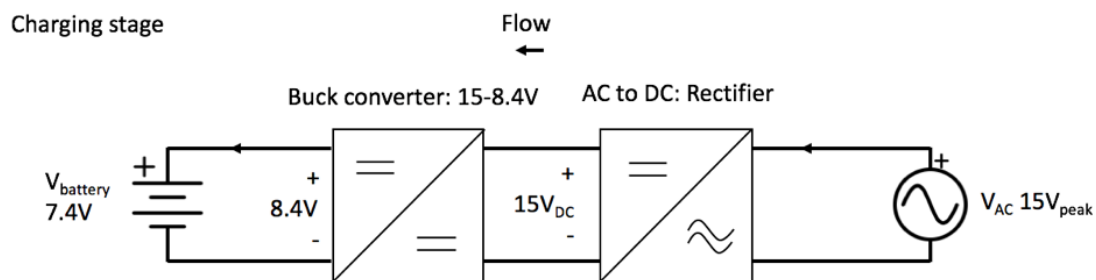
Figure 16. Charging station schematic.

The buck converter is necessary as batteries with different characteristics are tested. That is, not all these batteries have the same charging voltage. A lithium-ion cell needs to be charged at approximately 3.7V for example. Depending on the battery and of course the amount of batteries that are going to be put together, such as two batteries in series or two in parallel for example, a different voltage is required.

The rectifier was made from scratch and was made following the circuit below (*Figure 17*). The AC waveform will become a wave similar to the one shown in *Figure 18*.
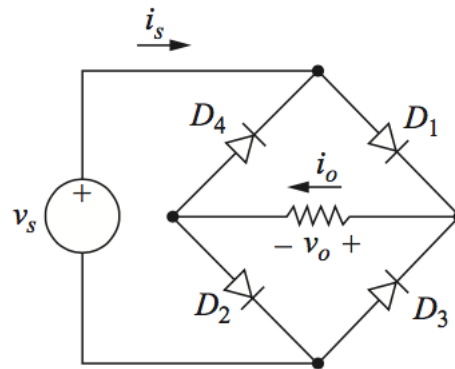
Figure 17. Full-wave rectifier schematic. [17]
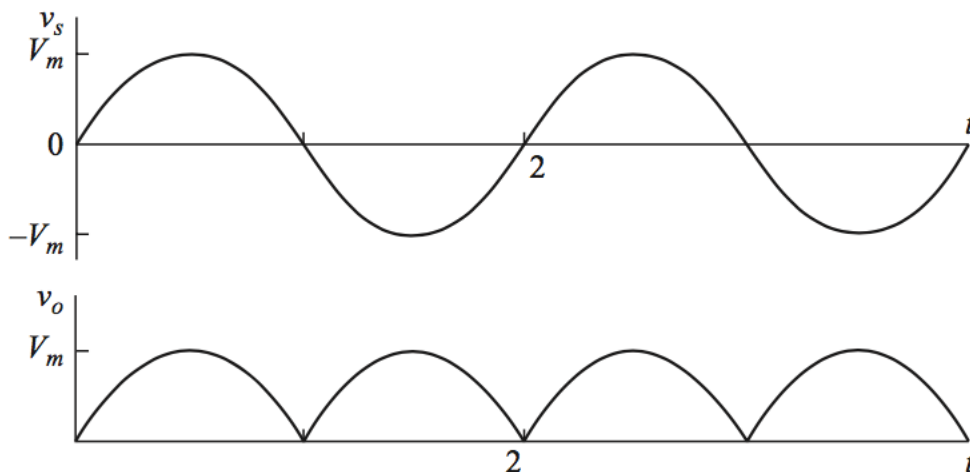
Figure 18. Input and output voltage of the rectifier. [18]

The average output voltage in the resistor can be calculated following the equation:

$$V_0 = \frac{2V_m}{\pi} = \frac{2 * 9.7}{\pi} = 6.18V$$

Equation 1. Average output voltage.

The rectifier was successfully tested using a 5Ω resistor, a 100mH inductor and 60Hz. The expected results can be calculated using the firsts terms in the current Fourier series:

$$I_0 = \frac{V_0}{R} = \frac{6.18}{5} = 1.24A$$

Equation 2. Average load current.

$$V_2 = \frac{2 * 9.7}{\pi}\left(\frac{1}{1} - \frac{1}{3}\right) = 4.12V$$

$$V_4 = \frac{2 * 9.7}{\pi}\left(\frac{1}{3} - \frac{1}{5}\right) = 0.82V$$

Equation 3. First voltages in the voltage Fourier Series.

$$I_2 = \frac{4.12}{|5 + j(2)(377)(0.01)|} = \frac{4.12}{9.05} = 0.46A$$

$$I_4 = \frac{0.82}{|5 + j(4)(377)(0.01)|} = \frac{0.82}{15.89} = 0.05A$$

Equation 4. First currents in the current Fourier Series.

$$I_{rms} = \sqrt{\sum I_{n,rms}^2} = \sqrt{(1.24)^2 + \left(\frac{0.46}{\sqrt{2}}\right)^2 + \left(\frac{0.05}{\sqrt{2}}\right)^2} = 1.26A$$

$$P = I_{rms}^2 * R = 1.26^2 * 5 = 7.94W$$

Equation 5. Power consumed in the load.

The buck converter was not built from scratch as it was purchased. The model was a DROK 90483 DC Car Power Supply Voltage Regulator Buck Converter.

Although both the rectifier and the buck-converter worked as expected the batteries were not being charged as no current was being drawn to them. A battery charging module was necessary for this purpose, but that stage in the project was not achieved. Charging modules are boards with a USB connection that is able to charge small batteries. The power is drawn from the USB and is transmitted to the battery. Charging modules normally have two leds: one to indicate when the battery is charging and another one to indicate when the battery is fully charged. Therefore, the schematic in *Figure 16* is incomplete as the battery charging module would be needed between the batteries and the buck-converter. In addition to this, duty cycle changes may have been necessary in the buck converter to adapt to the voltage required by the module. As well, several modules may have been needed as some modules are meant to be used to charge a specific battery.

- Discharging station:

In this section a brief overview of the discharging station will be given although it will be explained extensively in *Modeling Power Grid with Battery Storage. Demand curve modeling* by Teresa Jimenez-Castellanos Vida.

The discharging station is composed by three subsystems: a transformer, an inverter and a boost-converter.

- The boost-converter is used as the buck-converter in the charging station. Its main purpose is to adapt the voltage of the battery to the voltage required by the inverter.
- The transformer is as well necessary to adapt the grid voltage to the voltage required by the inverter.
- The inverter is used to transform the DC voltage to AC. The inverter posed a problem as it did not turn on from time to time. Small inverters are difficult to find so its integration with the rest of our small-scale grid was complicated.

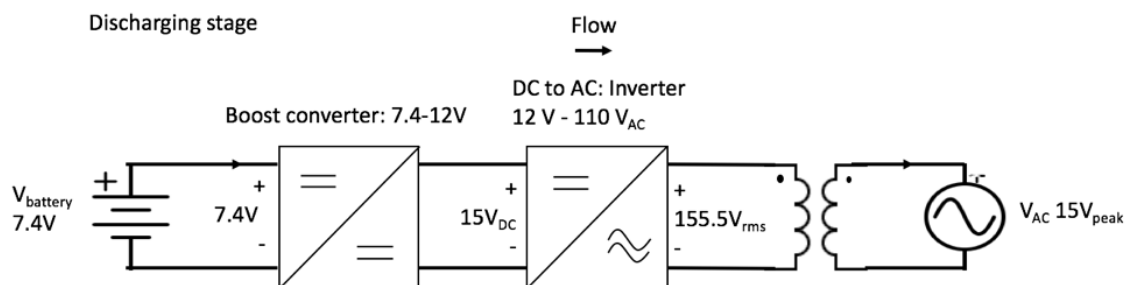
Figure 19. Discharging station schematic.

3.3.2.3. Data acquisition

One of the most important parts of the project is the data acquisition which includes the measurement, processing, display and storage of the data. The data acquisition serves three purposes: ensures security to an extent, enables the analysis of the results and serves as a way to control the charging and discharging mode.

The security part of the project was not finished completely. On the one hand, processing the data of the test in real time was accomplished. On the other hand, a response to certain values was not implemented. If the values of current exceeded certain values the system should automatically shut down. This would have been done with switches at the output of the generation system and at the output of the discharging battery system. Therefore, the loads or the charging battery system would stop receiving current in the case of an overcurrent.

As various measurements are read throughout the grid, the stage in which the demand curve is at the moment can be known. Therefore, based on that, the charging or discharging station can be activated to help the power generation plant meet the demand or to accumulate the excess of power in the batteries. This is done with a three-way switch: only the charging station connected, only the discharging station connected or both disconnected.

- Data measurement:

In this section a description of the sensors or circuits used to measure the data will be given. It is important to note that only using resistive loads are used to simulate the demand curve and therefore, only the active power is measured, as measuring the phase of the complex power would have complicated substantially the problem.

To do this, different circuits were used. Firstly, a table of where the circuits are located will be displayed below. Secondly, a description of how each circuit works will be explained.

	AC voltage circuit	DC voltage circuit	AC current circuit	DC current circuit
Generation	YES	-	YES	-
Load	YES	-	YES	-

Charging installation	YES	-	YES	-
Discharging installation	YES	-	YES	-
Output of the battery	-	YES	-	YES
Output of the boost converter	-	YES	-	-

Table 2. Location of the measurement circuits.

The circuit at the output of the boost converter cannot be considered a measurement circuit as it is only a DC voltage display integrated in the boost converter. Although it just displays the value of the voltage, it was worth mentioning as it gives information of the performance of the test. In this boost converter, the duty cycle could be regulated manually and therefore the output voltage could be changed.

1. DC and AC voltage measurement circuits:

Arduinos are used to read the voltage in both the AC and DC voltage measurement circuits. However, as arduinos have a range from 0 to 5V they would have not been able to read the values we were working with. The solution was to use a circuit with operational amplifiers. For the DC voltage circuit, the purpose of the op-amp is to step-down the value of the voltage from 9.7V (nominal value of the mock grid) to a value between 0 and 5V. Connected in a differential op-amp circuit, resistors are used to accomplish this (*Figure 20*).
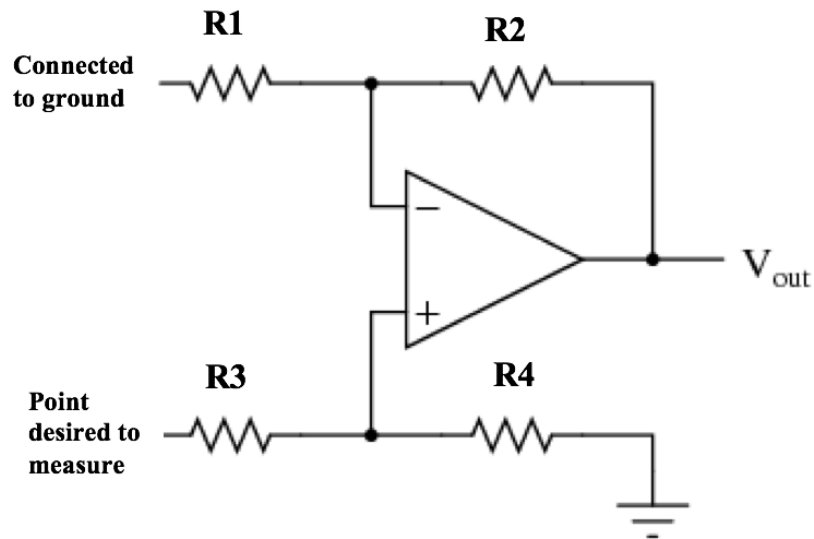
Figure 20. Voltage measurement circuit schematic.

The equations for this type of op-amp circuit are the ones following:

$$V_{out} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) * V_2 - \left(\frac{R_2}{R_1}\right) * V_1$$

Equation 6. Differential op-amp circuit.

If $R_3 = R_1$, $R_2 = R_4$ and having V_1 connected to ground, the equation can be reduced to:

$$V_{out} = \left(\frac{R_2}{R_1}\right) * (V_2 - V_1) \rightarrow V_{out} = \left(\frac{R_2}{R_1}\right) * V_1$$

Equation 7. Differential op-amp simplified circuit.

Note that a differential circuit is not entirely necessary for the purpose of measuring DC voltages as other op-amp configurations could have been used. However, as it was a necessary design for the AC measurement circuit as it will be explained later, the same circuit was used. This had the advantage of only having to order one PCB design which is easier and cheaper than ordering two different designs.

In addition to the differential op-amp configuration, a voltage follower (*Figure 21*) was added to ensure certain degree of isolation between the measurement circuit and the rest of the project. A voltage follower circuit does not have any gain but has a big resistance value.
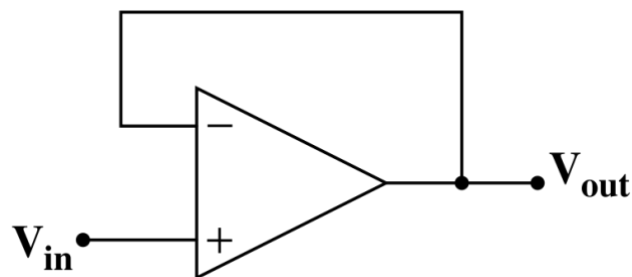
Figure 21. Voltage follower schematic.

As for the AC voltage, it is more difficult to measure. Reading a negative voltage with an arduino may break the microcontroller as it is only meant to read voltages from 0 to 5V. Therefore, with the differential op-amp configuration an offset of 2.5V was added and the voltage was reduced from its original value to a range of 0-2.5V as shown below.
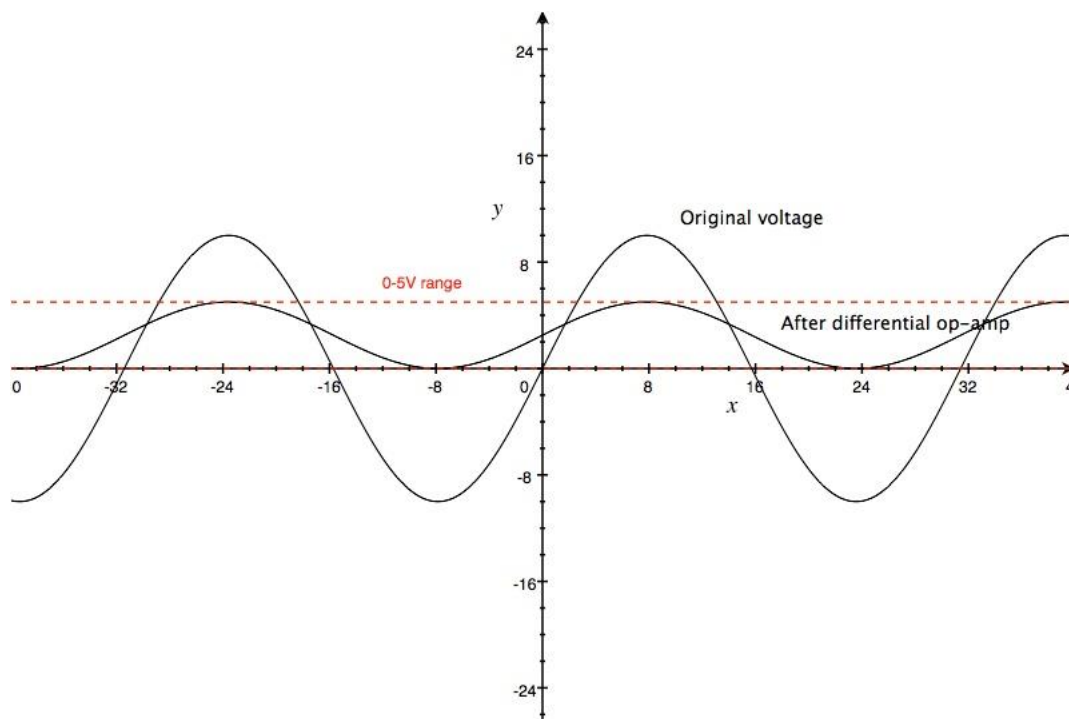
Figure 22. Voltage reduction after the differential configuration

The offset was achieved without using external DC sources other than arduino. Luckily, the arduino can output 5V so using a voltage divider it could be reduced to the needed 2.5V. The op-amp supply voltages are ground and the arduino's 5V.
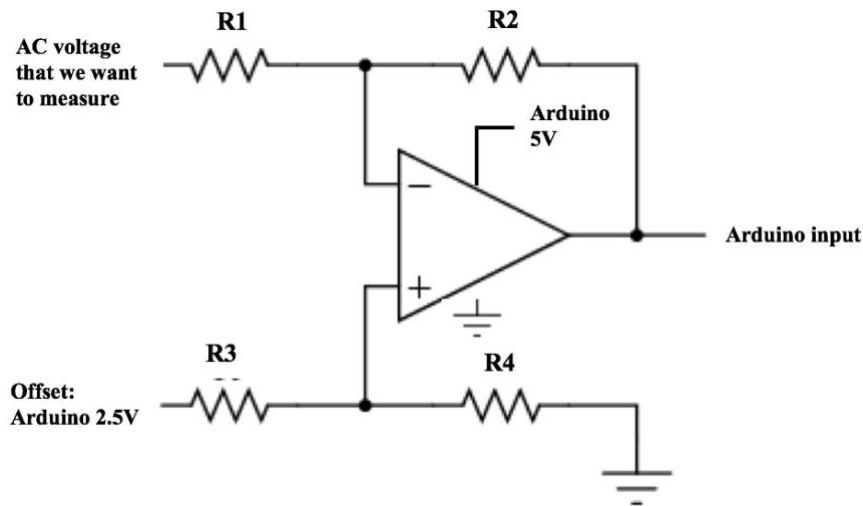
Figure 23. AC voltage measurement circuit schematic.

2. AC and DC current measurement:

Three different circuits were used to measure the current. The first one uses an ACS712 current sensor, the second uses an SCT-013-005 sensor and the third one is a circuit based on the Hall Effect that uses an L18P-003 sensor.

ACS712 sensor:

The use of this sensor is straightforward as shown in the figure below (*Figure 24*). It measures the current and outputs a proportional voltage value that the arduino can read. This is necessary because the arduino cannot measure current, only voltage. After making the connections, it just has to be calibrated in the arduino code. The calibration is necessary because not all of these sensors have the same sensitivity. It ranges from 66 to 185 mV/A.

This sensor can be used to read AC or DC current which is really useful. Nevertheless, its problem was its accuracy. This is the reason why, although the project was started with the use of this sensor, it was not used in the final derivable.
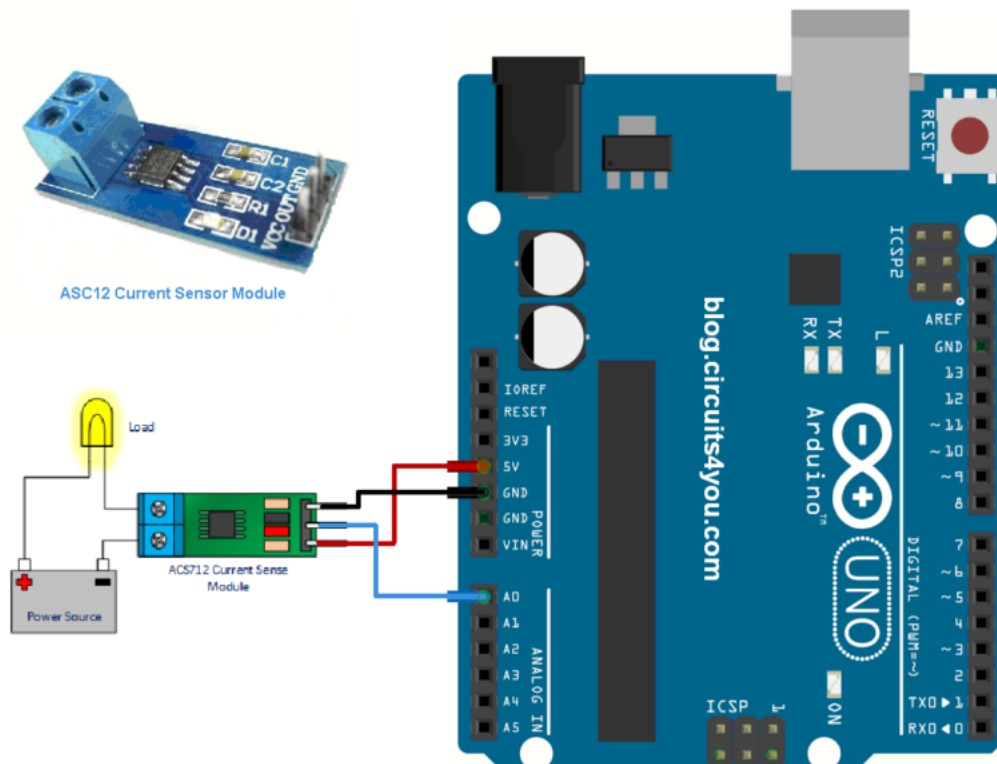
Figure 24. ACS712 connections schematic. [19]

SCT-013-005 sensor:

The SCT-013-005 is a clip-on sensor that relies on a transformer to step down the current. It then outputs a voltage proportional to this current. As it uses a non-invasive current transformer it can only be used to measure AC.
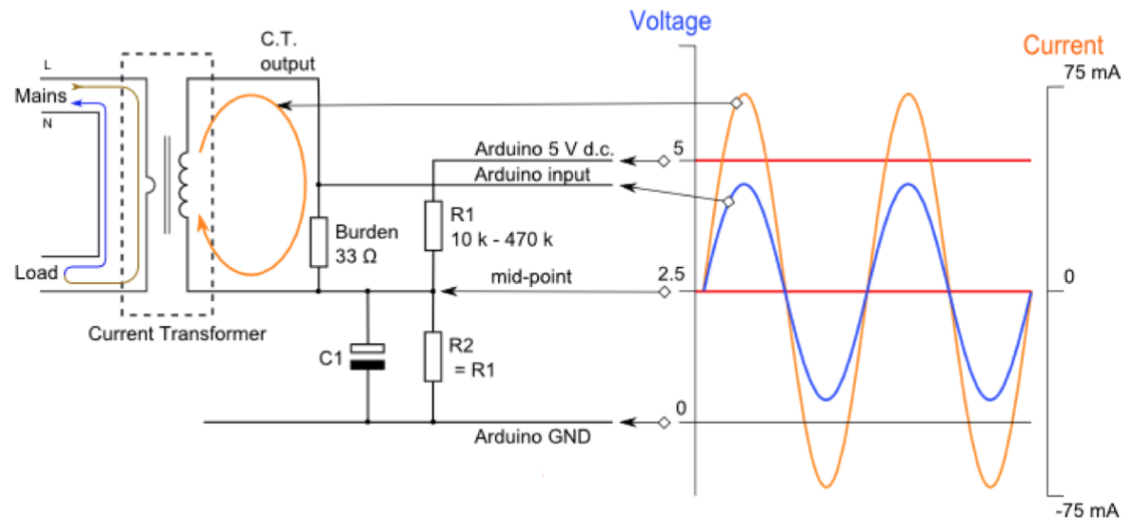
Figure 25. SCT-013-005 schematic. [20]

The SCT-013-005 has a sensitivity of 1V/5A. That is, it outputs 1V when the sensor is clipped-on to a wire through which a current of 5A circulates. The circuit firstly outputs a proportional voltage to the current but secondly, just as the voltage sensor, it adds an offset to the AC signal. It is not necessary to reduce its value as the maximum output is 1V.

With the help of the datasheet the optimal burden resistor for the circuit can be determined. The closer the burden resistor is to its theoretical value the more accurate the sensor is. To do this calculation, it is first necessary to compute the maximum current that circulates through the first and secondary coil.

Note that the maximum current is 5 A, the voltage reference is arduino's 5V and the number of turns of the transformer is 1800.

$$Imax_1 = 5 * \sqrt{2} = 7.07 \ A$$

$$Imax_2 = 5 * \sqrt{2}/1800 = 3.93 \ mA$$

$$R_{burden} = \frac{V_{reference}/2}{Imax_2} = \frac{2.5}{0.00393} = 636.13\Omega$$

Equation 8. Burden resistor calculation.

The closest standardized resistor that is not higher than the ideal burden resistor is 630 Ω. In addition to the burden resistor, as shown in the schematic, two 10k resistors and a $10\mu F$ capacitor were used. A connection of this circuit as well as a first approach to the voltage measurement circuit is shown in the figure below (*Figure 26*).
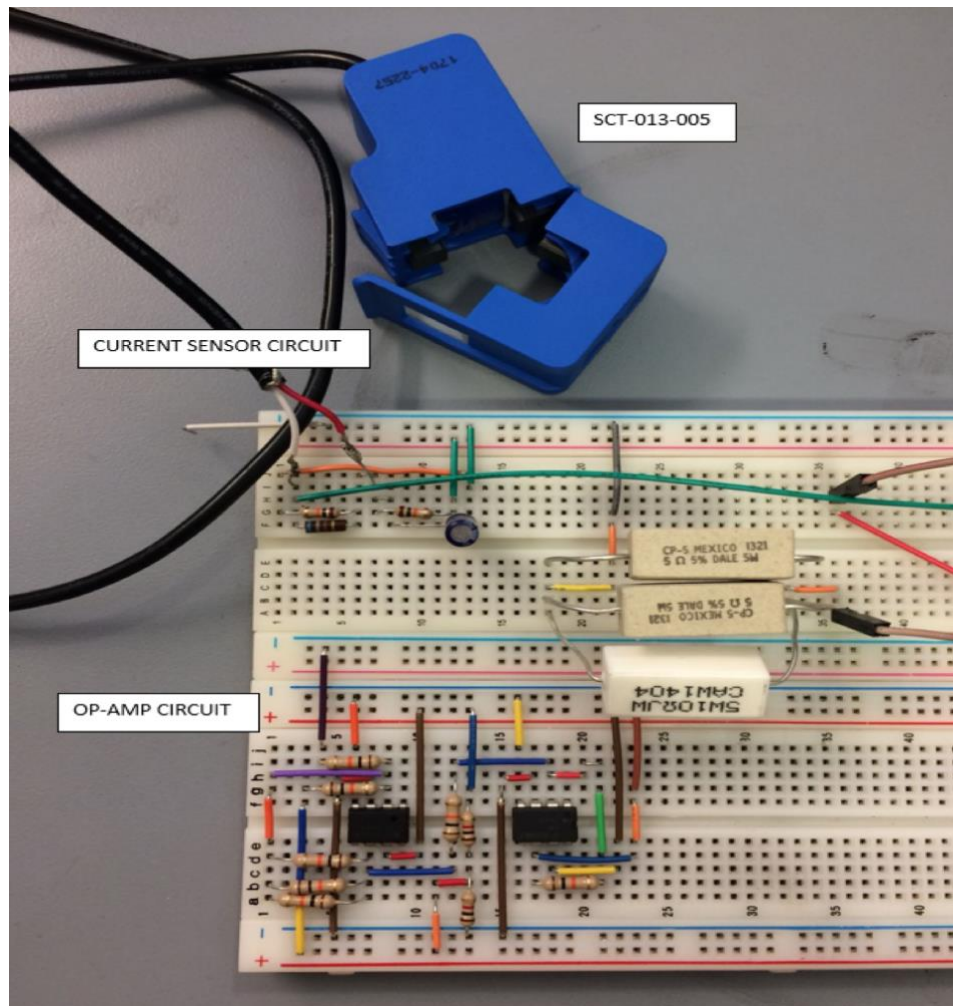
Figure 26. Voltage and current measurement circuits.

L18P-003 sensor:

The L18P-003 is a current sensor that uses a coil connected to a magnetic yoke. This yoke has a gap where we can find a Hall Effect device that outputs a voltage that is proportional to the current. Following the Hall Effect device there is an op-amp integrated in the sensor that amplifies the voltage.

After various tests it can be determined that this sensor is better than the previous ones as it can measure positive and negative currents as well as both AC and DC currents. In addition to this, this sensor is pretty accurate. It is however the most expensive one and its maximum current is only 3A, reason why it was not used in the last derivable of the project.
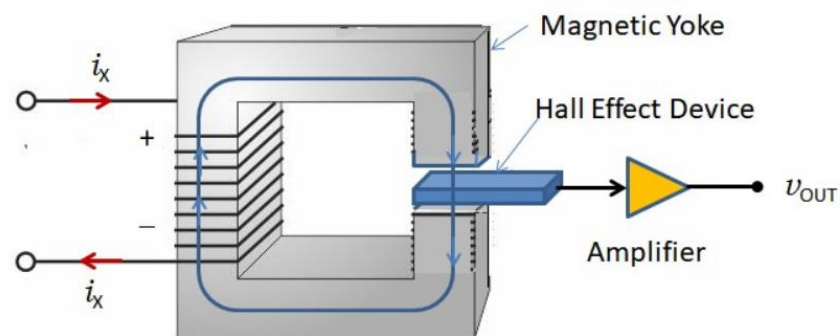
Figure 27. L18P-003 representation. [21]

As previously stated, the maximum current of the sensor is 3A, but it is also important to note that it requires a ±15V DC referenced to ground. To accomplish this, an external DC supply is necessary such as a Keysight Power Supply. This posed a problem the project is expected to be carried. It would have been really inconvenient to depend on a big power supply.

To use the sensor, it was soldered to a breadboard with a 10kΩ resistor. After that, it had to be calibrated by performing various tests. The test was done by connecting a supply voltage to an amplifier and to two transistors to increase the current-output capability. This circuit is shown below.
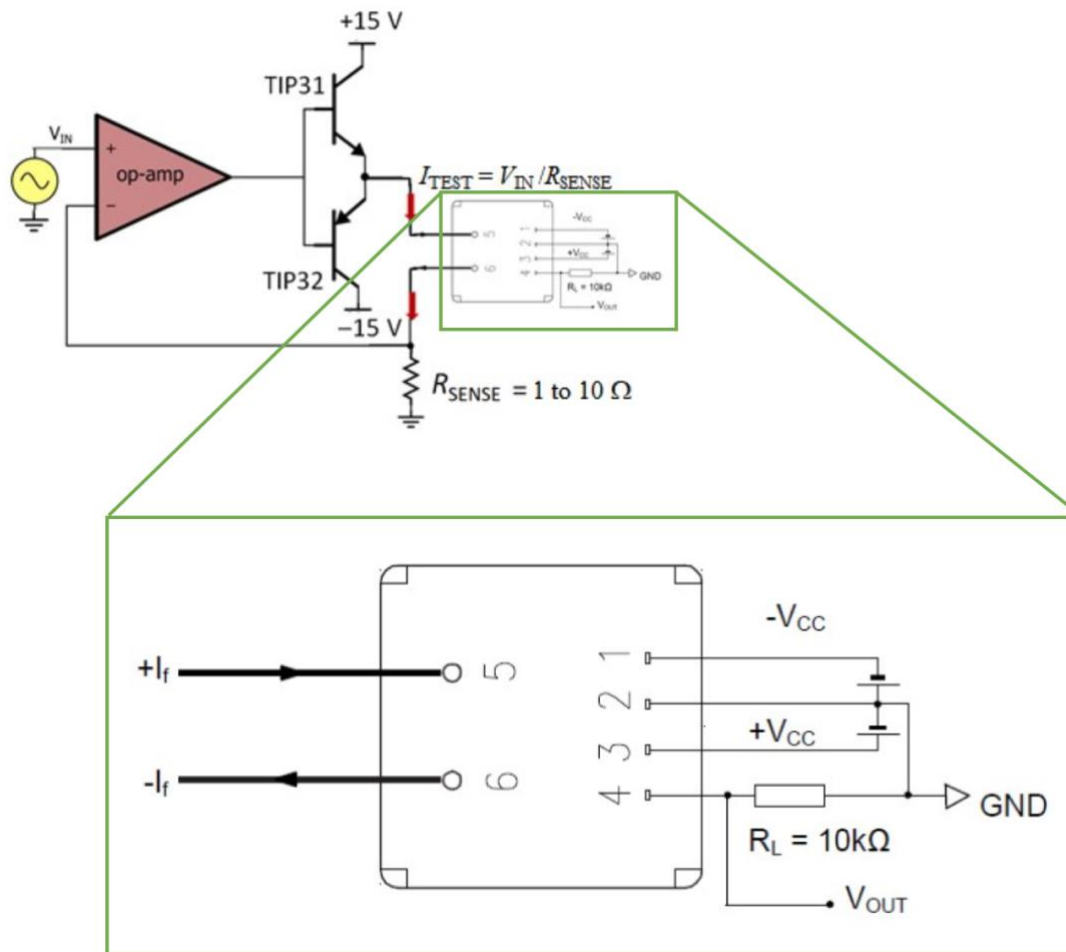
Figure 28. Schematic of the L18P-003 sensor. [22]

As we can see from the results below there is a correlation with little error.

DC calibration test (negative current)

DC calibration test (positive current)
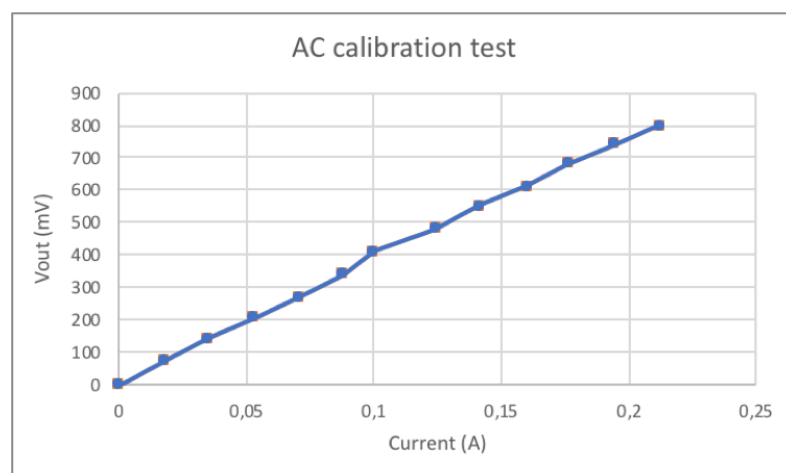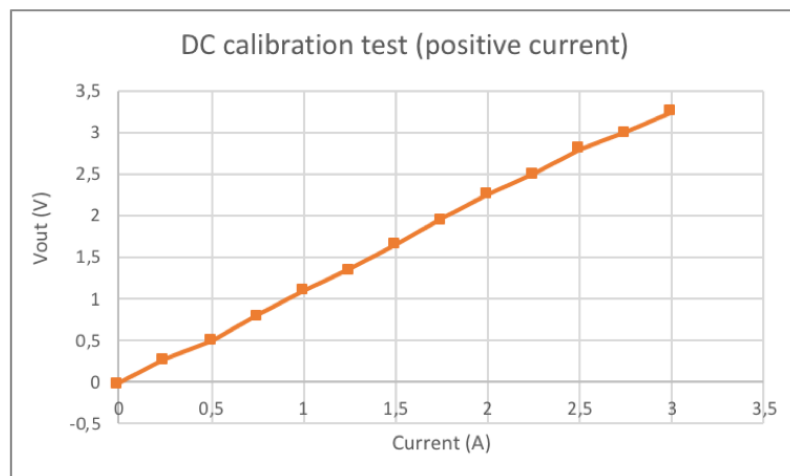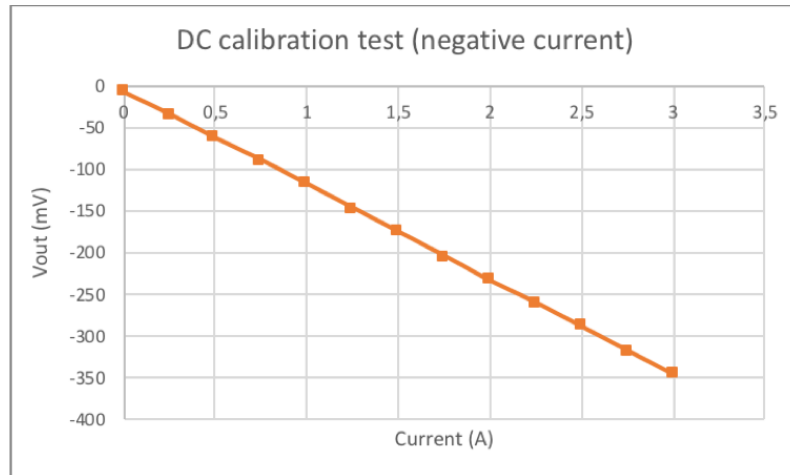
PCB:

BELD demanded that certain parts of the project were put into PCBs. A PCB is a printed circuit board. That is, a board where you can establish the connections of the circuit. A PCB has several advantages compared to the use of a regular breadboard. The first one and most significant is the neatness of the circuit as you eliminate wires flying around. The second one is the toughness of the circuit. That is, after soldering the components to the PCB having a loose wire is avoided.

To design the PCB the Altium software was used. The design is based on different layers to make all the connections. The design for the measurement circuits was done using a layer that covered most of the PCB and that would serve as ground. Small paths were made in that layer for the rest of connections (*Figure 30* and *Figure 32*).

As the PCB only established the connections the components had to be soldered later. However, in the design of the PCB their size and shape have to be taken into account so that they fit in the board. This is done using predesigned components such as resistors. However, some of these components were not included in Altium's software. An input header as well as an op-amp had to be designed in Altium. This is done measuring thoroughly the piece and adding all the pins of the component.

The PCB manufacturer, which is a different company from Altium called AllPCB, charged the customer on the complexity of the board and on the size of it. Therefore, in the designs, an efficient size was used eliminating the space that was not strictly necessary. The results of the designs are shown below:
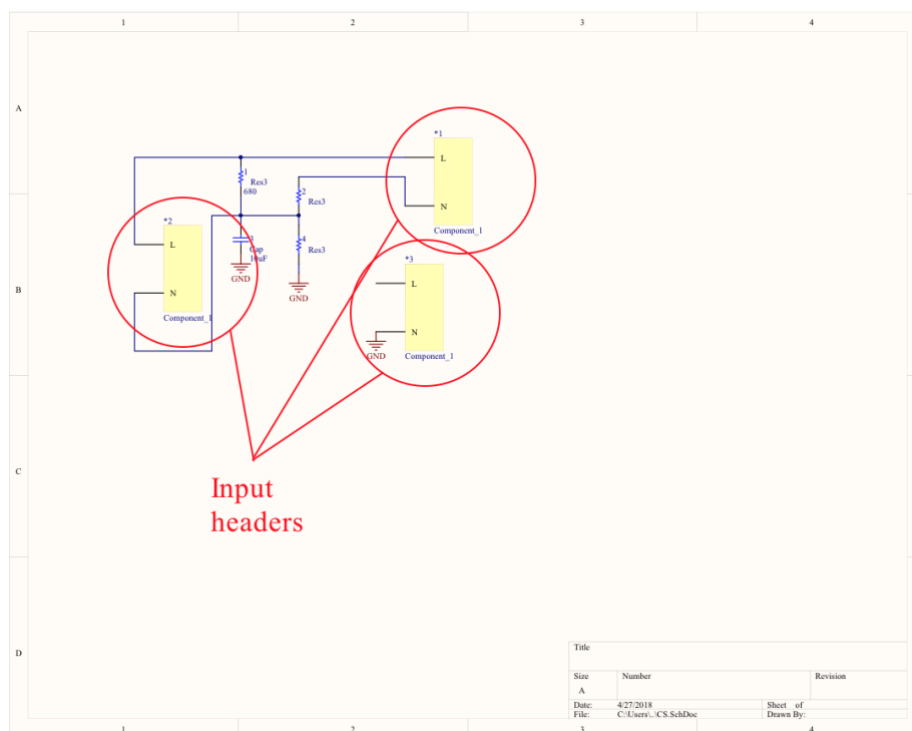
Figure 29. Current measurement circuit PCB schematic.
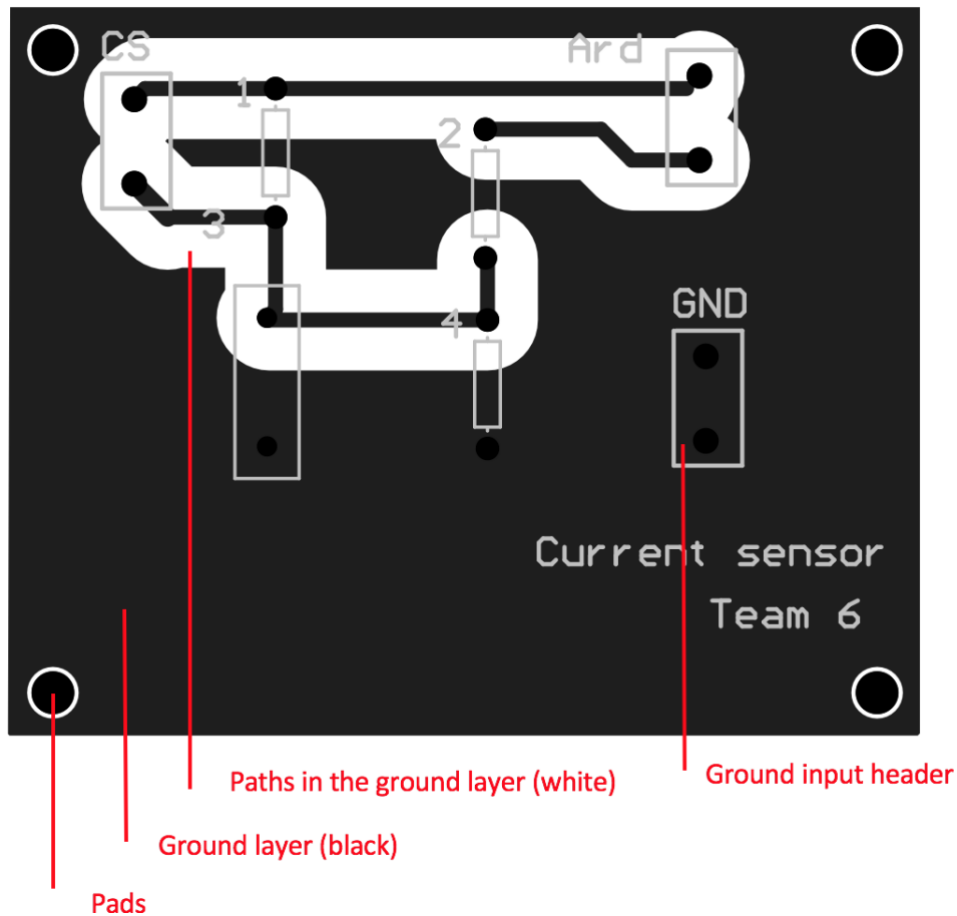
Figure 30. Current measurement circuit PCB design.

Some notes on the PCB design:

- As shown, the color black represents the ground layer, which covers most of the PCB. It is designed in a way that avoids unnecessary paths and connections, which implies bigger expenses.
- The pads are used to stick the PCB in a location. Screws are a common way to do this although a more elegant solution is the use of slide secure accessories which allows an easier removal of the PCB in case the user wants to repair it or change it.

Figure 31. Voltage measurement circuit PCB schematic.
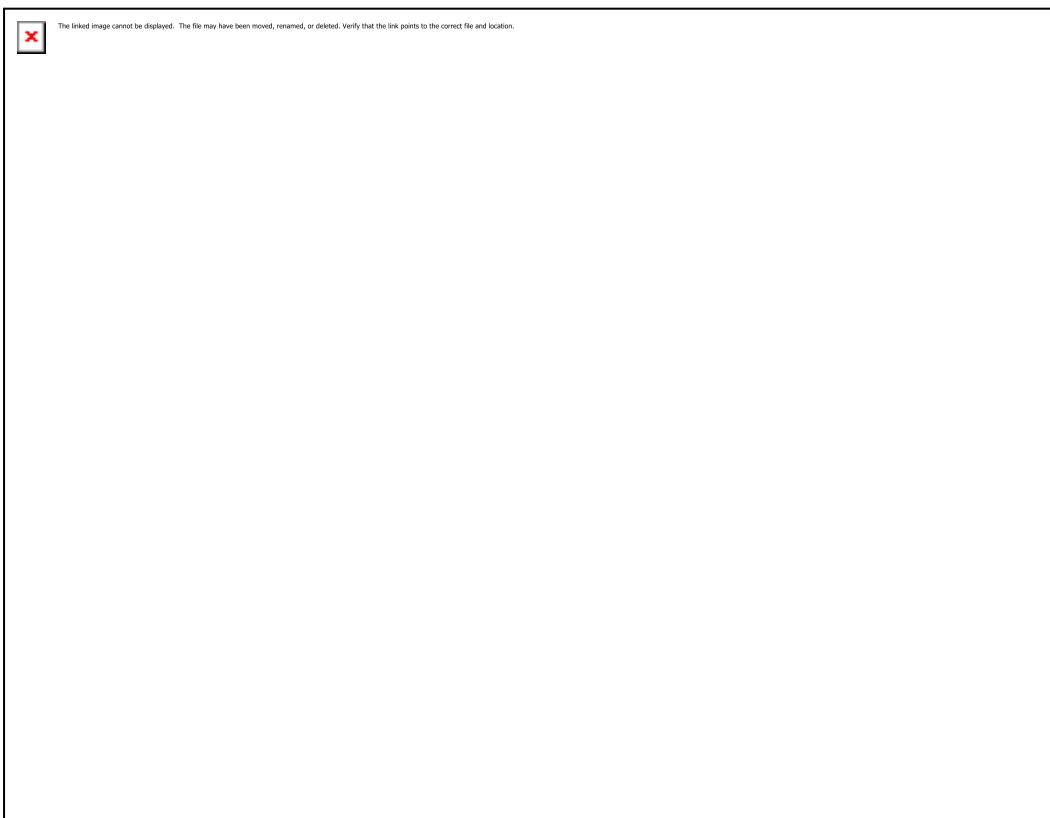
Figure 32. Voltage measurement circuit PCB design.

Initially, a different circuit to measure the voltage was designed. This design used two operational amplifiers. As the use of this second op-amp was not entirely necessary, this design was eliminated. However, it is worth mentioning as it uses other op-amp configurations (inverting amplifier and non-inverting) that could be relevant for other projects. The PCB design can be seen in *Figure 33*.
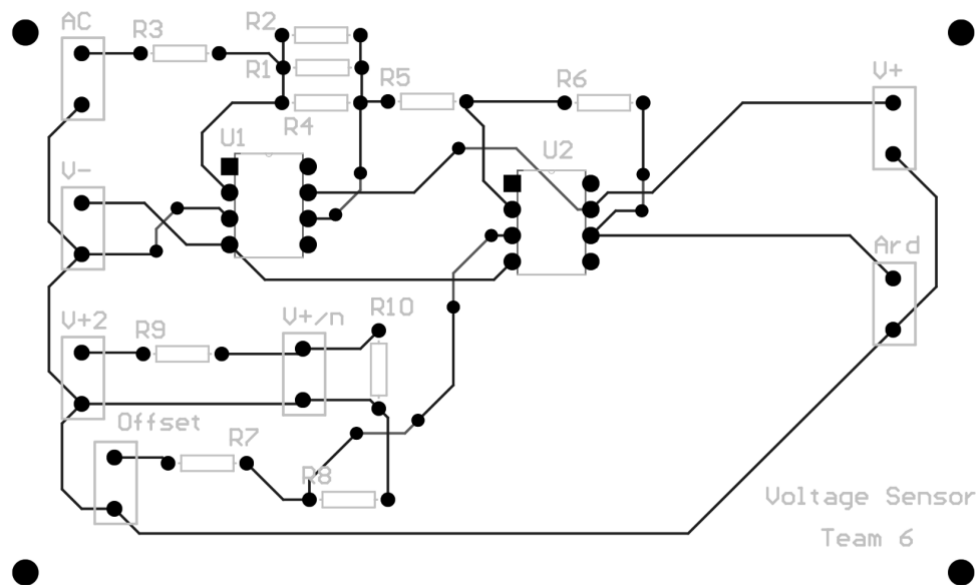
Figure 33. Schematic of our first voltage measurement circuit.

- Data reading:

As previously described, the data processing will be done using Arduino Uno. Arduino's capacity for storing and displaying the information is very limited so another software is needed for these purposes. After the study of different options, Processing was the software used as it had numerous display options and synergy with. Note: "Arduino", with capital letter, is the computer software, and "arduino", the physical microcontroller.

To acquire the data, Arduino reads the ports in which the measurement circuits are connected and stores them in a matrix. This matrix contains the voltage and current and it stores them approximately every three tenths of a second. It is worth noticing that

Arduino can read much faster. However, to improve the accuracy of the reading and mitigate the effect of outlier points, the arduino reads several values and average them every three tenths of a second. For the tests that are performed it is not necessary to obtain values faster so the arduino will store them at that speed ratio.

Depending on the point of the grid that the Arduino is reading, the Arduino code varied as it had to read DC in one point and AC on the rest. On the one hand, the reading of DC voltages and currents is straightforward as only an average of the values is needed to make accurate measurements. On the other hand, reading AC waves is more complicated as values that range from the peak value of the wave to its opposite negative value are obtained. In addition to this, some of the sinusoidal waves were not perfect.

There are several ways to measure sine waves, but we finally opted for a rudimentary code that compares each value with its last one and stores the maximum of the two. Repeating this process several times, the peak value is obtained.

- Data transfer:

As explained in the last section the transfer of the data will be between Arduino and Processing. In order to do this, the serial port of the arduino is necessary. A serial port is used in microcontrollers to establish communication with other microcontrollers.

Arduino Uno only has one serial port and that posed a problem as it meant that the arduino could only send one value at a time. As the objective of the measurement system is to measure power both the current and the voltage, which are two different variables, needed to be sent. If Arduino sends both these values through the same port, Processing would not be able to recognize which was the voltage and which the current. First, a successful communication with only one variable being transferred was ensured and then the problem of sending two variables was solved. To do this, several options were studied.

Firstly, two ranges within which the voltage and current would be were established in Processing. That is, Processing would recognize values that were between 0 and 3.5 and

assigned them to the current as the maximum current expected is 3A. The voltage is not expected to be lower than 9V so any value higher than that would be recognized as voltage by Processing. This solution which was simple and worked had an obvious flow: although the values were expected to be in those ranges, one of the objectives of the measurement system is to ensure certain degree of safety by recognizing if the current or voltage are higher than expected. If for any reason the current starts to increase substantially and goes above 3.5A the user would not be able to notice. In the laboratory, tests do not always go according to plan and having those ranges could be dangerous.

Secondly, another option was to establish a very precise communication between Arduino and Processing. By timing when Arduino sends a value and when Processing receives it, the times could be balanced. The voltage and current value would be sent every second but at different moments. That is, every half of a second Arduino would send a value. Processing would receive a voltage value, half a second later a current value, half a second later a voltage value, half a second later a current value, etc. This option could be accomplished having a very precise communication between the two. However, a problem appeared. The arduino's serial port sends values constantly and sometimes the measurement process is not able to read the voltage or current from the grid in time. This results in the serial port sending to Processing *null* values that disturb the data transfer. This could be solved by making Arduino not send data until the values are read correctly (eliminating *null* values) but that distorts the time balance between Arduino and Processing.

Lastly, the approach to this problem was done with a simple but effective way to recognize which value is what variable. Instead of sending numbers, Arduino would send a *string* composed by a letter and a number. The letter "c" or "v" depending on the value would mean current or voltage respectively. The number is the value of the variable.
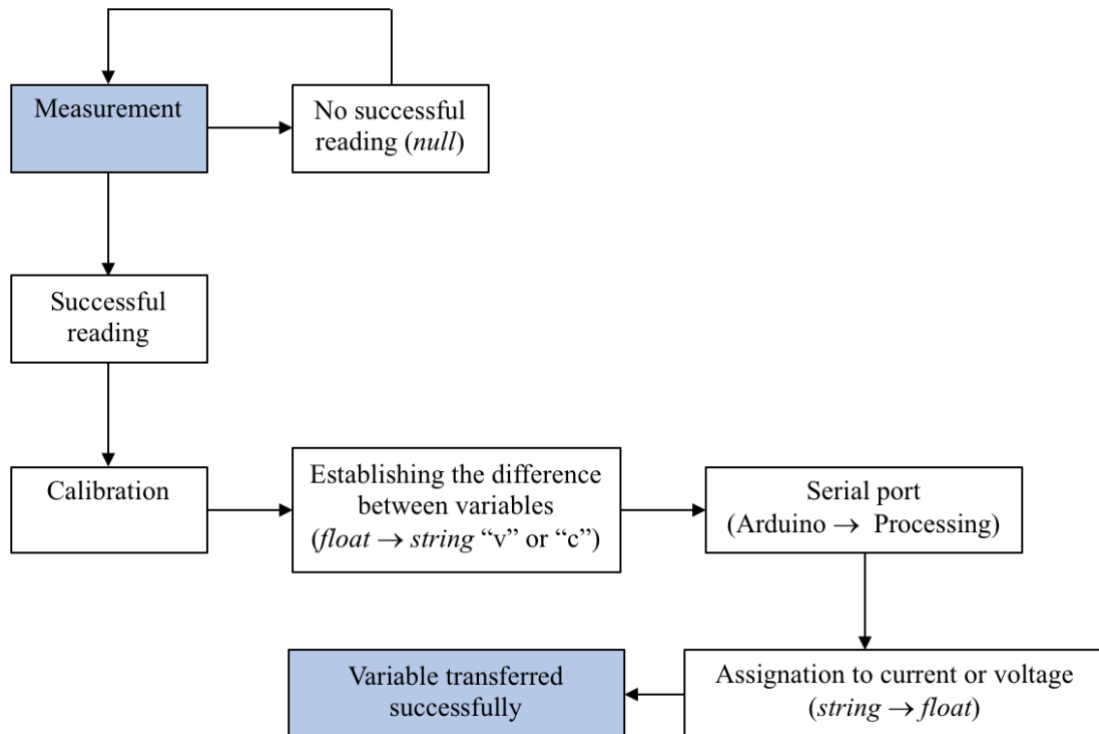
Figure 34. Data transfer schematic.

- Data storage:

The data storage is done with Processing. Once the data is transferred from Arduino the code indicates Processing to create an Excel file and start filling it in with the values. This is done automatically, and the user will realize that without any further operation at the end of the test a file has been generated with all the data. A basic spreadsheet of this is composed by the current, voltage and power (*Table 3*). Functionalities like editing the file name and adding more calculations to obtain the characteristics of the batteries can also be included.

Time	Voltage	Current	Power
1	4,14	0,41	1,6974
2	3,67	0,36	1,3212001
3	3,52	NaN	NaN
4	10,46	NaN	NaN
5	10,46	0,96	10,0416
6	8,79	0,96	8,438399
7	8,79	0,83	7,2956996
8	7,75	0,83	6,4325
9	7,75	0,71	5,5025
10	5,99	0,71	4,2528996
11	5,99	0,56	3,3544
12	5,04	0,56	2,8224
13	5,04	0,51	2,5704
14	4,95	0,51	2,5245
15	4,95	0,49	2,4255
16	4,65	0,49	2,2785
17	4,65	0,41	1,9065
18	3,93	0,41	1,6113
19	3,93	0,39	1,5327
20	4,14	0,39	1,6146
21	4,14	0,42	1,7387999
22	4,32	0,42	1,8144
23	4,32	0,4	1,728
24	3,76	0,4	1,5040001

Table 3. Excel sheet generated by Processing example.

Figure 35. Schematic of the software used to store the data.

- Data display

In the first stages of the project the data was displayed using arduino tools called Monitor Serie and Serial Plotter. The first one just displays the value in a list (*Figure 36*) and the second one graphs the values in real time (*Figure 37*).
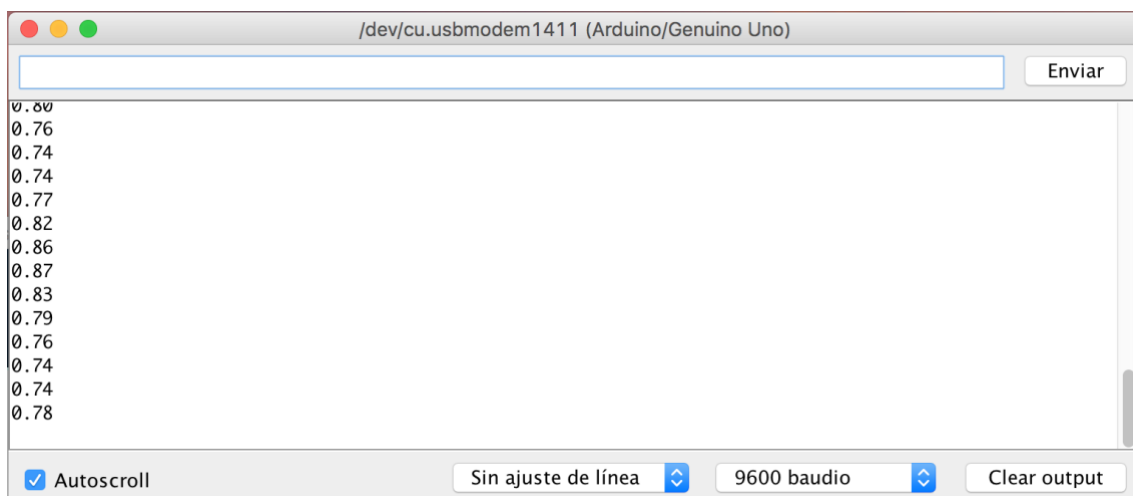
Figure 36. Monitor serie.
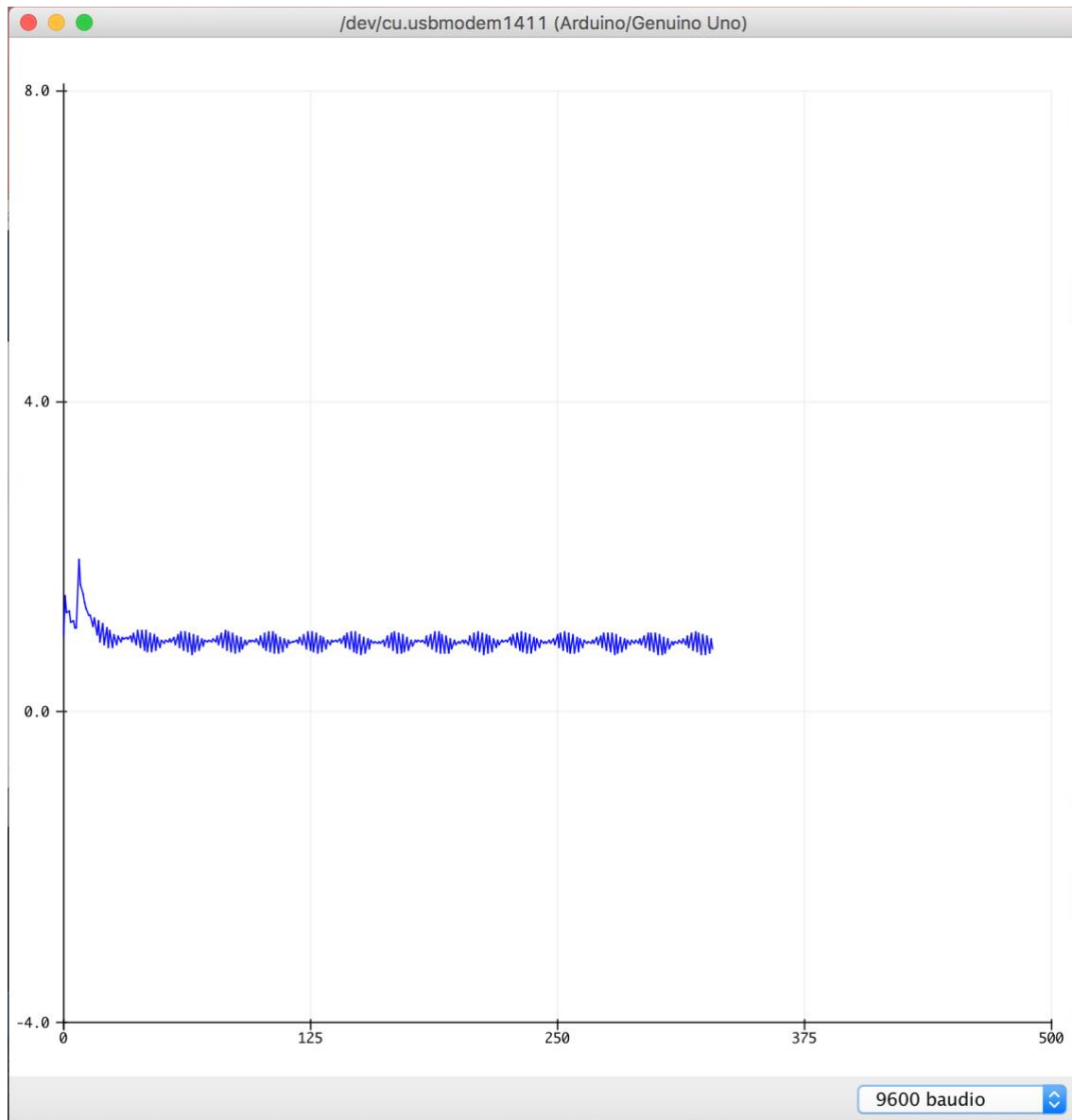
Figure 37. Serial plotter.

However, as the project advanced other capabilities were necessary. Firstly, four LCD screens where added to the arduinos (*Figure 38*). The connections between the LCD screens and the arduino can be found in the Arduino Forum (*Figure 39*). They displayed the voltage, the current and the power being drawn or supplied.
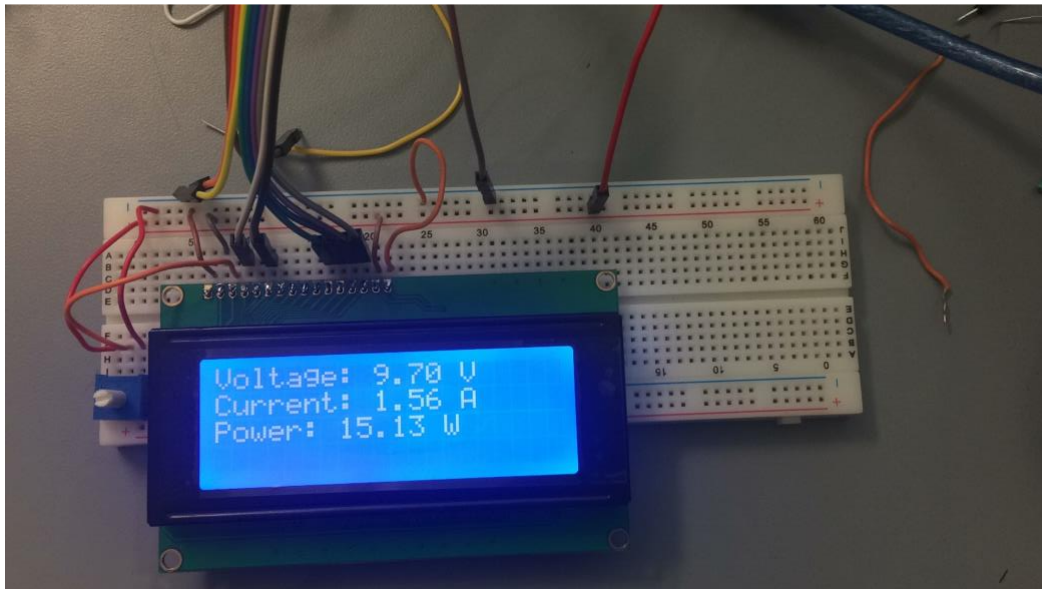
Figure 38. RioRand LCD Module for Arduino.
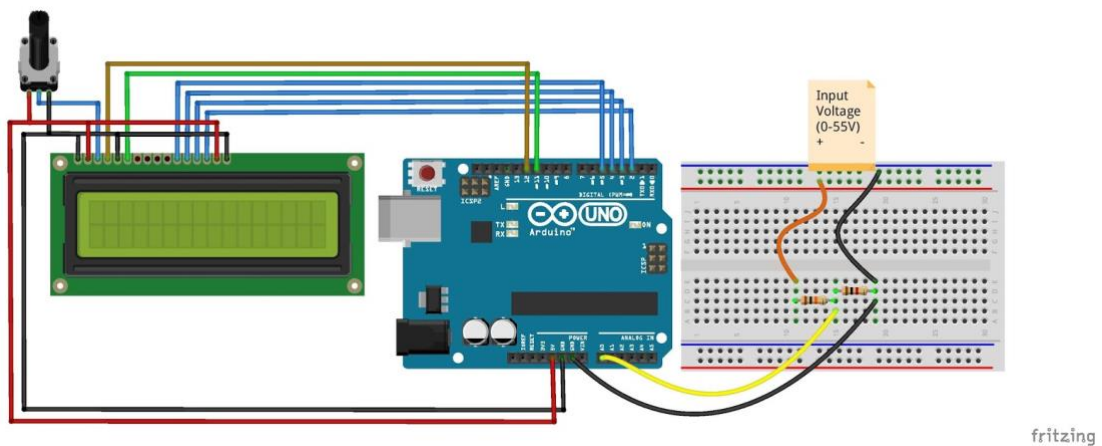
Figure 39. LCD connections schematic. [23]

Secondly, using the Processing software a series of graphs displaying the voltage, current and power were generated automatically (*Figure 40*). It is important to note that these graphs are created at the end of a test. LCD screens are therefore necessary to make sure the test is going according to plan and is performing correctly while it is still running.
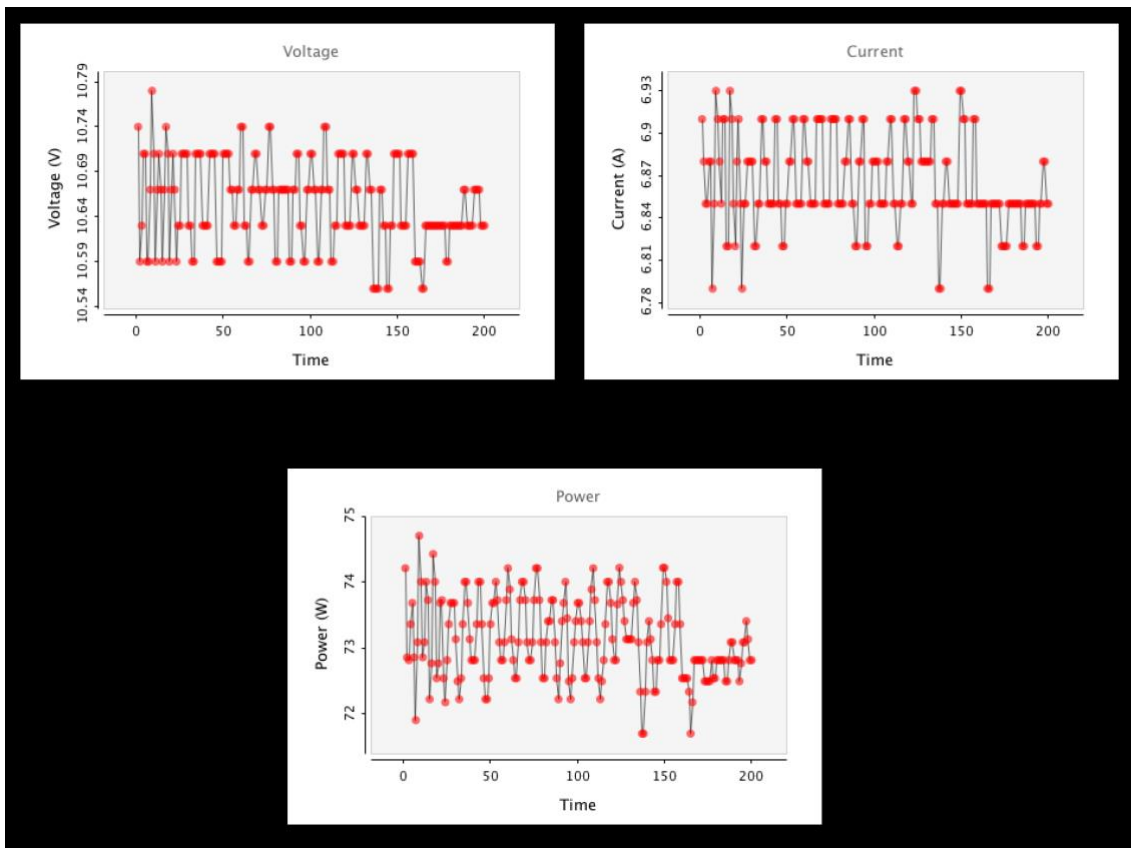
Figure 40. Processing display.

3.3.2.4. Demand curve modeling

In this section a brief explanation of how the demand curve is modelled in the mock grid is given. Note that a further explanation of this subsystem of the project will be given in *Modeling Power Grid with Battery Storage. Demand curve modeling* by Teresa Jimenez-Castellanos Vida.

The demand curve will be modelled with a variable load. Throughout the day the power demand varies substantially, reaching a peak during the afternoon. The variable load consists of six resistors and six switches that will turn on and off depending of the time the day. Two of these loads will be always consuming power and as a consequence, we can simulate the different stages of the demand curve as four steps (*Figure 42*), changing the total power consumed.
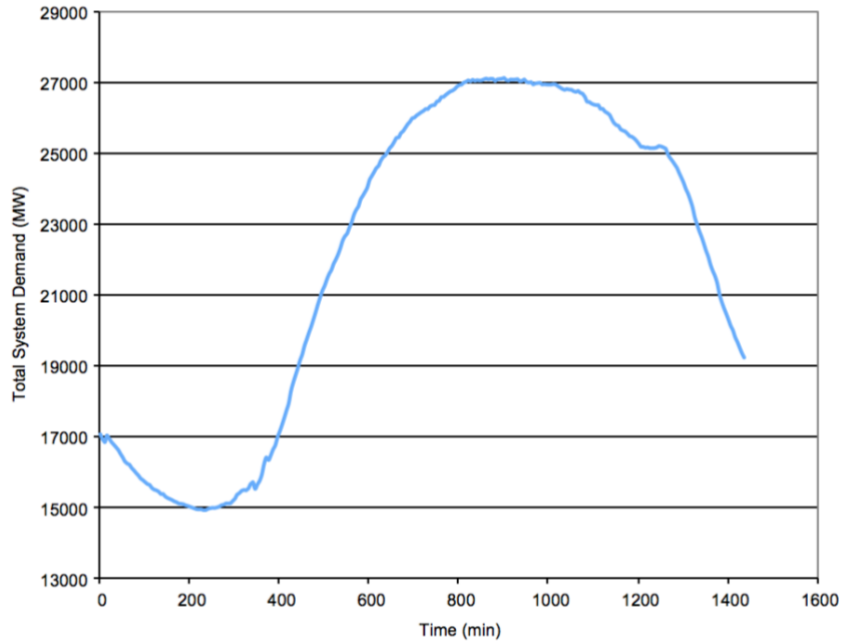
Figure 41. Typical summer demand curve ISO New England.
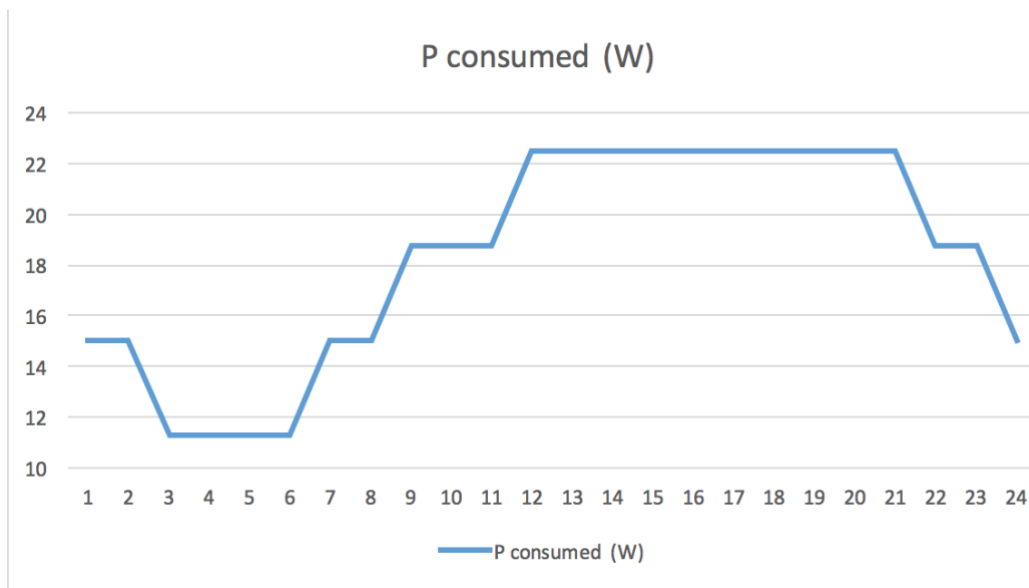
Figure 42. Simulation of the power demand curve.

1.3.2.4. Integration

The integration of the project has two main parts: the synchronization of the battery station with the generation system and the control of all the subsystems.

Firstly, it is important to be able to synchronize the battery installation with the generation subsystem so that in times of peak demand, the load receives power from both the power generation and the battery station (discharging state).

Synchronizing the generation's AC voltage wave with an AC power supply was tested before trying it with the battery installation. To do so, a small circuit with a resistor, a led and a switch was designed. In this circuit the led remained on while the two waves were out of phase. On the contrary, it turned off when they were in phase and therefore the switch was pressed in that moment and the two waves were synchronized. However, a problem with the synchronization of the two waves appeared: once together, the two waves started to steadily reduce their peak value until extinguishing. This process happened in one or two seconds. Although the waves arrived to the 0V value, after that they started to increase steadily until achieving the original voltage value. This happened as well in one or two seconds. The process repeated itself for as long as the two waves were synchronized, increasing and reducing their values in a matter of seconds. The problem was thought initially to be due to the difference in frequency between the two waves and therefore it could have improved. However, in reality, the reason why the synchronization was not being completed successfully was the necessity of having a rotational motor such as an induction motor that is able to change its frequency to adapt. This solution will be further explained in *Modeling Power Grid with Battery Storage for BELD. Power demand curve simulation* by Teresa Jimenez-Castellanos Vida.

Secondly, the control of all the parts working together was, at first, going to be automatic. However, some restrictions that were overlooked at the beginning of the project were encountered. To start with, the available computers only had two USB ports each and four arduinos were needed. Although it is possible to have two different arduinos working at the same time with the same computer the integration of the measurements of the four

of them would have been impossible as two of them are in separate computers. Even so, the integration of two arduinos in the same computer is not an easy task. It is possible to open two different Arduino IDEs and run them simultaneously. Nevertheless, it would have required a different software, such as Processing, to put together the data gathered by the two separate arduinos.

A different solution would have been to make the measurements of several points of the grid with the same arduino. This option which is easier than the last had some problems as well. The arduino has six analog inputs and two of them are needed to measure the current and the voltage of one point of the grid. This means that theoretically, three points of the grid could have been measured using the same arduino. However, we needed an arduino for each LCD screen as only one of them already occupies several digital pins in addition to a Ground and a 5V pin. Although this is a complicated solution, it would have been our final approach to the problem.

This is the reason why the LCD screens work as a guide to turn on or off the battery installation instead of being fully automatic. It requires the assistance of the user. By measuring the power being consumed by the load and the battery stage of charge in the same arduino (which could have been done as it is only two measurements in the same arduino) the arduino would be able to determine if the batteries should be charging or discharging. A display of the result would be shown in the LCD screen advising the user to turn on or off the switch controlling the battery system.

1.3.2.5. Enclosure

The enclosure is essential for the security of the system. The batteries, if exposed to high currents could burn or even explode. This is the reason why the batteries are covered by the glass top. The cover is made of acrylic glass and is secured on top of a wooden base where the project is placed. If needed for maintenance purposes or battery changes the cover can be removed but it is recommended to have the cover at all times during a test. The cover has several gaps where the microcontrollers wires can go through to connect

to a computer. Apart from the variac, which is outside the cover due to its big size, the rest of components are inside the enclosure.
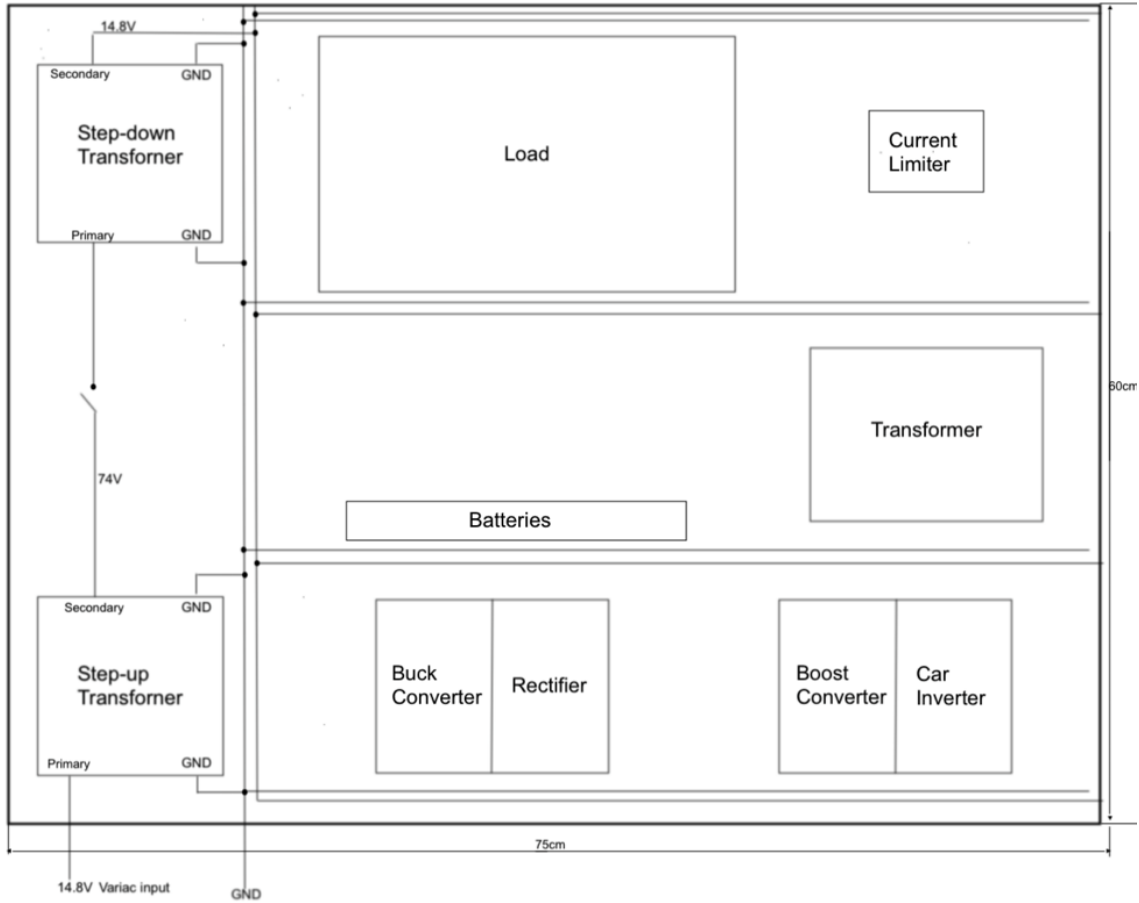
Figure 43. Components location enclosure schematic.
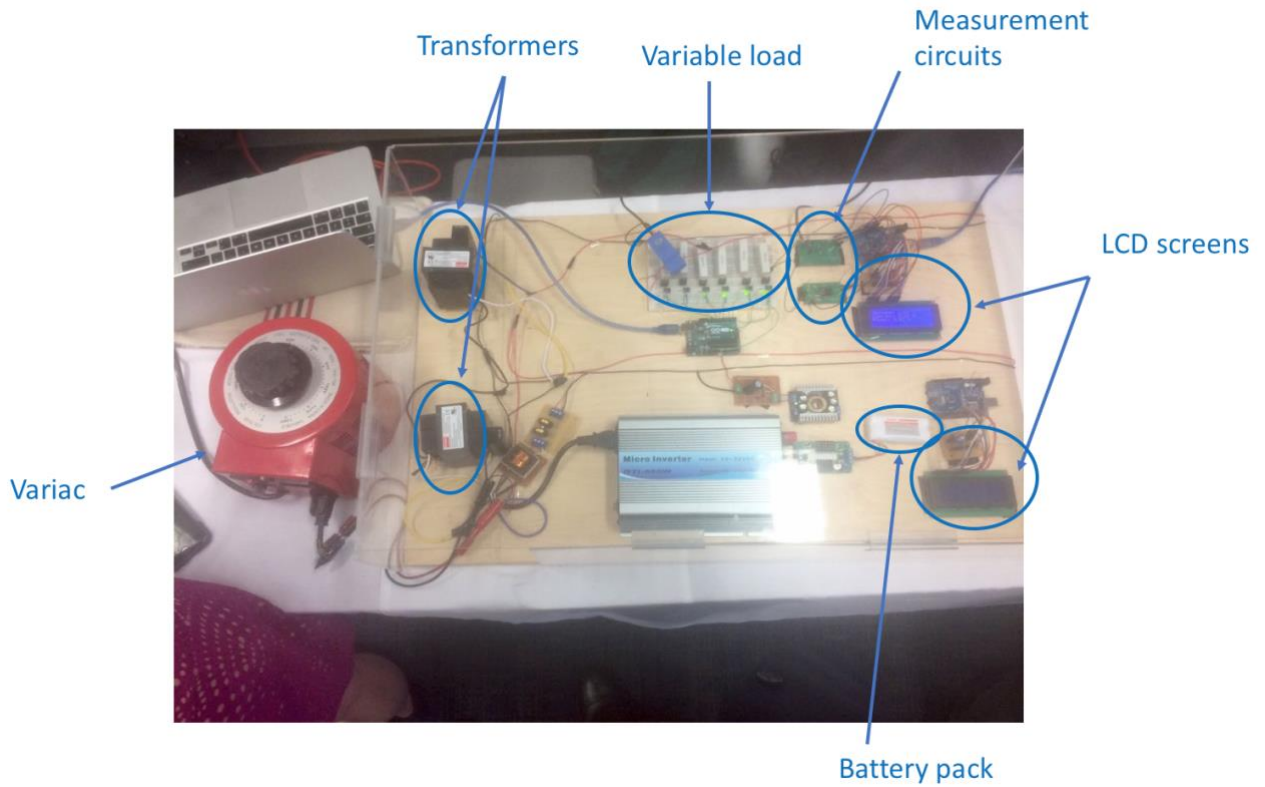
Figure 44. Project overview (1).
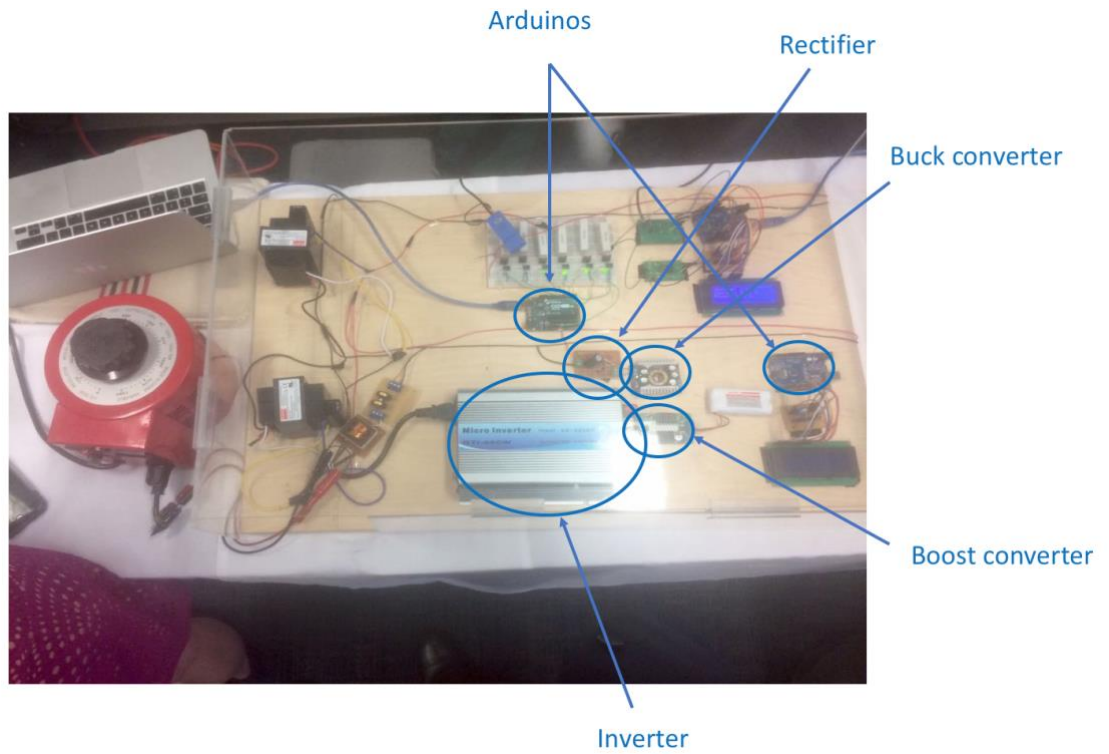
Figure 45. Project overview (2).

Chapter 4: Final remarks

4.1. Accomplishments and improvements for future continuations of the project

In this section, the accomplishments of the team as well as my individual contribution will be discussed. These accomplishments will be based on the objectives set at the beginning of the project. Firstly, the engineering requirements will be examined and secondly, the wider overall objectives.

The engineering requirements that were successfully completed by the group were: the creation of a physical small-scale mock grid that works at a frequency of 60 Hz, the simulation of the power demand curve using a variable load that can represent different scenarios, the use of AC instead of DC and the duplicate, to an extent, of BELD's loop distribution grid with two transformers. All the security requirements were also accomplished: the enclosure of the grid in a small box that can fit through a standard door, the maximum values of 30V for the voltage and 3A for the current.

In my individual part of the project all requirements were accomplished although there is room for improvement. These requirements were: the voltage, current and power can be read in at least four points of the grid, the user must be able to store the data obtained from a test, the interface needs to be user-friendly, the data will be automatically displayed after a test and the data needs to be visible during the test to certify that the values are in range and to make sure that the overall development of the test is going as expected.

A few remarks on these last requirements:

Firstly, as described in the battery installation section, the charging and discharging station were not fully completed and therefore, four points of the grid were not measured as it made no sense measuring the battery installation if it was not integrated in the rest

of the system. The rest of the relevant points of the grid (the power generation and distribution and the variable load) were measured.

Secondly, the interface is, to an extent, user-friendly. However, in this area there is still room for improvement as there are some steps the user needs to know and follow in order to save the data and run the system. A more automatic system would reduce the amount and difficulty of the steps that the user needs to perform (a description of all these steps is given in the appendix: User Manual).

Lastly, the visibility of the data during the tests is done with the use of LCD screens. As the battery installation was not fully completed, an LCD screen was not added to this part of the system although it would not require much work once the battery system is completed.

As for the overall objectives of the project not all of them were accomplished but in future continuations of the project they can be achieved. This project shows how understanding the demand curve and using battery storage technologies can help with the reliability of the grid and with the reduction of the costs by peak shaving the supply curve. However, it fails to provide a definitive decision on which battery chemistry is optimal for BELD. All the instruments and keys to achieve this objective such as measurement circuits, replica of the demand curve and power generation have been created. With the improvement of the battery installation system this project will be able to determine, to an extent, the optimal battery chemistry for BELD as well as determine key characteristics of the batteries that are tested.

For the continuation of the project several key factors need to be taken into consideration: the need for a charging module to charge the batteries, the need for an inverter that can work along the rest of the grid and the need for a software other than Arduino to acquire the data as Arduino is not capable of doing this. On this last one a brief comment is that with the use of other microcontrollers such as Raspberry Pi the measurement can be easier. The use of the software Processing is not a must as other software can achieve similar feats.

4.2. Conclusion

This project focused on battery storage and its relevance in the future of the power grid. The development of battery storage in the past years suggests that an increase in the power stored in utility-scale batteries, a reduction of their costs and an improvement in their capacity can be expected. Power storage technologies can improve the grid's reliability as well as provide other benefits such as maintaining power quality and reducing the price of electricity during periods of high demand (peak-shaving).

In comparison to other storage technologies, batteries have not yet evolved significantly enough to substitute these other technologies such as flywheels or pumped hydro. However, there is an undeniable increase of the utility scale battery installations, mostly focused on lithium-ion.

As for the model of the power grid with battery storage, there are several notes to be made. On the one hand, the model was built as a physical small-scale mock grid. This approach to the problem may have not been the best, as other tools such as a computer simulation of the grid can have more relevance for utility scale battery storage. The problem of scaling our results to the utilities bigger picture may have been problematic. On the other hand, working not only with the theory but also hands down in a laboratory, makes the researcher much more aware of the problems that can surface in addition to the restrictions in terms of budget, space, materials or time to build the project.

To some degree, the accomplishments of this project were as expected, keeping in mind that this project is meant to be continued in the future. Students can improve the model and develop an analysis based on the results of the tests that can be performed with the tool that we have provided.

Chapter 5: Budget

In this section a summary of the main components and the budget that was used will be given. The components will be classified depending on the part of the project in which they were used.

The budget was obtained through three sources of financing. Firstly, Boston University (BU), entity in which the project was developed, finances their projects with $500. Secondly, the students of BU developing the project are expected to help with $100 each. Lastly, the project won a grant of $5,000 given by the APPA (American Public Power Association).

APPA promotes projects and thesis by awarding grants, internships or prizes. Our project was selected by them to receive this year's grant as well as a trip to North Carolina where our achievements were presented in their annual conference. Having this in mind our final budget for the project was $5,900.

Demand curve modeling			
Item	Quantity	Unit price	Total price
Optocoupler IL420, Phototriac	1	8,00	8,00
Optocoupler 4N25, Phototransistor	1	5,75	5,75
100 W, 12 V light bulb, Philips	1	9,99	9,99
TRIAC NTE 5645	1	4,34	4,34
100 W light bulb	1	6,23	6,23
Vishay semiconductor, IL420, optocoupler	6	4,26	25,55
10 pieces, 30 Ω, 10 W resistors	2	20,64	41,27
TRIAC NTE 5645	6	8,85	53,10
PCB	1	33,44	33,44
Optoisolator NTE 3220	1	7,51	7,51
MOSFET IRF510	7	1,00	7,00
Circuit breaker	1	12,99	12,99
Power resistors, LEDs	1	2,40	2,40
MOSFET	1	4,00	4,00
TOTAL		$221,57	

Power generation and distribution			
Item	Quantity	Unit price	Total price
4VZF5 Cls 2 Transformer, Open, Foot	2	28,8	71,45
Philmore TR121 12VCT 1A Power Transformer	1	8,68	13,67
TOTAL		$85,12	

Battery installation			
Item	Quantity	Unit price	Total price
PCB	5	8	41,72
MBRB2545CT (Diode)	3	1,59	4,77
LT3748	4	7,43	29,72
IRFH6200(Power Mosfet)	2	1,75	3,5
LT1716	2	2,5	5
Battery Protection Circuit	5	7	7
Variac variable AC Power Transformer 0-130V	1	73,99	73,99
Current Sensors	1	9,34	9,34
Car Inverter	1	11,8	11,8
Solder Kit	1	20	20
Lithium Ion Battery	1	13,29	13,29
EK 307 Kit	1	1	19,99
NMOSFET	1	1	1
Iher	1	1	3
NMOS	1	1	1
Tape	1	1	6,9
Ferrit Core	1	5,8	5,8
Clamp, U Shaped Clip	1	1,36	1,36
Coil Former Vertical	1	1,16	1,16
Solder	1	10	10
Copper Wire	1	9,46	9,46
Battery Switch Scheme PCB	1	20,47	20,47
1600 mAh BBTY0651101 Cordless Phone Battery	1	8,99	8,99
DROK DC Car Power Supply Voltage Regulator Buck Converter	1	10,99	10,99
DROK LTC1871 3.5V-30V DC Boost Converter Power TFM	1	15,95	15,95
orlov 50pcs 18650 Battery Bracket Double Holder with Pure Nickel Solder tabs	1	11,99	11,99
10PCS 3.7V 5000mAh 18650 Battery Rechargeable Batteries	1	15,99	15,99
UPG UB645 Sealed Lead Acid Batteries (2 Pack)	1	15,25	15,25
2 of GEILIENERGY 8 Pieces Set Yellow Color AA Size NiCd	2	3,9	7,89
BESTEK Pure Sine Wave 300W Power Inverter	1	43,99	43,99
eBoot 5 Pack Boost Converter Module XL6009	1	12,59	12,59
DROK LM2596 Analog Control Buck Converter DC-DC 4-32V	1	8,89	8,89
ANBES Soldering Iron Kit Electronics, 60W Adjustable Temperature Welding Tool,	1	19,99	19,99
Enkey 150W Car Power Inverter DC 12V to 110V AC Converter	1	11,8	11,8
AuBreey 5PCS/LOT 2S 3A Li-ion Lithium Battery 7.4v 8.4V 18650 Charger Protection	1	6,99	6,99
Grid Tied Inverter	1	94	94
18650 5000mah Lithium Ion batteries	1	15,99	15,99
50 pcs 18650 Battery Holders with Nickel Solder Tabs	1	11,99	11,99
TOTAL		$121,98	

Data acquisition				
Current sensor and voltage sensor PCB		1	31,37	31,37
RioRand LCD Screen		3	7,99	24,58
Uxcell SCT-013-005		1	26,18	26,18
Uxcell SCT-013-005 2		1	24,25	24,25
Uxcell SCT-013-005 3		1	26,24	26,24
Uxcell SCT-013-005 4		1	37,66	37,66
RioRand LCD Screen 2		1	19,03	19,03
RioRand LCD Screen 3		1	14,5	14,5
Arduino		1	10	10
	TOTAL		$213,81	
Additional purchases				
NTE 56050 TRIAC		1	12,36	12,36
IRF520 MOSFET		1	17	17
IRF520 Driver		1	19,57	19,57
	TOTAL		48,93	
Total Hardware Expenses from **ALL** group members			$691,41	

Figure 46. Cost of the components.

PART II: BIBLIOGRAPHY

[1] Braintree Electric Light Department. BELD's power mix, 2015.

[2] Braintree Electric Light Department. The Potter Generation Station, 2017.

[3] Braintree Electric Light Department. The Thomas A. Watson Generating Station, 2015.

[4] Braintree Electric Light Department. BELD's power mix, 2015.

[5] Braintree Electric Light Department. The Potter Generation Station, 2017.

[6] Braintree Electric Light Department. BELD and Borrego Solar Systems receive grant from Massachusetts Clean Energy Center, 2017.

[7] April Lee. U.S. Energy Information Administration EIA. "Batteries perform many different functions on the power grid", 2018.

[8] U.S. Energy Information Administration EIA. Form EIA-860M "Preliminary Monthly Electric Generator Inventory", 2018.

[9] Fletcher Fields, Cara Marcy. U.S. Energy Information Administration EIA. "The design and application of utility scale battery storage varies by region", 2018.

[10] ARUP. "Five-minute guide: Electric Storage Technologies", 2017.

[11] U.S. Energy Information Administration, Form EIA-860. "Annual Electric Generator Report", 2016.

[12] ARUP. "Five-minute guide: Electric Storage Technologies", 2017.

[13] ARUP. "Five-minute guide: Electric Storage Technologies", 2017.

[14] U.S. Energy Information Administration, EIA. "Electricity storage technologies can be used for energy management and power quality", 2011.

[15] Fletcher Fields, Cara Marcy. U.S. Energy Information Administration, Form EIA-860. "Annual Electric Generator Report: Costs of different batteries storage technologies depend on technical characteristics", 2018.

[16] Richard Blowers. U.S. Energy Information Administration EIA. "Energy storage and renewables beyond wind, hydro, solar make up 4% of U.S. power capacity", 2017.

[17] Daniel W. Hart. "Power Electronics", 2010.

[18] Daniel W. Hart. "Power Electronics", 2010.

[19] blog.circuits4you.com. Arduino forum.

[20] Open Energy Monitor. Archived forum.

[21] Power Electronics for Energy Systems. Build and calibrate Hall-Effect Current Probe.

[22] Power Electronics for Energy Systems. Build and calibrate Hall-Effect Current Probe.

[23] Fritzing. LCD screen set up tutorial.

PART III: APPENDIX

1. USER MANUAL

This section of the appendix intends to show the step by step process of using the physical grid as well as a user interface guide. This section has not been written entirely by the author of this report but by the whole group that helped build the project. This section of the appendix is meant to be a guide for future users of the tool on how to turn on/off the different components and parts of the project.

1.1. User interface

Generation and distribution

The user interaction in the generation system consist mainly of the ON/OFF switch of the variac and the synchronization circuit. The variac should be connected to the wall outlet and the switch pressed once we make sure everything seems in order. The synchronization circuit is simple to interact with, consisting on two switches whose state needs to be changed by the user. Detailed information of its use is provided in the sections below.

Demand curve modeling

The load requires almost no user interaction, apart from running the appropriate code in Arduino. It has been designed to follow the demand curve automatically and the user only needs to make sure everything is working correctly.

Battery installation

The battery installation system requires more user interaction. First of all, the user should select the type of battery chemistry that is going to be tested and connect it in the indicated place. Then, when the simulation is running, two different LEDs will turn on for the user to know when the battery system should be connected or disconnected. Detailed information is provided in the sections below.

Data acquisition

As for the data acquisition several steps have to be followed. First off, the Arduino code should be run and afterwards the Processing code. After the test is finished the user has to save the obtained data as follows: open Excel, File > Import, select File CSV and click import, search within the documents in the computer for the folder "Data", click Next, select "Comma" as the delimiter and click next, Finish, Accept. The user should now have the file in the right format, so it can be saved normally in Excel.

1.2. Installation, set up and support

The only two power supplies that are going to provide current to the resistive loads are the variac and the batteries. In order to operate the variac, a 3-prong cord must be inserted into the wall outlet while the orange switch in the front panel is on the 'on' position. An orange light beneath the switch will indicate the user that the variac is up and running. Because the grid voltage of our system is set at $9.7V_{rms}$, the black knob on the top of the variac must be set to $13.7V_{AC}$.

There are more steps to follow in order to operate the battery installation system (BIS). Because the BIS is split into two branches: one for charging and the other one for discharging, a switch scheme has been implemented. When they need to charge, the user will toggle on the first switch while the other switches are off. For discharging, switch number two can be on and switch one off. However, if the system needs to be isolated from the grid, then both switches will be off, cutting off any current to and from the

batteries. No two switches can be turned on at the same time because that can potentially create a fault in the system. It can disrupt any data analysis as well as damage the circuit of the BIS.

For the power measurement circuit, there are two circuits: the voltage and current sensor, that will be used to calculate the power in several points. The voltage sensor must be connected to a 15V$_{DC}$ power supply. With the arduino, the voltage is measured and displayed on the serial monitor of the IDE of the arduino software. To measure the current, a current probe clamp will be coupled to any part of the circuit, next to the voltage sensor so that the user can ultimately read the power at the point he or she wishes. The arduino will read this measurement like it did with the voltage sensor, and by multiplying the voltage by the current we get power (P = V·I). This reading is then sent from the arduino to an excel sheet file so that the user can read the data and further analyze it.

To operate the power load circuit, it must be connected to the grid. The power load circuit is an automated system which enables the overall power consumption to change depending on the period of the experiment, which follows the summer power demand trend in New England. Coupling the arduino microcontroller to each of the six triacs of the circuit and running the code on the IDE via a computer will set in motion the power consumption of the system. The triacs are the controlled switches for the opening and closing of the resistive loads. However, before the code can be compiled, the arduino has to be supplied by a 5V supply. When the arduino is on and the code is compiled on the IDE, three 5mm green LEDs will blink indicating that it is ready and no faults have occurred.

1.3. Operation of the project

1.3.1. Operating normal mode

Battery installation

As mentioned previously in the report, there are two modes of operation the battery installation system: charge and discharge mode. These modes of operation depend upon the power demand of the grid which is dependent on the power demand circuit. As the user of this mock power grid system, full control of the battery system is imperative. In order to know when the batteries should charge or discharge, an indication will be given by LED lights. During times of peak demand, a red LED will turn on indicating that additional power from the batteries are needed to support the "power plant" or in our case the variac transformer. To discharge the batteries, a switch on the DC-AC inverter, as shown in the figure below, is enabled to discharge the DC current from the batteries into AC for the load on the grid.

Figure 47. Switch on DC-AC inverter for discharge station.

For the charge mode, a white LED signifies that the batteries ought to be charged. The LED will turn on during early period of the experiment when the cost of electricity is cheaper. When the white LED is on, the user will have the option to flip the switch on the charging system, similar to that of the discharge system. When the switch is on, current will be able to go from AC to DC, via the rectifier circuit, and then to the batteries after going through a boost converter to make sure that the charge voltage is set.

The batteries will not be charging/discharging at all times, so isolation of the battery installation from the grid is vitally important. Therefore, additional switches will be placed before being coupled to the transmission line. In addition, a circuit breaker will be added in case that the limit of 3A goes through the system.

Data acquisition

Electrical characteristics have to be measured across multiple locations of the power grid such as the batteries, the variac, and the loads. These power measurement modules will be placed on these specific locations. To display and acquire this data several steps have to be followed. First off, the user should run the Arduino code and afterwards the Processing code. Once this is done, the user will be able to read the voltage, current, and power on the LCD display. The user, at this point, will be also able to see the voltage, current and power graphed in the computer monitor. In order to save the data and after the test is finished the user has to import the file as follows: open Excel, File > Import, select File CSV and click import, search within the documents in the computer for the folder "Data", click Next, select "Comma" as the delimiter and click next, Finish, Accept. The user should now have the file in the right format, so it can be saved normally in Excel.

Generation

The first step for operating the system is to plug in the main power cord of the variac. After that, an orange switch in the front panel of the variac should be turned. A knob on top of the variac should be adjusted until we make sure the LCD screen that displays the voltage and current of the source indicates 9.7V rms.

Demand curve modeling

In order to make the loads follow the power demand curve, we should connect the USB to Arduino and run the appropriate program. The operator needs to make sure that three

of the LEDs have turned on to indicate that it has compiled successfully, and that the current of the LCD near the load changes at the same time a new LED is turned on or off

Synchronization

A led will indicate when the batteries should be connected or disconnected. When the LED is on, the user should manually connect the batteries by closing a switch. Now the user should synchronize the two AC waveforms, the output of the variac and the output of the battery installation system. The steps for the synchronization are the following:

1. Turn on the switch. The LED will illuminate. It will start to turn on and off at a determined frequency.
2. When the LED is completely OFF (or dimmest), close the switch.
   a. This is made even easier using an oscilloscope with two probes. Connect a probe to both inputs to the synchronization circuit and look at the waveforms. Users will need to close the switch when the waveforms are in phase. This method also is more visually demonstrative of the synchronization process.

The user should also check with the oscilloscope that the frequency is approximately 60Hz.

1.1.2. Operating abnormal mode

When the user is operating the battery installation system to switch to the discharge mode from another state such as isolation, the user may need multiple attempts to get the system to be fully functional. To enable the discharge system a switch on the inverter must be on and a green light indicating no faults must show. A red light indicates that there has been a fault. In this case the user simply has to turn off the switch and turn it back on.

In the power load system, the user needs to make sure that once the code is running, some green leds are turned on. If there aren't any green leds on, the user should make sure the connection between Arduino and the computer is done correctly.

1.1.3. Safety issues

Our project will have an enclosure to make ensure the user's safety during operation. However, the variac will be outside of the enclosure with its input wires coming into the enclosure through a hole that was cut. The only precaution to the user is that the variac should not exceed the reading of 9.7Vrms when the knob on top of the variac is being rotated to read the predetermined grid voltage of our system.

In addition, the highest output current that will be allowed to go through our power grid is 3A. To make sure that this limit is not exceeded, a circuit breaker will be located at the discharge branch of the batteries and outside the last transformer where in the input voltage is source is the variac itself. The variac has a built in 20A fuse, but for our system 3A is our limit.

2.   ARDUINO CODE

Arduino: AC Measurement

```
#include <LiquidCrystal.h>

LiquidCrystal lcd(8, 9, 4, 5, 6, 7);

int samplesNumber = 200;
int samplesNumber2 = 200;

void setup()
{
  Serial.begin(9600);
  lcd.begin(20,4);
}

void loop()
{

  //VOLTAGE MEASUREMENT
  float voltageMax = getVoltage(samplesNumber);
  float voltageMax2 = voltageMax*8.625599087;
  float voltageMax3 = voltageMax*6.09922*0.940865*0.995*0.966802;
  float voltageMax4 = voltageMax3;


  //VOLTAGE CORRECTION
  if((voltageMax3<=12) && (voltageMax3>10.5)){

    if((voltageMax3<=12)&&(voltageMax3>11.75)) {
      float voltageMax4=voltageMax3*0.986335;
    }
    if((voltageMax3<=11.75)&&(voltageMax3>11.5)) {
      float voltageMax4=voltageMax3*0.985976;
    }
    if((voltageMax3<=11.5)&&(voltageMax3>11.25)) {
      float voltageMax4=voltageMax3;
    }
    if((voltageMax3<=11.25)&&(voltageMax3>11)) {
      float voltageMax4=voltageMax3*0.982703911;
    }
    if((voltageMax3<=11)&&(voltageMax3>10.75)) {
      float voltageMax4=voltageMax3*0.98606774;
    }
    if((voltageMax3<=10.75)&&(voltageMax3>10.5)) {
      float voltageMax4=voltageMax3*0.985839766;
    }
    if((voltageMax3<=10.5)&&(voltageMax3>10.25)) {
      float voltageMax4=voltageMax3*0.987957534;
    }
    if((voltageMax3<=10.25)&&(voltageMax3>10)) {
      float voltageMax4=voltageMax3*0.9894865;
    }
  }

  if((voltageMax3<=10) && (voltageMax3>9.5)){
```

```
    float voltageMax4=voltageMax3*1.02392545*1.02;
  }

  if((voltageMax3<=9.5) && (voltageMax3>9.1)){

    float voltageMax4=voltageMax3*1.03372297*1.02;
  }

  if((voltageMax3<=9.1) && (voltageMax3>8.7)){

    float voltageMax4=voltageMax3*1.0396882*1.02;
  }

  if((voltageMax3<=8.7) && (voltageMax3>8)){

    float voltageMax4=voltageMax3*1.045660016*1.02;
  }

  //VOLTAGE EMISSION
  String voltage2 = String(voltageMax4);
  String voltage3 = "v";
  String voltage4=voltage3 + voltage2;
  Serial.println(voltage4);
  //delay(100);

  //CURRENT MEASUREMENT
  float currentMax = getCurrent(samplesNumber2);
  float currentMax2=currentMax*5.67419;
  float currentMax3=currentMax2;
  float currentMax4=currentMax3;

  //CURRENT CALIBRATION
  /*if((currentMax<=1.76) && (currentMax>1.64)){

    float calibration = -2.8835*currentMax+6.0021;
    float currentMax3 = currentMax2*calibration;
  }*/

  //CURRENT EMISSION
  String current2 = String(currentMax4);
  String current3 = "c";
  String current4=current3 + current2;
  Serial.println(current4);
  //delay(100);

float power=voltageMax4*currentMax4;

  // first position, first row
  lcd.setCursor(0,0);
  lcd.print("Voltage: ");
  lcd.print(voltageMax3);
  lcd.print(" V  ");

  // first position, second row
  lcd.setCursor(0,1);
  lcd.print("Current: ");
  lcd.print(currentMax4);
```

```
  lcd.print(" A  ");

  // first position, third row
  lcd.setCursor(0,2);
  lcd.print("Power: ");
  lcd.print(power);
  lcd.print(" W  ");

  delay(200);
}


  //FUNCTIONS

float getVoltage(int samplesNumber)
{

   float voltageMax=0;
   float value=0;
   for (int i = 0; i < samplesNumber; i++)
   {
   value= (analogRead(A0) * 5.0/ 1023.0)-2.395;   //Volver a meter el
-2.59 cuando se pruebe con el de verdad
    if(value>voltageMax)
    {
      voltageMax=value;
    }
   }
   return(voltageMax);
}

float getCurrent(int samplesNumber2)
{

   float currentMax=0;
   float value=0;
   for (int i = 0; i < samplesNumber2; i++)
   {
   value= (analogRead(A1) * 5.0/ 1023.0)-2.501;
    if(value>currentMax)
    {
      currentMax=value;
    }
   }
   return(currentMax);
}
```

Arduino: DC Measurement

```
#include <LiquidCrystal.h>

LiquidCrystal lcd(8, 9, 4, 5, 6, 7);

int samplesNumber = 200;

const int analogIn = A1;
```

```
int mVperAmp = 100; //185; // use 100 for 20A Module and 66 for 30A
Module
int RawValue= 0;
int ACSoffset = 2500;
double Voltage = 0;
double Amps = 0;
int samplesNumber2 = 20;
float sumaADC = 0;

void setup()
{
  Serial.begin(9600);
  lcd.begin(20,4);
}

void loop()
{

  //VOLTAGE MEASUREMENT
  float voltageMax = getVoltage(samplesNumber);
  float voltageMax2 = voltageMax*8.625599087;
  float voltageMax3 =
voltageMax*6.09922*0.940865*0.995*0.966802/0.7157;
  float voltageMax4 = voltageMax3;


  //VOLTAGE CORRECTION
  if((voltageMax3<=12) && (voltageMax3>10.5)){

    if((voltageMax3<=12)&&(voltageMax3>11.75)) {
      float voltageMax4=voltageMax3*0.986335;
    }
    if((voltageMax3<=11.75)&&(voltageMax3>11.5)) {
      float voltageMax4=voltageMax3*0.985976;
    }
    if((voltageMax3<=11.5)&&(voltageMax3>11.25)) {
      float voltageMax4=voltageMax3;
    }
    if((voltageMax3<=11.25)&&(voltageMax3>11)) {
      float voltageMax4=voltageMax3*0.982703911;
    }
    if((voltageMax3<=11)&&(voltageMax3>10.75)) {
      float voltageMax4=voltageMax3*0.98606774;
    }
    if((voltageMax3<=10.75)&&(voltageMax3>10.5)) {
      float voltageMax4=voltageMax3*0.985839766;
    }
    if((voltageMax3<=10.5)&&(voltageMax3>10.25)) {
      float voltageMax4=voltageMax3*0.987957534;
    }
    if((voltageMax3<=10.25)&&(voltageMax3>10)) {
      float voltageMax4=voltageMax3*0.9894865;
    }
  }

  if((voltageMax3<=10) && (voltageMax3>9.5)){

    float voltageMax4=voltageMax3*1.02392545*1.02;
```

```
}

if((voltageMax3<=9.5) && (voltageMax3>9.1)){

  float voltageMax4=voltageMax3*1.03372297*1.02;
}

if((voltageMax3<=9.1) && (voltageMax3>8.7)){

  float voltageMax4=voltageMax3*1.0396882*1.02;
}

if((voltageMax3<=8.7) && (voltageMax3>8)){

  float voltageMax4=voltageMax3*1.045660016*1.02;
}

//VOLTAGE EMISSION
String voltage2 = String(voltageMax4);
String voltage3 = "v";
String voltage4=voltage3 + voltage2;
Serial.println(voltage4);
//delay(100);

/*
//CURRENT MEASUREMENT
float currentMax = getCurrent(samplesNumber2);
float currentMax2=currentMax*5.67419;
float currentMax3=currentMax2;
float currentMax4=currentMax3;

//CURRENT CALIBRATION
/*if((currentMax<=1.76) && (currentMax>1.64)){

  float calibration = -2.8835*currentMax+6.0021;
  float currentMax3 = currentMax2*calibration;
}*/

sumaADC = 0;
int i=0;

while (i<=50){
  RawValue = analogRead(analogIn);
  Voltage = (RawValue / 1024.0) * 5000; // Gets you mV
  Amps = ((Voltage - ACSoffset) / mVperAmp)*1.084;
  //Serial.println(Amps);
  sumaADC += Amps;
  i++;
  delay(100);
}

float promedio = (float) (sumaADC/i);
//CURRENT EMISSION
String current2 = String(promedio);
String current3 = "c";
String current4=current3 + current2;
//Serial.println(current4);
//delay(100);
```

```
float power=voltageMax4*promedio;

  // first position, first row
  lcd.setCursor(0,0);
  lcd.print("Voltage: ");
  lcd.print(voltageMax3);
  lcd.print(" V  ");

  // first position, second row
  lcd.setCursor(0,1);
  lcd.print("Current: ");
  lcd.print(promedio);
  lcd.print(" A  ");

  // first position, third row
  lcd.setCursor(0,2);
  lcd.print("Power: ");
  lcd.print(power);
  lcd.print(" W  ");

  delay(200);
}


  //FUNCTIONS

float getVoltage(int samplesNumber)
{

   float voltageMax=0;
   float value=0;
   for (int i = 0; i < samplesNumber; i++)
   {
   value= (analogRead(A0) * 5.0/ 1023.0)-2.395;   //Volver a meter el
-2.59 cuando se pruebe con el de verdad
    if(value>voltageMax)
    {
      voltageMax=value;
    }
   }
   return(voltageMax);
}

float getCurrent(int samplesNumber2)
{

   float currentMax=0;
   float value=0;
   for (int i = 0; i < samplesNumber2; i++)
   {
   value= (analogRead(A1) * 5.0/ 1023.0)-2.501;
    if(value>currentMax)
    {
      currentMax=value;
    }
   }
   return(currentMax);
```

```
}


Processing

import grafica.*;
import processing.serial.*;

public GPlot plot, plot1;

float voltage1;
float current1;
float voltage4;
float current4;
float power=0;

int size = 201;

Table table;

String val;  // Data received from the serial port
String voltage;
String current;
String firstletter;
String v = "v";
String c = "c";

Serial myPort;  // Create object from Serial class


void setup()
{
  String portName = Serial.list()[2]; //change the 0 to a 1 or 2 etc.
to match your port
  myPort = new Serial(this, portName, 9600);

  table = new Table();  //Creates a table in excel

  table.addColumn("N");  //Creates a column with name "id"
  table.addColumn("Voltage");
  table.addColumn("Current");
  table.addColumn("Power");

  size(1000, 750);
  background(150);

}
void draw()
{

  float[] voltage2 = new float[size];
  float[] current2 = new float[size];
  float[] power = new float[size];

  for (int i=1;i<=200;i++){
    int h=0;
    int k=0;
    while(h*k == 0){
```

```
    if ( myPort.available() > 0) {
    val = myPort.readStringUntil('\n');
    }
    if (val!=null && val!="0.0") {
      background(0);
      firstletter = val.substring(0,1);

      //VOLTAGE STORAGE
      if(firstletter.equals(v) == true && h!=1){
        voltage = val.substring(1,7);
        voltage1=float(voltage);
        if(voltage1!=0){
        voltage2[i]=voltage1;
        h=1;
        delay(10);
        //println("voltage");
        }
      }

      //CURRENT STORAGE
      if(firstletter.equals(c) == true && k!=1){
        current = val.substring(1,7);
        current1=float(current);
        if(current1!=0){
        current2[i]=current1;
        k=1;
        //println("current");
        delay(10);
        }
      }
    }
  }

  println(i);

  power[i]=voltage2[i]*current2[i];
  //LOCATE IN EXCEL
  table.setInt(i-1, "Time(s)", i);
  table.setFloat(i-1, "Voltage", voltage2[i]);
  table.setFloat(i-1, "Current", current2[i]);
  table.setFloat(i-1, "Power", power[i]);
}
println("Data stored in Data.csv");
// Prepare the points for the plot
int nPoints = 201;
GPointsArray points = new GPointsArray(nPoints);
GPointsArray points1 = new GPointsArray(nPoints);
GPointsArray points2 = new GPointsArray(nPoints);

for(int i = 1; i < nPoints; i++){
  points.add(i, voltage2[i]);
  points1.add(i, current2[i]);
  points2.add(i, power[i]);
}

// Create a new plot and set its position on the screen
GPlot plot = new GPlot(this);
plot.setPos(25, 25);
```

```
GPlot plot1 = new GPlot(this);
plot1.setPos(500, 25);
GPlot plot2 = new GPlot(this);
plot2.setPos(250, 400);

// Set the plot title and the axis labels
plot.setPoints(points);
plot.getXAxis().setAxisLabelText("Time");
plot.getYAxis().setAxisLabelText("Voltage (V)");
plot.setTitleText("Voltage");

plot1.setPoints(points1);
plot1.getXAxis().setAxisLabelText("Time");
plot1.getYAxis().setAxisLabelText("Current (A)");
plot1.setTitleText("Current");

plot2.setPoints(points2);
plot2.getXAxis().setAxisLabelText("Time");
plot2.getYAxis().setAxisLabelText("Power (W)");
plot2.setTitleText("Power consumed by the battery");


// Draw it!
plot.defaultDraw();
plot1.defaultDraw();
plot2.defaultDraw();

delay(5000);
saveTable(table, "data/Data.csv"); //"hola" es el nombre del
documento Excel

}
```

3. DATASHEETS OF COMPONENTS:

- ACS712
- L18P-003
- SCT-013-005

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor

Not for New Design

These parts are in production but have been determined to be NOT FOR NEW DESIGN. This classification indicates that sale of this device is currently restricted to existing customer applications. The device should not be purchased for new design applications because obsolescence in the near future is probable. Samples are no longer available.

Date of status change: June 5, 2017

Recommended Substitutions:

For existing customer transition, and for new customers or new applications, use ACS723.

NOTE: For detailed information on purchasing options, contact your local Allegro field applications engineer or sales representative.

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor

Features and Benefits

- Low-noise analog signal path
- Device bandwidth is set via the new FILTER pin
- 5 µs output rise time in response to step input current
- 80 kHz bandwidth
- Total output error 1.5% at T_A = 25°C
- Small footprint, low-profile SOIC8 package
- 1.2 mΩ internal conductor resistance
- 2.1 kVRMS minimum isolation voltage from pins 1-4 to pins 5-8
- 5.0 V, single supply operation
- 66 to 185 mV/A output sensitivity
- Output voltage proportional to AC or DC currents
- Factory-trimmed for accuracy
- Extremely stable output offset voltage
- Nearly zero magnetic hysteresis
- Ratiometric output from supply voltage

TÜV America
Certificate Number:
U8V 06 05 54214 010

Package: 8 Lead SOIC (suffix LC)
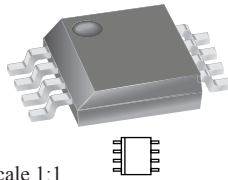
Approximate Scale 1:1

Description

The Allegro™ ACS712 provides economical and precise solutions for AC or DC current sensing in industrial, commercial, and communications systems. The device package allows for easy implementation by the customer. Typical applications include motor control, load detection and management, switch-mode power supplies, and overcurrent fault protection. The device is not intended for automotive applications.

The device consists of a precise, low-offset, linear Hall circuit with a copper conduction path located near the surface of the die. Applied current flowing through this copper conduction path generates a magnetic field which the Hall IC converts into a proportional voltage. Device accuracy is optimized through the close proximity of the magnetic signal to the Hall transducer. A precise, proportional voltage is provided by the low-offset, chopper-stabilized BiCMOS Hall IC, which is programmed for accuracy after packaging.

The output of the device has a positive slope (>$V_{IOUT(Q)}$) when an increasing current flows through the primary copper conduction path (from pins 1 and 2, to pins 3 and 4), which is the path used for current sampling. The internal resistance of this conductive path is 1.2 mΩ typical, providing low power loss. The thickness of the copper conductor allows survival of

Continued on the next page…

Typical Application
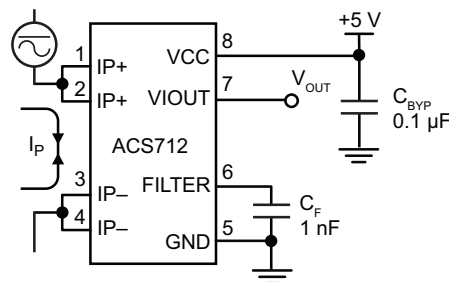
Application 1. The ACS712 outputs an analog signal, V_{OUT}. that varies linearly with the uni- or bi-directional AC or DC primary sampled current, I_P, within the range specified. C_F is recommended for noise management, with values that depend on the application.

ACS712

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor

Description (continued)

the device at up to 5× overcurrent conditions. The terminals of the conductive path are electrically isolated from the signal leads (pins 5 through 8). This allows the ACS712 to be used in applications requiring electrical isolation without the use of opto-isolators or other costly isolation techniques.

The ACS712 is provided in a small, surface mount SOIC8 package. The leadframe is plated with 100% matte tin, which is compatible with standard lead (Pb) free printed circuit board assembly processes. Internally, the device is Pb-free, except for flip-chip high-temperature Pb-based solder balls, currently exempt from RoHS. The device is fully calibrated prior to shipment from the factory.

Selection Guide

Part Number	Packing*	T_A (°C)	Optimized Range, I_P (A)	Sensitivity, Sens (Typ) (mV/A)
ACS712ELCTR-05B-T	Tape and reel, 3000 pieces/reel	–40 to 85	±5	185
ACS712ELCTR-20A-T	Tape and reel, 3000 pieces/reel	–40 to 85	±20	100
ACS712ELCTR-30A-T	Tape and reel, 3000 pieces/reel	–40 to 85	±30	66

*Contact Allegro for additional packing options.

Absolute Maximum Ratings

Characteristic	Symbol	Notes	Rating	Units
Supply Voltage	V_{CC}		8	V
Reverse Supply Voltage	V_{RCC}		–0.1	V
Output Voltage	V_{IOUT}		8	V
Reverse Output Voltage	V_{RIOUT}		–0.1	V
Output Current Source	$I_{IOUT(Source)}$		3	mA
Output Current Sink	$I_{IOUT(Sink)}$		10	mA
Overcurrent Transient Tolerance	I_P	1 pulse, 100 ms	100	A
Nominal Operating Ambient Temperature	T_A	Range E	–40 to 85	°C
Maximum Junction Temperature	$T_J(max)$		165	°C
Storage Temperature	T_{stg}		–65 to 170	°C

Isolation Characteristics

Characteristic	Symbol	Notes	Rating	Unit
Dielectric Strength Test Voltage*	V_{ISO}	Agency type-tested for 60 seconds per UL standard 60950-1, 1st Edition	2100	VAC
Working Voltage for Basic Isolation	V_{WFSI}	For basic (single) isolation per UL standard 60950-1, 1st Edition	354	VDC or V_{pk}
Working Voltage for Reinforced Isolation	V_{WFRI}	For reinforced (double) isolation per UL standard 60950-1, 1st Edition	184	VDC or V_{pk}

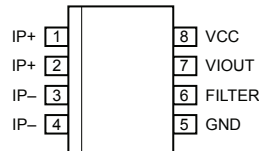* Allegro does not conduct 60-second testing. It is done only during the UL certification process.

Parameter	Specification
Fire and Electric Shock	CAN/CSA-C22.2 No. 60950-1-03 UL 60950-1:2003 EN 60950-1:2001

ACS712

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor

Functional Block Diagram

Pin-out Diagram

IP+	1		8	VCC
IP+	2		7	VIOUT
IP–	3		6	FILTER
IP–	4		5	GND
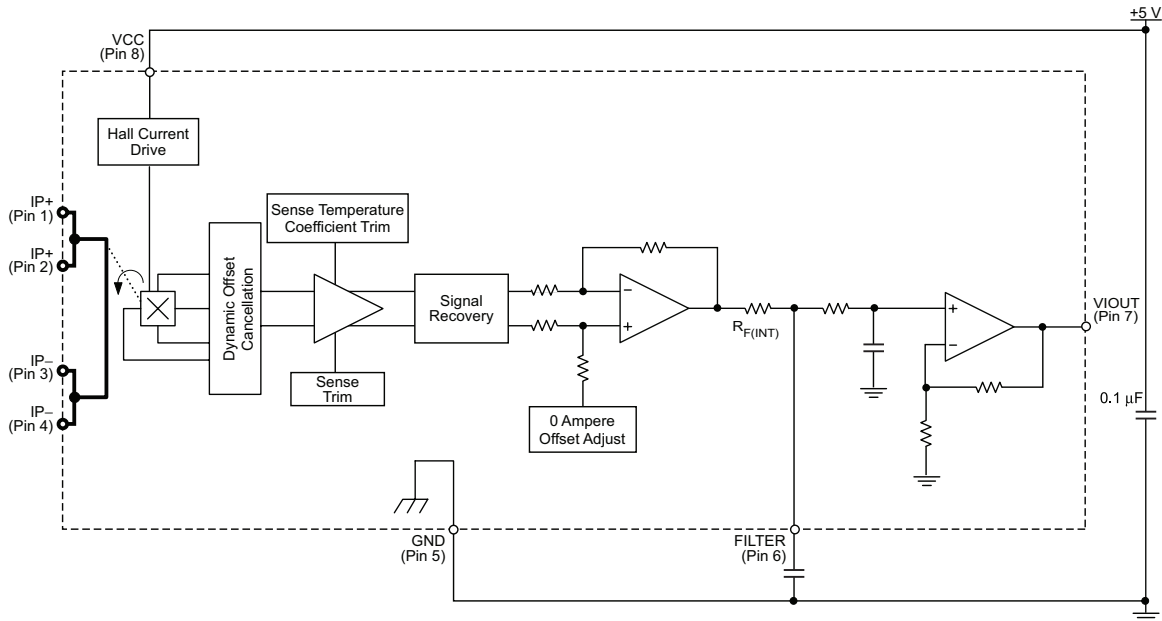
Terminal List Table

Number	Name	Description
1 and 2	IP+	Terminals for current being sampled; fused internally
3 and 4	IP–	Terminals for current being sampled; fused internally
5	GND	Signal ground terminal
6	FILTER	Terminal for external capacitor that sets bandwidth
7	VIOUT	Analog output signal
8	VCC	Device power supply terminal

Allegro MicroSystems, LLC
115 Northeast Cutoff
Worcester, Massachusetts 01615-0036 U.S.A.
1.508.853.5000; www.allegromicro.com

3

ACS712

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor

COMMON OPERATING CHARACTERISTICS[1] over full range of T_A, C_F = 1 nF, and V_{CC} = 5 V, unless otherwise specified

Characteristic	Symbol	Test Conditions	Min.	Typ.	Max.	Units
ELECTRICAL CHARACTERISTICS						
Supply Voltage	V_{CC}		4.5	5.0	5.5	V
Supply Current	I_{CC}	V_{CC} = 5.0 V, output open	–	10	13	mA
Output Capacitance Load	C_{LOAD}	VIOUT to GND	–	–	10	nF
Output Resistive Load	R_{LOAD}	VIOUT to GND	4.7	–	–	kΩ
Primary Conductor Resistance	$R_{PRIMARY}$	T_A = 25°C	–	1.2	–	mΩ
Rise Time	t_r	I_P = I_P(max), T_A = 25°C, C_{OUT} = open	–	3.5	–	µs
Frequency Bandwidth	f	–3 dB, T_A = 25°C; I_P is 10 A peak-to-peak	–	80	–	kHz
Nonlinearity	E_{LIN}	Over full range of I_P	–	1.5	–	%
Symmetry	E_{SYM}	Over full range of I_P	98	100	102	%
Zero Current Output Voltage	$V_{IOUT(Q)}$	Bidirectional; I_P = 0 A, T_A = 25°C	–	V_{CC} × 0.5	–	V
Power-On Time	t_{PO}	Output reaches 90% of steady-state level, T_J = 25°C, 20 A present on leadframe	–	35	–	µs
Magnetic Coupling[2]			–	12	–	G/A
Internal Filter Resistance[3]	$R_{F(INT)}$			1.7		kΩ

[1]Device may be operated at higher primary current levels, I_P, and ambient, T_A, and internal leadframe temperatures, T_A, provided that the Maximum Junction Temperature, T_J(max), is not exceeded.

[2]1G = 0.1 mT.

[3]$R_{F(INT)}$ forms an RC circuit via the FILTER pin.

COMMON THERMAL CHARACTERISTICS[1]

			Min.	Typ.	Max.	Units
Operating Internal Leadframe Temperature	T_A	E range	–40	–	85	°C
					Value	Units
Junction-to-Lead Thermal Resistance[2]	$R_{\theta JL}$	Mounted on the Allegro ASEK 712 evaluation board			5	°C/W
Junction-to-Ambient Thermal Resistance	$R_{\theta JA}$	Mounted on the Allegro 85-0322 evaluation board, includes the power consumed by the board			23	°C/W

[1]Additional thermal information is available on the Allegro website.

[2]The Allegro evaluation board has 1500 mm[2] of 2 oz. copper on each side, connected to pins 1 and 2, and to pins 3 and 4, with thermal vias connecting the layers. Performance values include the power consumed by the PCB. Further details on the board are available from the Frequently Asked Questions document on our website. Further information about board design and thermal performance also can be found in the Applications Information section of this datasheet.

Allegro MicroSystems, LLC
115 Northeast Cutoff
Worcester, Massachusetts 01615-0036 U.S.A.
1.508.853.5000; www.allegromicro.com

4

ACS712

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor

x05B PERFORMANCE CHARACTERISTICS[1] T_A = –40°C to 85°C, C_F = 1 nF, and V_{CC} = 5 V, unless otherwise specified

Characteristic	Symbol	Test Conditions	Min.	Typ.	Max.	Units
Optimized Accuracy Range	I_P		–5	–	5	A
Sensitivity	Sens	Over full range of I_P, T_A = 25°C	180	185	190	mV/A
Noise	$V_{NOISE(PP)}$	Peak-to-peak, T_A = 25°C, 185 mV/A programmed Sensitivity, C_F = 47 nF, C_{OUT} = open, 2 kHz bandwidth	–	21	–	mV
Zero Current Output Slope	$\Delta V_{OUT(Q)}$	T_A = –40°C to 25°C	–	–0.26	–	mV/°C
		T_A = 25°C to 150°C	–	–0.08	–	mV/°C
Sensitivity Slope	ΔSens	T_A = –40°C to 25°C	–	0.054	–	mV/A/°C
		T_A = 25°C to 150°C	–	–0.008	–	mV/A/°C
Total Output Error[2]	E_{TOT}	I_P =±5 A, T_A = 25°C	–	±1.5	–	%

[1]Device may be operated at higher primary current levels, I_P, and ambient temperatures, T_A, provided that the Maximum Junction Temperature, $T_{J(max)}$, is not exceeded.

[2]Percentage of I_P, with I_P = 5 A. Output filtered.

x20A PERFORMANCE CHARACTERISTICS[1] T_A = –40°C to 85°C, C_F = 1 nF, and V_{CC} = 5 V, unless otherwise specified

Characteristic	Symbol	Test Conditions	Min.	Typ.	Max.	Units
Optimized Accuracy Range	I_P		–20	–	20	A
Sensitivity	Sens	Over full range of I_P, T_A = 25°C	96	100	104	mV/A
Noise	$V_{NOISE(PP)}$	Peak-to-peak, T_A = 25°C, 100 mV/A programmed Sensitivity, C_F = 47 nF, C_{OUT} = open, 2 kHz bandwidth	–	11	–	mV
Zero Current Output Slope	$\Delta V_{OUT(Q)}$	T_A = –40°C to 25°C	–	–0.34	–	mV/°C
		T_A = 25°C to 150°C	–	–0.07	–	mV/°C
Sensitivity Slope	ΔSens	T_A = –40°C to 25°C	–	0.017	–	mV/A/°C
		T_A = 25°C to 150°C	–	–0.004	–	mV/A/°C
Total Output Error[2]	E_{TOT}	I_P =±20 A, T_A = 25°C	–	±1.5	–	%

[1]Device may be operated at higher primary current levels, I_P, and ambient temperatures, T_A, provided that the Maximum Junction Temperature, T_J(max), is not exceeded.

[2]Percentage of I_P, with I_P = 20 A. Output filtered.

x30A PERFORMANCE CHARACTERISTICS[1] T_A = –40°C to 85°C, C_F = 1 nF, and V_{CC} = 5 V, unless otherwise specified

Characteristic	Symbol	Test Conditions	Min.	Typ.	Max.	Units
Optimized Accuracy Range	I_P		–30	–	30	A
Sensitivity	Sens	Over full range of I_P, T_A = 25°C	63	66	69	mV/A
Noise	$V_{NOISE(PP)}$	Peak-to-peak, T_A = 25°C, 66 mV/A programmed Sensitivity, C_F = 47 nF, C_{OUT} = open, 2 kHz bandwidth	–	7	–	mV
Zero Current Output Slope	$\Delta V_{OUT(Q)}$	T_A = –40°C to 25°C	–	–0.35	–	mV/°C
		T_A = 25°C to 150°C	–	–0.08	–	mV/°C
Sensitivity Slope	ΔSens	T_A = –40°C to 25°C	–	0.007	–	mV/A/°C
		T_A = 25°C to 150°C	–	–0.002	–	mV/A/°C
Total Output Error[2]	E_{TOT}	I_P = ±30 A, T_A = 25°C	–	±1.5	–	%

[1]Device may be operated at higher primary current levels, I_P, and ambient temperatures, T_A, provided that the Maximum Junction Temperature, T_J(max), is not exceeded.

[2]Percentage of I_P, with I_P = 30 A. Output filtered.

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5

ACS712

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor

Characteristic Performance

I_P = 5 A, unless otherwise specified
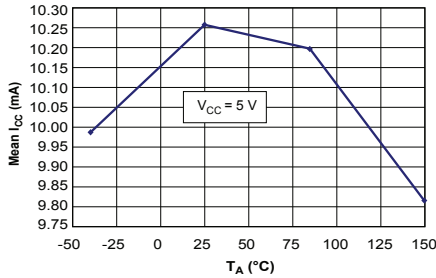
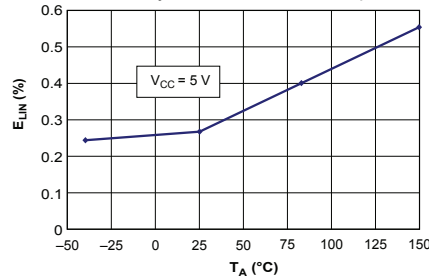Mean Supply Current versus Ambient Temperature
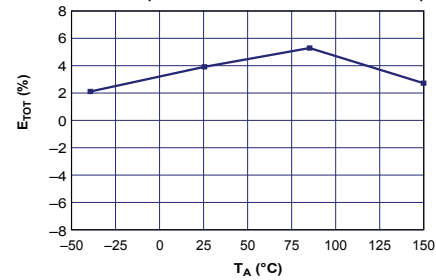

Supply Current versus Supply Voltage
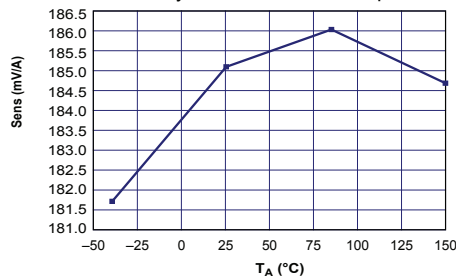

Magnetic Offset versus Ambient Temperature
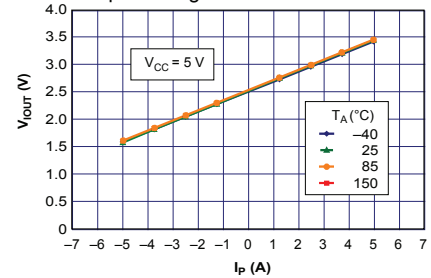

Nonlinearity versus Ambient Temperature
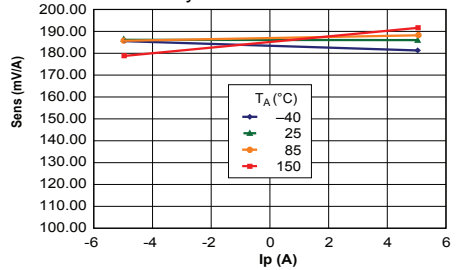

Mean Total Output Error versus Ambient Temperature
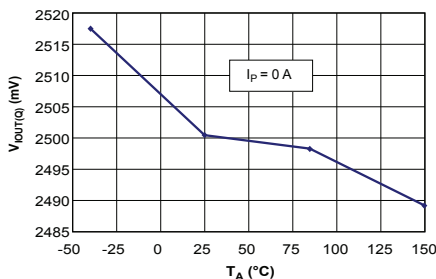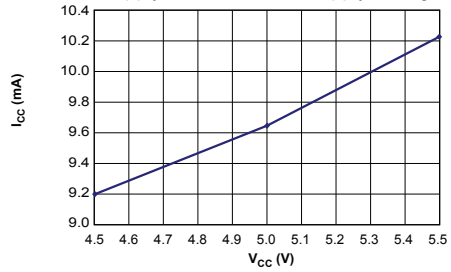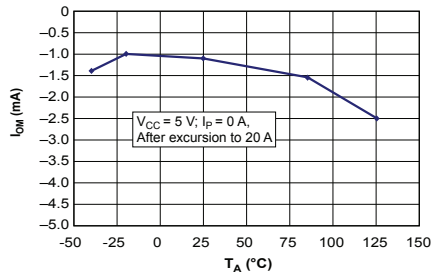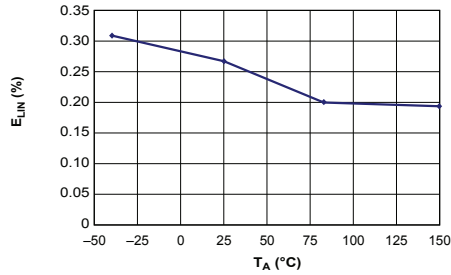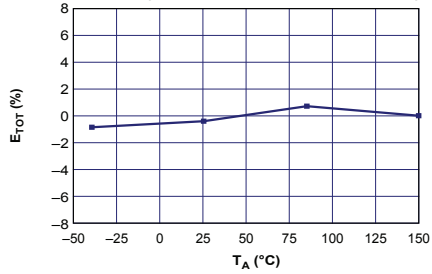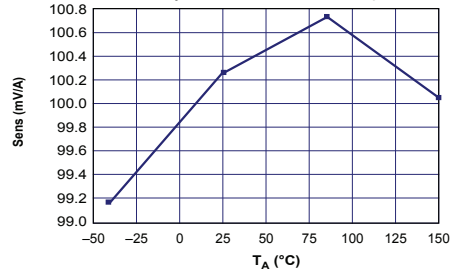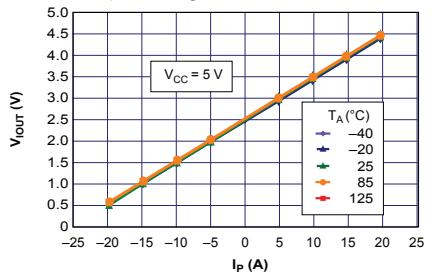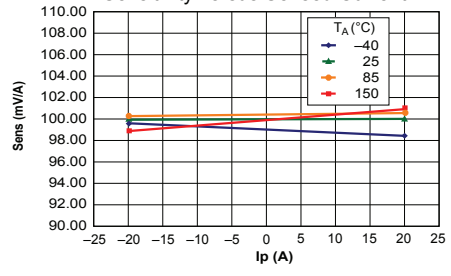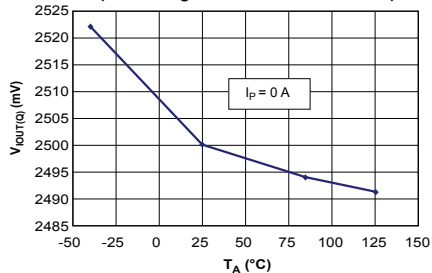

Sensitivity versus Ambient Temperature

Output Voltage versus Sensed Current

Sensitivity versus Sensed Current

0 A Output Voltage versus Ambient Temperature

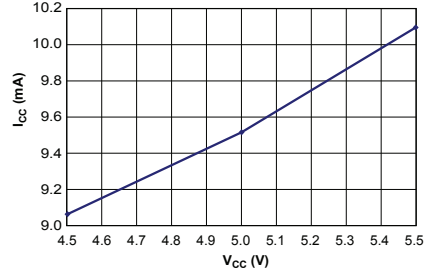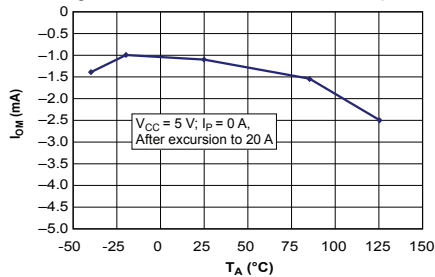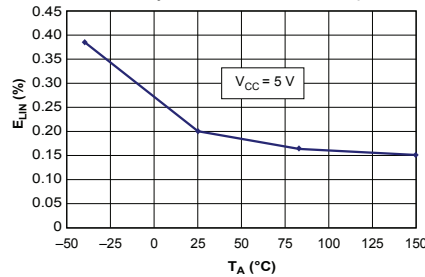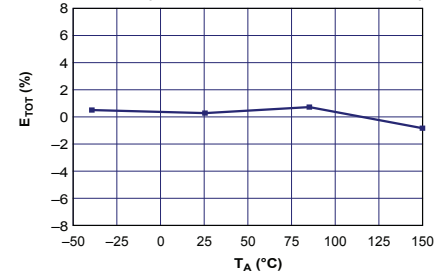0 A Output Voltage Current versus Ambient Temperature

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6

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Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor
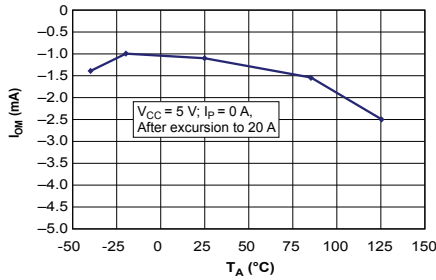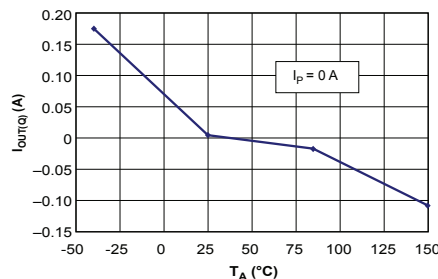
Characteristic Performance

I_P = 20 A, unless otherwise specified
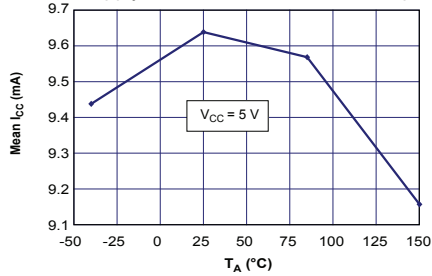
Mean Supply Current versus Ambient Temperature

Supply Current versus Supply Voltage

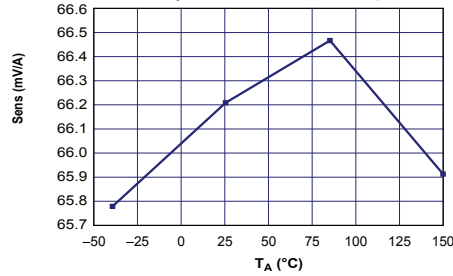### Magnetic Offset versus Ambient Temperature

Nonlinearity versus Ambient Temperature
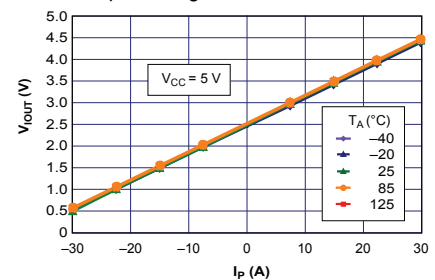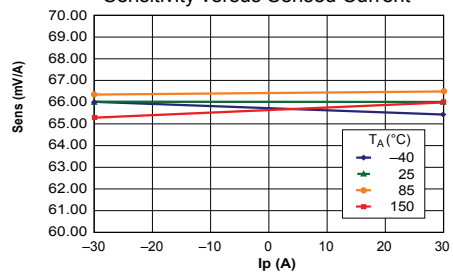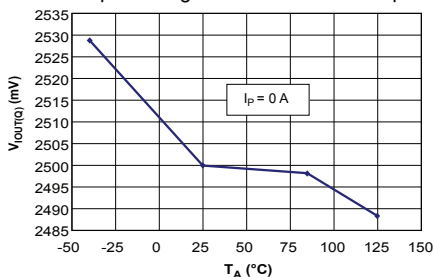

Mean Total Output Error versus Ambient Temperature

Sensitivity versus Ambient Temperature

Output Voltage versus Sensed Current

Sensitivity versus Sensed Current

0 A Output Voltage versus Ambient Temperature

0 A Output Voltage Current versus Ambient Temperature

ACS712

*Fully Integrated, Hall Effect-Based Linear Current Sensor IC
with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor*
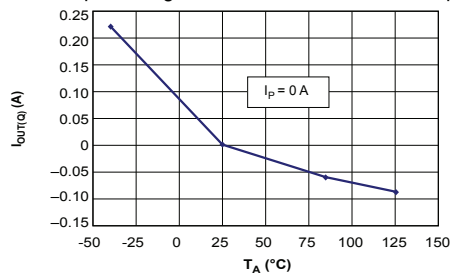
Characteristic Performance

I_P = 30 A, unless otherwise specified
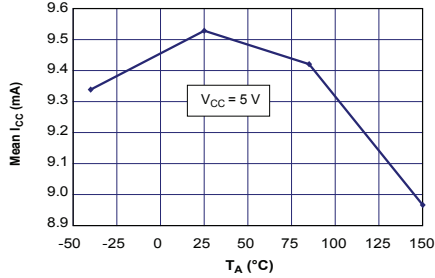
Mean Supply Current versus Ambient Temperature

Supply Current versus Supply Voltage

Magnetic Offset versus Ambient Temperature

Nonlinearity versus Ambient Temperature

Mean Total Output Error versus Ambient Temperature

Sensitivity versus Ambient Temperature

Output Voltage versus Sensed Current

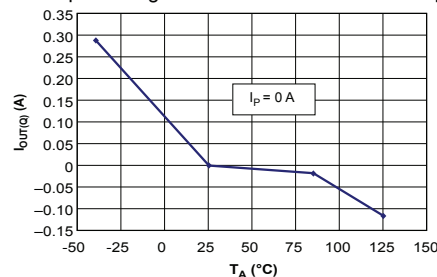Sensitivity versus Sensed Current

0 A Output Voltage versus Ambient Temperature

0 A Output Voltage Current versus Ambient Temperature

ACS712

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor

Definitions of Accuracy Characteristics

Sensitivity (Sens). The change in device output in response to a 1A change through the primary conductor. The sensitivity is the product of the magnetic circuit sensitivity (G/A) and the linear IC amplifier gain (mV/G). The linear IC amplifier gain is programmed at the factory to optimize the sensitivity (mV/A) for the full-scale current of the device.

Noise (V_{NOISE}). The product of the linear IC amplifier gain (mV/G) and the noise floor for the Allegro Hall effect linear IC (≈1 G). The noise floor is derived from the thermal and shot noise observed in Hall elements. Dividing the noise (mV) by the sensitivity (mV/A) provides the smallest current that the device is able to resolve.

Linearity (E_{LIN}). The degree to which the voltage output from the IC varies in direct proportion to the primary current through its full-scale amplitude. Nonlinearity in the output can be attributed to the saturation of the flux concentrator approaching the full-scale current. The following equation is used to derive the linearity:

$$100 \left\{ 1 - \left[\frac{\Delta \text{ gain} \times \% \text{ sat} (V_{\text{IOUT\_full-scale amperes}} - V_{\text{IOUT(Q)}})}{2 (V_{\text{IOUT\_half-scale amperes}} - V_{\text{IOUT(Q)}})} \right] \right\}$$

where $V_{\text{IOUT\_full-scale amperes}}$ = the output voltage (V) when the sampled current approximates full-scale $\pm I_P$.

Symmetry (E_{SYM}). The degree to which the absolute voltage output from the IC varies in proportion to either a positive or negative full-scale primary current. The following formula is used to derive symmetry:

$$100 \left(\frac{V_{\text{IOUT\_+ full-scale amperes}} - V_{\text{IOUT(Q)}}}{V_{\text{IOUT(Q)}} - V_{\text{IOUT\_–full-scale amperes}}} \right)$$

Quiescent output voltage ($V_{IOUT(Q)}$). The output of the device when the primary current is zero. For a unipolar supply voltage, it nominally remains at $V_{CC}/2$. Thus, V_{CC} = 5 V translates into $V_{IOUT(Q)}$ = 2.5 V. Variation in $V_{IOUT(Q)}$ can be attributed to the resolution of the Allegro linear IC quiescent voltage trim and thermal drift.

Electrical offset voltage (V_{OE}). The deviation of the device output from its ideal quiescent value of $V_{CC}/2$ due to nonmagnetic causes. To convert this voltage to amperes, divide by the device sensitivity, Sens.

Accuracy (E_{TOT}). The accuracy represents the maximum deviation of the actual output from its ideal value. This is also known as the total output error. The accuracy is illustrated graphically in the output voltage versus current chart at right.

Accuracy is divided into four areas:

- **0 A at 25°C.** Accuracy at the zero current flow at 25°C, without the effects of temperature.

- **0 A over Δ temperature.** Accuracy at the zero current flow including temperature effects.

- **Full-scale current at 25°C.** Accuracy at the the full-scale current at 25°C, without the effects of temperature.

- **Full-scale current over Δ temperature.** Accuracy at the full-scale current flow including temperature effects.
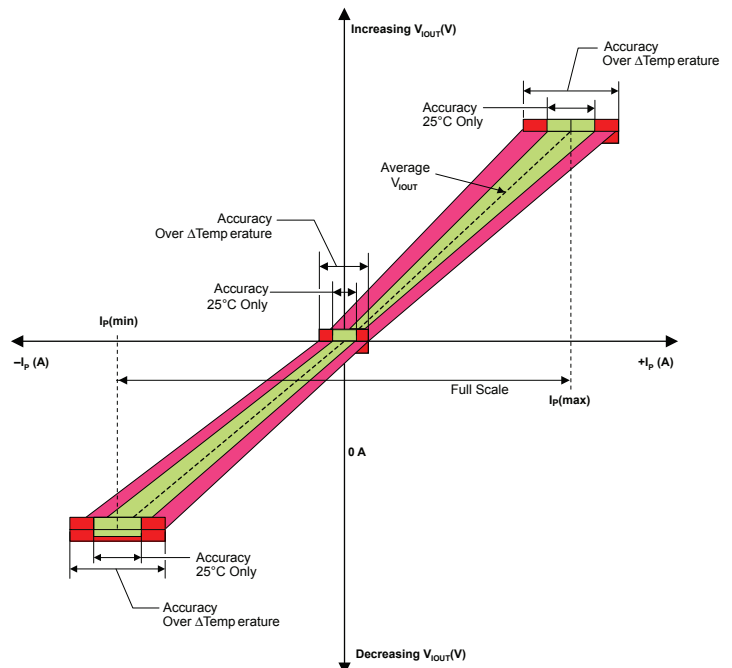
Ratiometry. The ratiometric feature means that its 0 A output, $V_{IOUT(Q)}$, (nominally equal to V_{CC}/2) and sensitivity, Sens, are proportional to its supply voltage, V_{CC}. The following formula is used to derive the ratiometric change in 0 A output voltage, $\Delta V_{IOUT(Q)RAT}$ (%).

$$100 \left(\frac{V_{\text{IOUT(Q)VCC}} / V_{\text{IOUT(Q)5V}}}{V_{CC} / 5 \text{ V}} \right)$$

The ratiometric change in sensitivity, $\Delta Sens_{RAT}$ (%), is defined as:

$$100 \left(\frac{Sens_{VCC} / Sens_{5V}}{V_{CC} / 5 \text{ V}} \right)$$

Output Voltage versus Sampled Current
Accuracy at 0 A and at Full-Scale Current

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9

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Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor
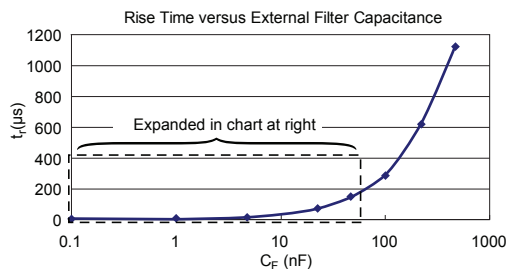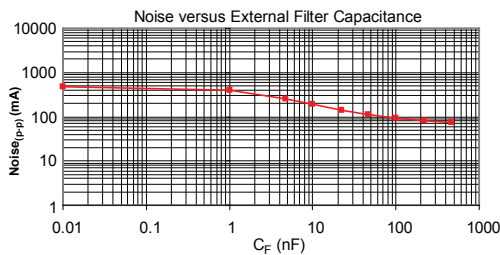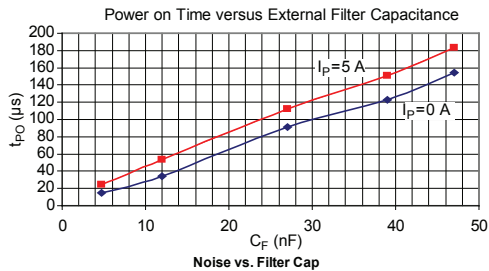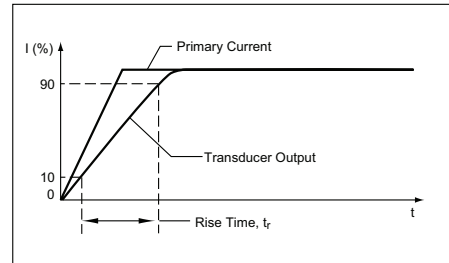
Definitions of Dynamic Response Characteristics

Power-On Time (t_{PO}). When the supply is ramped to its operating voltage, the device requires a finite time to power its internal components before responding to an input magnetic field. Power-On Time, t_{PO} , is defined as the time it takes for the output voltage to settle within ±10% of its steady state value under an applied magnetic field, after the power supply has reached its minimum specified operating voltage, V_{CC}(min), as shown in the chart at right.
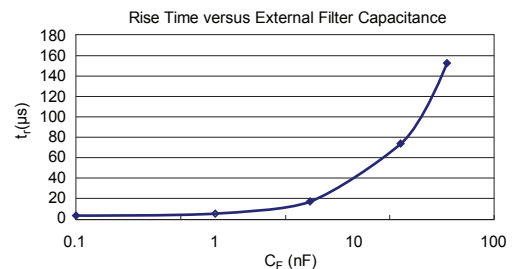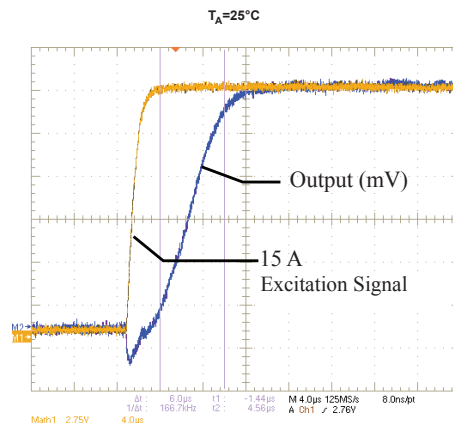

t_1= time at which power supply reaches minimum specified operating voltage

t_2= time at which output voltage settles within ±10% of its steady state value under an applied magnetic field
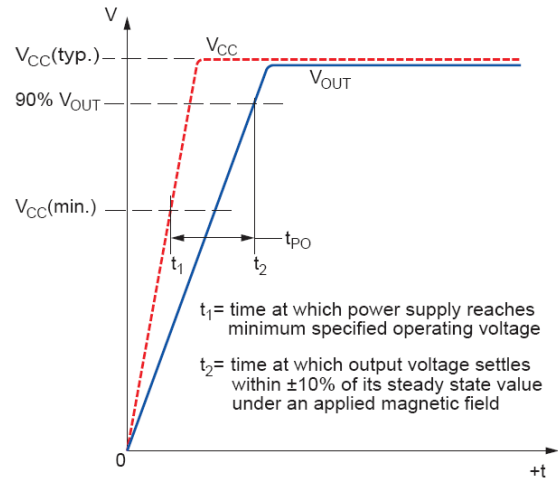
Rise time (t_r). The time interval between a) when the device reaches 10% of its full scale value, and b) when it reaches 90% of its full scale value. The rise time to a step response is used to derive the bandwidth of the device, in which $f(-3 \text{ dB}) = 0.35/t_r$. Both t_r and $t_{RESPONSE}$ are detrimentally affected by eddy current losses observed in the conductive IC ground plane.

Power on Time versus External Filter Capacitance

Noise vs. Filter Cap

Noise versus External Filter Capacitance

Step Response

T_A=25°C

Output (mV)

15 A Excitation Signal

Rise Time versus External Filter Capacitance

Expanded in chart at right

C_F (nF)	t_r (µs)
Open	3.5
1	5.8
4.7	17.5
22	73.5
47	88.2
100	291.3
220	623
470	1120

Rise Time versus External Filter Capacitance

ACS712

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor
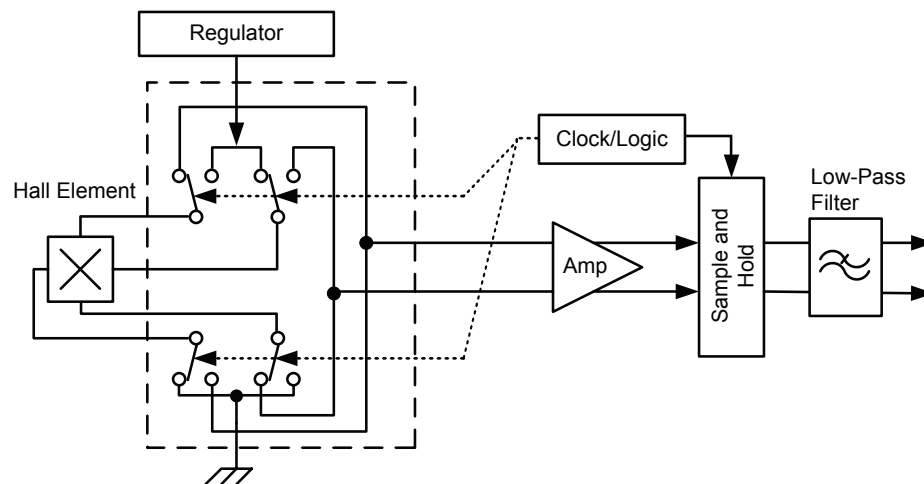
Chopper Stabilization Technique

Chopper Stabilization is an innovative circuit technique that is used to minimize the offset voltage of a Hall element and an associated on-chip amplifier. Allegro has a Chopper Stabilization technique that nearly eliminates Hall IC output drift induced by temperature or package stress effects. This offset reduction technique is based on a signal modulation-demodulation process. Modulation is used to separate the undesired DC offset signal from the magnetically induced signal in the frequency domain. Then, using a low-pass filter, the modulated DC offset is suppressed while the magnetically induced signal passes through
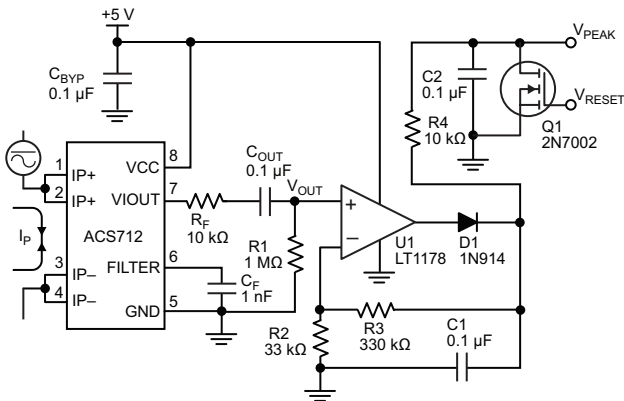
the filter. As a result of this chopper stabilization approach, the output voltage from the Hall IC is desensitized to the effects of temperature and mechanical stress. This technique produces devices that have an extremely stable Electrical Offset Voltage, are immune to thermal stress, and have precise recoverability after temperature cycling.

This technique is made possible through the use of a BiCMOS process that allows the use of low-offset and low-noise amplifiers in combination with high-density logic integration and sample and hold circuits.
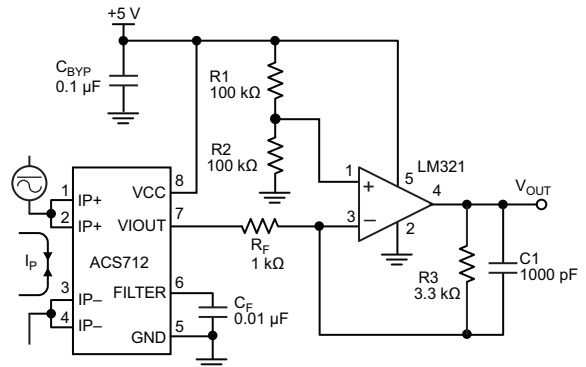

Concept of Chopper Stabilization Technique

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11

ACS712

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor
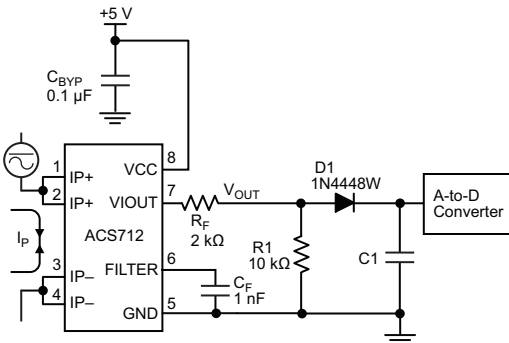
Typical Applications

Application 2. Peak Detecting Circuit

Application 3. This configuration increases gain to 610 mV/A (tested using the ACS712ELC-05A).

Application 4. Rectified Output. 3.3 V scaling and rectification application for A-to-D converters. Replaces current transformer solutions with simpler ACS circuit. C1 is a function of the load resistance and filtering desired. R1 can be omitted if the full range is desired.
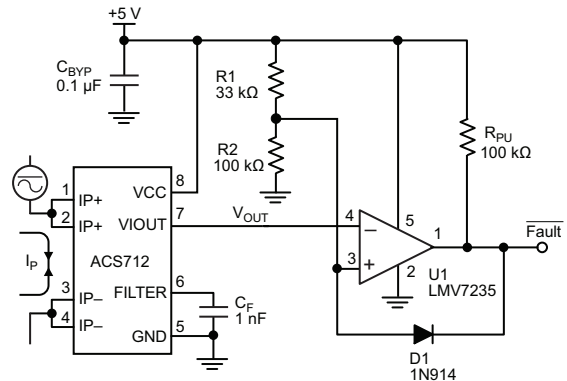
Application 5. 10 A Overcurrent Fault Latch. Fault threshold set by R1 and R2. This circuit latches an overcurrent fault and holds it until the 5 V rail is powered down.

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12

ACS712

Fully Integrated, Hall Effect-Based Linear Current Sensor IC
with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor

Improving Sensing System Accuracy Using the FILTER Pin

In low-frequency sensing applications, it is often advantageous to add a simple RC filter to the output of the device. Such a low-pass filter improves the signal-to-noise ratio, and therefore the resolution, of the device output signal. However, the addition of an RC filter to the output of a sensor IC can result in undesirable device output attenuation — even for DC signals.

Signal attenuation, ΔV_{ATT}, is a result of the resistive divider effect between the resistance of the external filter, R_F (see Application 6), and the input impedance and resistance of the customer interface circuit, R_{INTFC}. The transfer function of this resistive divider is given by:

$$\Delta V_{ATT} = V_{IOUT}\left(\frac{R_{INTFC}}{R_F + R_{INTFC}}\right) \quad .$$

Even if R_F and R_{INTFC} are designed to match, the two individual resistance values will most likely drift by different amounts over
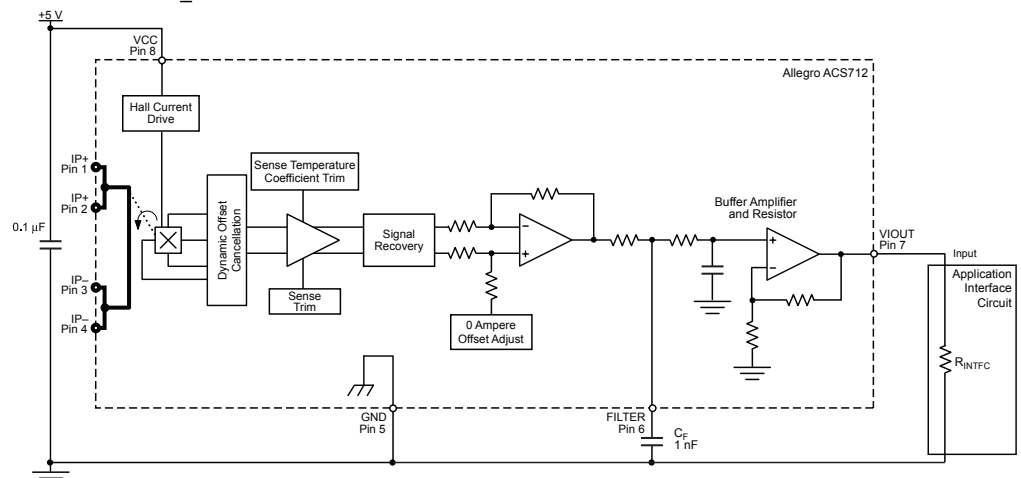
temperature. Therefore, signal attenuation will vary as a function of temperature. Note that, in many cases, the input impedance, R_{INTFC}, of a typical analog-to-digital converter (ADC) can be as low as 10 kΩ.

The ACS712 contains an internal resistor, a FILTER pin connection to the printed circuit board, and an internal buffer amplifier. With this circuit architecture, users can implement a simple RC filter via the addition of a capacitor, C_F (see Application 7) from the FILTER pin to ground. The buffer amplifier inside of the ACS712 (located after the internal resistor and FILTER pin connection) eliminates the attenuation caused by the resistive divider effect described in the equation for ΔV_{ATT}. Therefore, the ACS712 device is ideal for use in high-accuracy applications that cannot afford the signal attenuation associated with the use of an external RC low-pass filter.
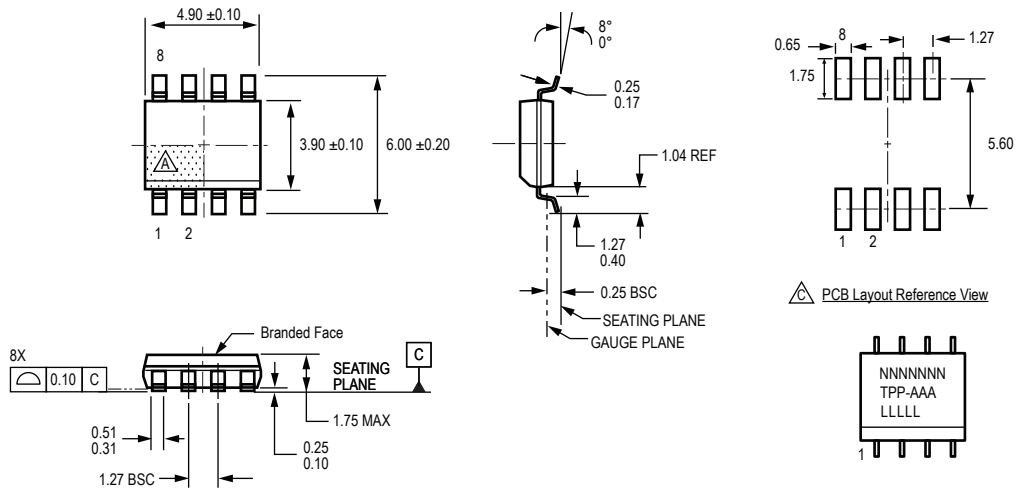

Application 6. When a low pass filter is constructed externally to a standard Hall effect device, a resistive divider may exist between the filter resistor, R_F, and the resistance of the customer interface circuit, R_{INTFC}. This resistive divider will cause excessive attenuation, as given by the transfer function for ΔV_{ATT}.
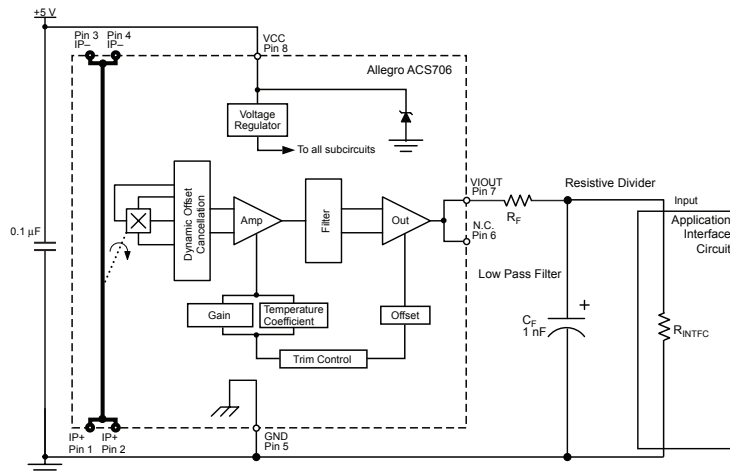
Application 7. Using the FILTER pin provided on the ACS712 eliminates the attenuation effects of the resistor divider between R_F and R_{INTFC}, shown in Application 6.

ACS712

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor

Package LC, 8-pin SOIC

4.90 ±0.10

8

3.90 ±0.10   6.00 ±0.20

1   2

8°
0°

0.25
0.17

1.04 REF

1.27
0.40

0.25 BSC

SEATING PLANE
GAUGE PLANE

0.65   8   1.27

1.75

5.60

1   2

PCB Layout Reference View

8X

⌴ 0.10 C

Branded Face

SEATING PLANE

C

1.75 MAX

0.51
0.31

0.25
0.10

1.27 BSC

NNNNNNN
TPP-AAA
LLLLL

1

Standard Branding Reference View

N = Device part number
T = Device temperature range
P = Package Designator
A = Amperage
L = Lot number
Belly Brand = Country of Origin

For Reference Only; not for tooling use (reference MS-012AA)
Dimensions in millimeters
Dimensions exclusive of mold flash, gate burrs, and dambar protrusions
Exact case and lead configuration at supplier discretion within limits shown

Terminal #1 mark area

Branding scale and appearance at supplier discretion

Reference land pattern layout (reference IPC7351

SOIC127P600X175-8M); all pads a minimum of 0.20 mm from all
adjacent pads; adjust as necessary to meet application process
requirements and PCB layout tolerances

Allegro MicroSystems, LLC
115 Northeast Cutoff
Worcester, Massachusetts 01615-0036 U.S.A.
1.508.853.5000; www.allegromicro.com

14

ACS712

*Fully Integrated, Hall Effect-Based Linear Current Sensor IC
with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor*

Revision History

Revision	Revision Date	Description of Revision
15	November 16, 2012	Update rise time and isolation, I_{OUT} reference data, patents
16	June 5, 2017	Updated product status

For the latest version of this document, visit our website:

www.allegromicro.com

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Worcester, Massachusetts 01615-0036 U.S.A.
1.508.853.5000; www.allegromicro.com

15

Hall Effect Current Sensors L18P***D15 Series
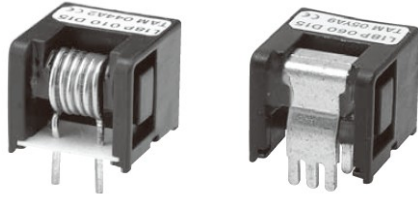
Features:

- Open Loop type
- Printed circuit board mounting
- Integrated primary
- Voltage output
- Busbar version from 40A to 60A
- Insulated plastic case according to UL94V0
- UL Recognition

Advantage:

- Excellent accuracy and linearity
- Wide nominal current range
- Low temperature drift
- Wide frequency bandwidth
- No insertion loss
- High Immunity To External Interference
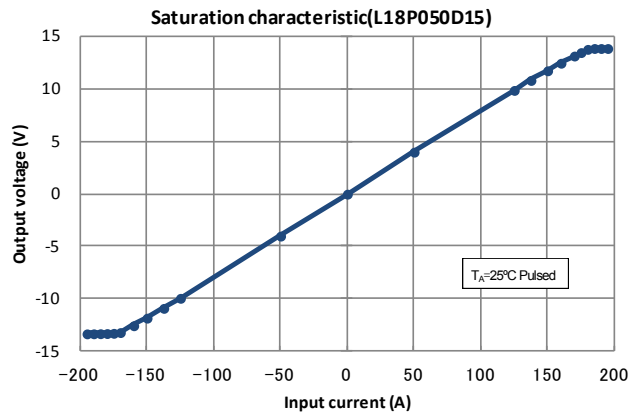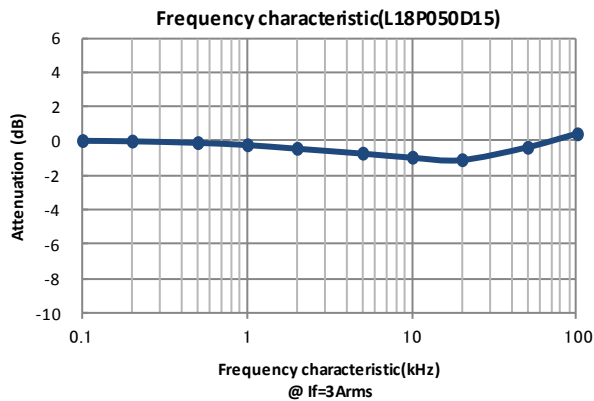- Optimised response time
- Current overload capability

Specifications

$T_A=25ºC$, $V_{CC}=\pm15V$, $R_L=10k\Omega$

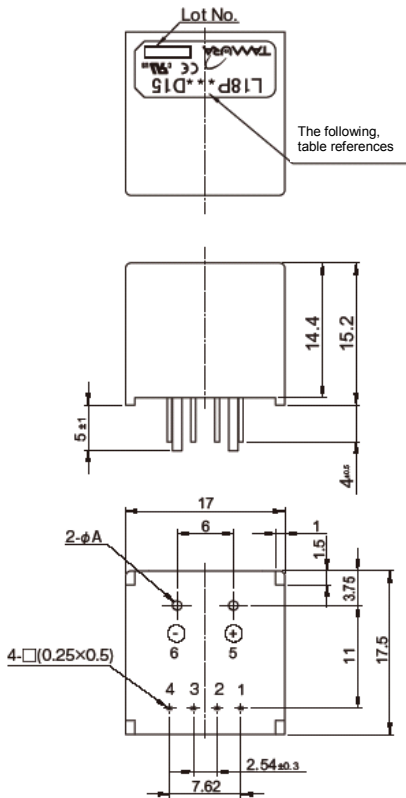| Parameters	Symbol	L18P003 D15	L18P005 D15	L18P010 D15	L18P015 D15	L18P020 D15	L18P025 D15	L18P030 D15	L18P040 D15	L18P050 D15	L18P060 D15
Primary nominal current	I_f	3A	5A	10A	15A	20A	25A	30A	40A	50A	60A
Saturation current	I_{fmax}	$\geq \pm$ If x 3									
Rated output voltage	V_o	4V ±0.040V (at If)							4V ±0.050V (at If)		
Offset voltage[1]	V_{of}	$\leq \pm0.040V$ (at If=0A)							$\leq \pm0.050V$ (at If=0A)		
Output linearity[2] (0A~If)	ε_L	$\leq \pm1\%$ (at If)									
Power supply voltage	V_{CC}	±15V ±5%									
Consumption current	I_{cc}	$\leq \pm15mA$									
Response time[3]	t_r	$\leq 5\mu s$ (at di/dt = I_f / μs)									
Thermal drift of gain[4]	T_cV_o	$\leq \pm0.1\%$/ ºC									
Thermal drift of offset	T_cV_{of}	$\leq \pm1.5mV$/ ºC									
Hysteresis error (at If=0A→If→0A)	V_{OH}	$\leq 25mV$							$\leq 40mV$		
Insulation voltage	V_d	AC3000V for 1minute (sensing current 0.5mA), primary $\Leftrightarrow$ secondary									
Insulation resistance	R_{IS}	$\geq 500M\Omega$ (at DC500V), primary $\Leftrightarrow$ secondary									
Ambient operation temperature	T_A	-30ºC~+80ºC									
Ambient storage temperature	T_S	-40ºC~+85ºC									

[1] After removal of core hysteresis— [2] Without offset —[3] Time between 10% input current full scale and 90% of sensor output full scale — [4] Without Thermal drift of offset

Electrical Performances

Frequency characteristic(L18P050D15)
Frequency characteristic(kHz) @ If=3Arms

Saturation characteristic(L18P050D15)
$T_A=25ºC$ Pulsed
Input current (A)

Tamura reserve the right to modify its products in order to improve them without prior notice

Hall Effect Current Sensors L18P***D15 Series

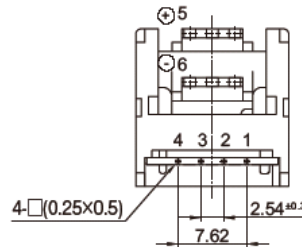## Mechanical dimensions
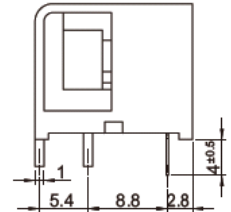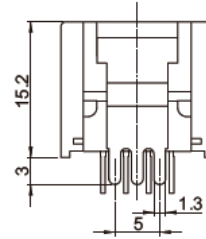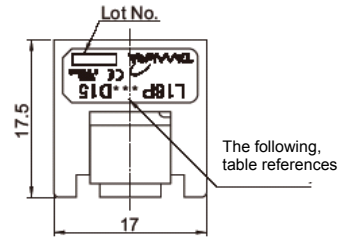
Lot No.

L18P*..D15

The following,
table references

Terminal Number:
1: -V$_{CC}$(-15V)
2: GND
3: +V$_{CC}$(+15V)
4: V$_{OUT}$
5: Primary input current (+)
6: Primary input current (-)

Current	XXX	φA
3A	003	φ0.6
5A	005	φ0.8
10A	010	φ1.1
15A	015	φ1.4
20A	020	φ1.6
25A	025	φ1.6
30A	030	φ1.6

NOTES
1. Unit is mm
2. Tolerance is 0.5mm
3. Cover is optional parts.

Current	XXX
40A	040
50A	050
60A	060

Primary :Busbar

Electrical connection diagram

+I$_f$
-I$_f$

-V$_{CC}$
+V$_{CC}$
GND
R$_L$ = 10kΩ
V$_{OUT}$
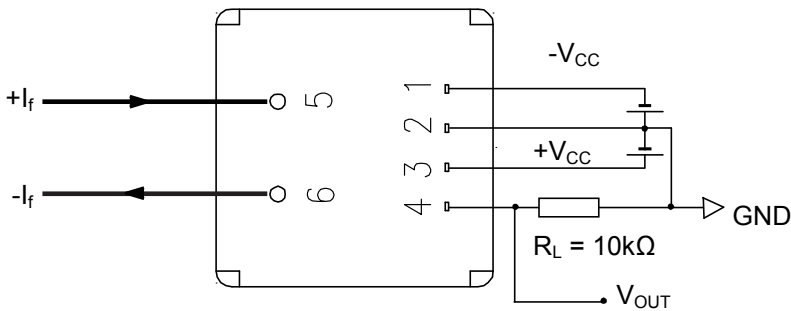
UL Standard

UL 508 , CSA C22.2 No.14
(UL FILE No.E243511)

• For use in Pollution Degree 2 Environment.
• Maximum Surrounding air temperature rating, 80˚C.

Package & Weight Information

nominal current	Weight	Pcs/box	Pcs/carton	Pcs/pallet
10A..60A	8g	100	600	12000
3A , 5A	8g	50	1200	28800

Tamura reserve the right to modify its products in order to improve them without prior notice

Split core current transformer

Model: SCT-013	Rated input current：5A/100A

Characteristics：Openning size: 13mm*13mm,

Non-linerity±3%（10%—120% of rated input current）

1m leading wire, standard Φ3.5 three core plug output.

Current output type and voltage output type (voltage output

type built-in sampling resistor)

Purpose：Used for current measurement, monitor and protection for AC motor,

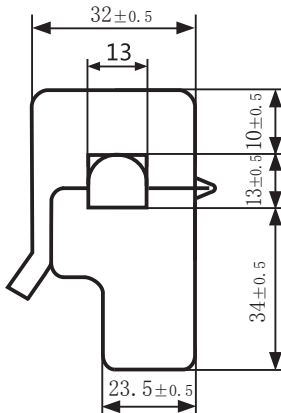lighting equipment, air compressor etc

Core material: ferrite

Mechanical strength: the number of switching is not less than 1000 times(test at 25℃)

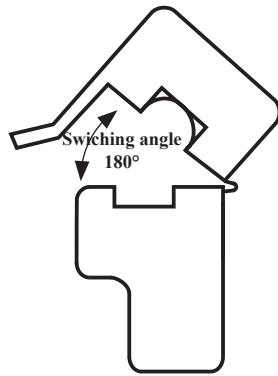**Safty index**：Dielectric strength(between shell and output)1000V AC/1min

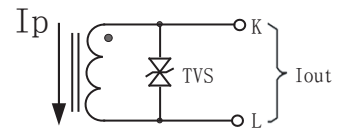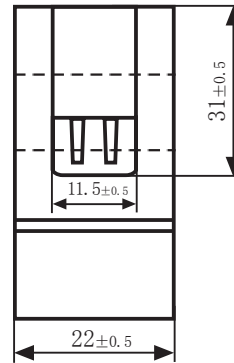Fire resistance property: In accordance with UL94-Vo

Work temperature: -25℃～+70℃

Outline size diagram: (in mm)

Front View

Side View

Swiching angle 180°

32 ± 0.5
13
13 ± 0.5
10 ± 0.5
34 ± 0.5
23.5 ± 0.5
31 ± 0.5
11.5 ± 0.5
22 ± 0.5

Ip — K — Iout — L
Current output type
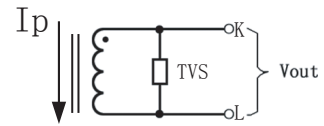
Ip — K — Vout — L
Voltage output type

Schematic diagram

35.3

L Output Vacancy K Output

ΦY

1m

X
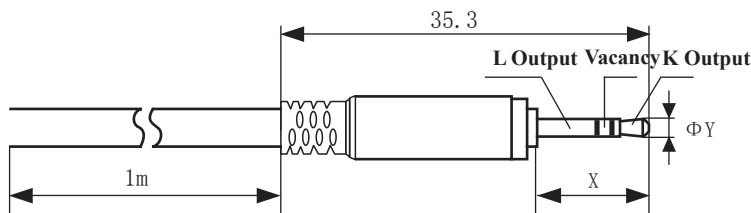
Diagram for standard three-core plug

Three-core plug size

	X	Y	
2.5mm Audio Plug	11.9	2.5	Optional
3.5mm Audio Plug	15.0	3.5	standard

Table of technical parameter：

Model	SCT-013-000	SCT-013-005	SCT-013-010	SCT-013-015	SCT-013-020
Input current	0-100A	0-5A	0-10A	0-15A	0-20A
Output type	0-50mA	0-1V	0-1V	0-1V	0-1V
Model	SCT-013-025	SCT-013-030	SCT-013-050	SCT-013-060	SCT-013-000V
Input current	0-25A	0-30A	0-50A	0-60A	0-100A
Output type	0-1V	0-1V	0-1V	0-1V	0-1V

※ Output type: voltage output type built-in sampling resistor, current output type built-in protective diode.