ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)
GRADO EN INGENIERÍA ELECTROMECÁNICA

Especialidad Eléctrica

MODELING POWER GRID WITH BATTERY STORAGE FOR BELD. POWER DEMAND CURVE SIMULATION.

Autor: Teresa Jiménez-Castellanos Vida
Director: Alan Pisano

Madrid
Julio 2018

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Modeling Power Grid with Battery Storage for BELD.
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Director: Pisano, Alan.

Entidad Colaboradora: Boston University.

RESUMEN DEL PROYECTO

Palabras clave: Almacenamiento de energía, baterías, curva de demanda.

1. Introducción

La energía constituye indudablemente una de las necesidades esenciales de las sociedades modernas, y su uso se ha expandido rápidamente con el crecimiento de la población mundial y del consumo per cápita. Los pronósticos para los próximos cien años de la demanda energética predicen un gran incremento en el consumo mundial de energía, debido en gran parte al desarrollo de nuevas economías emergentes. Para hacer frente a dicha demanda, una nueva generación de tecnologías impulsoras de las energías renovables y un incremento en la eficiencia de la producción y el uso de energía resultan esenciales.

Una solución a este reto es el almacenamiento de energía, respuesta necesaria para afrontar cuatro grandes cuestiones: gestionabilidad, respondiendo a fluctuaciones en la demanda de electricidad; capacidad de interrupción, reaccionando ante las fuentes de energía intermitentes; eficiencia, recuperando energía perdida para un posterior uso; y necesidades regulatorias, alcanzando los requerimientos nacionales, regionales, estatales y locales, expandiendo a la vez la capacidad de distribución y transmisión. [1]

La energía puede ser almacenada de diferentes formas: potencial, cinética, térmica, química y eléctrica. Actualmente, hay varias tecnologías que permiten su almacenamiento; algunas ya implementadas y otras todavía en proceso de desarrollo. El objetivo de la investigación es conseguir aumentar su capacidad, reducir el tiempo de carga e incrementar su vida útil, disminuyendo a su vez el coste de mantenimiento.

Acumulación por bombeo, sistemas de aire comprimido, volantes de inercia, supercondensadores, superconductores magnéticos y baterías son algunas de las tecnologías utilizadas para el almacenamiento de energía. La opción de almacenamiento más popular y tecnológicamente desarrollada, las baterías, constituye el principal tema del presente trabajo.

Este proyecto tiene como objetivo construir una red eléctrica a pequeña escala con un sistema de baterías integrado, con el fin de analizar diferentes tipos de baterías como de iones de Litio, de Plomo-Ácido o de Níquel-Cadmio.

Este trabajo se ha desarrollado en paralelo con un proyecto real de instalación de baterías llevado a cabo por Braintree Electric Light Department, compañía eléctrica situada en Braintree, Massachusetts, Estados Unidos, y cliente del presente proyecto.

2. Metodología

La red eléctrica propuesta trabajará con corriente alterna (una sola fase) a una tensión de $10V_{rms}$ y 60Hz, frecuencia estándar en Estados Unidos. Dicha red comprende cuatro subsistemas diferentes: generación y distribución, resistencia variable, sistema de instalación de baterías y sistema de adquisición y display de datos, mostrados en la Ilustración 1. En la mencionada figura, flechas rojas y negras representan el flujo de potencia, flechas azules indican los puntos de la red donde se tomarán medidas y flechas verdes se refieren a las conexiones externas de la red.

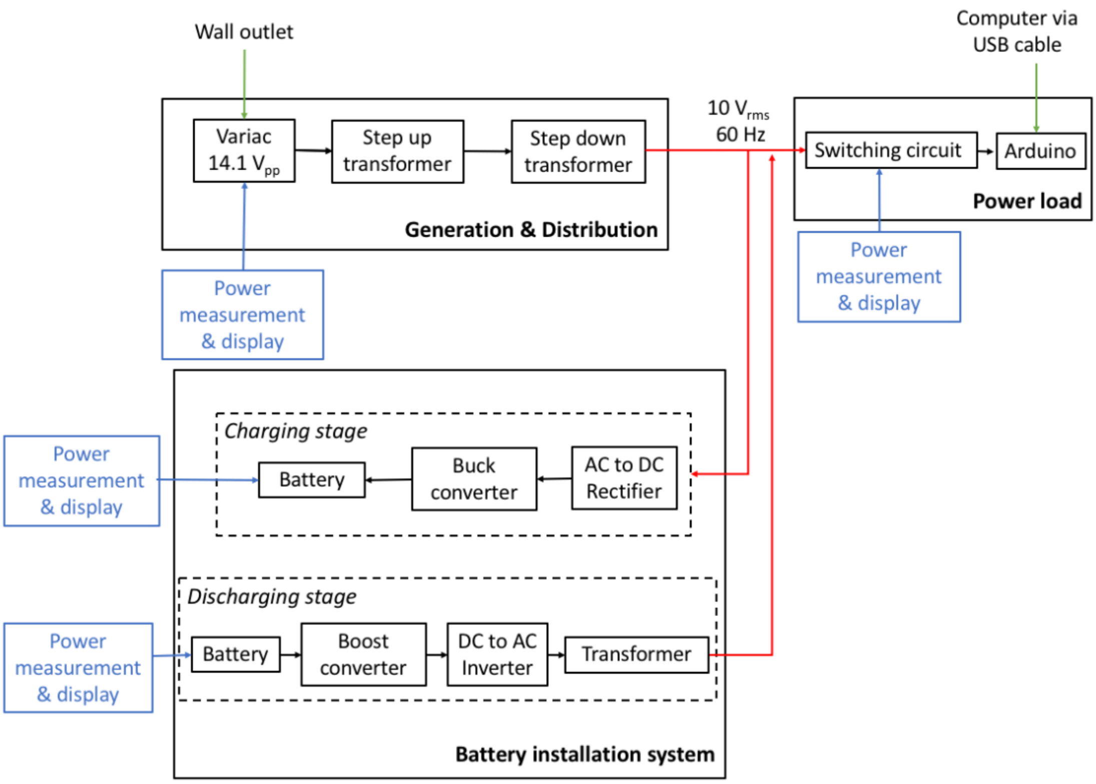

Ilustración 1. Diagrama de bloques del proyecto.

El principal objetivo de cada uno de los cuatro subsistemas es el siguiente:

-El sistema de generación, que modela los generadores de BELD usando un transformador Variac, y las líneas de transporte y distribución aumentando en primer lugar y disminuyendo posteriormente la tensión con dos transformadores distintos.

-La resistencia variable, cuya función principal es modelar la curva de demanda de electricidad de la red, modificando la resistencia total del circuito.

-El sistema de instalación de baterías, que inyectará o consumirá potencia de la red. Aportará potencia a la red en periodos de picos de demanda y cargará las baterías en valles de demanda.

-Finalmente, el sistema de adquisición y display de datos tomará medidas en puntos significativos de la red (generación, baterías y cargas) con el fin de realizar un posterior análisis y mostrará en tiempo real las mediciones.

Especial énfasis se hará en el modelo de la curva de demanda de la red, eje primordial sobre el que girará el presente documento.

El objetivo último de la resistencia variable es modelar la curva de demanda del verano en Nueva Inglaterra. A lo largo del día, la demanda de electricidad fluctúa, siendo baja de madrugada, aumentando por la mañana hasta alcanzar su máximo pasado el mediodía y disminuyendo de nuevo por la tarde hasta la noche.

Esto se ha conseguido usando TRIACS (triodos para corriente alterna) actuando como interruptores. El circuito diseñado tiene seis escalones de potencia distintos y seis resistencias de 30Ω, siendo la máxima potencia consumida 20W y la máxima corriente a través del circuito 2A.

El microprocesador presente en la placa Arduino Uno se usará para programar la curva de demanda. Para aislar el microprocesador, el cual sólo soporta una corriente de 40mA, del resto del circuito, se usarán optoacopladores.

El montaje final del proyecto se ha realizado construyendo una base de madera, que soporta todos los componentes de la red a excepción del Variac, y una cubierta de cristal acrílico para dotar al usuario de mayor seguridad.

3. Resultados

Centrándonos primero en la resistencia variable, la curva de demanda del verano en Nueva Inglaterra ha sido simulada con éxito y una PCB ha sido diseñada, fabricada y puesta en funcionamiento.

El código programado para tal efecto es flexible y fácil de utilizar, y permite al usuario simular una curva de demanda diferente de la propuesta. A pesar de la ausencia de requerimientos iniciales relacionados con el tiempo de simulación (tiempo que se tarda en simular una curva de demanda), éste puede ser modificado fácilmente de acuerdo con el propio criterio del usuario.

En relación al proyecto en general, la mayor parte de los subsistemas ha sido correctamente ejecutada.

El sistema de generación y distribución presenta como salida a la red una onda de $10V_{rms}$, 60Hz y dos transformadores simulan con éxito las líneas de transporte y distribución.

El sistema de adquisición y display de datos muestra en tiempo real tensión, corriente y potencia en puntos significativos de la red, usando pantallas LCD. Además, los resultados obtenidos se archivan automáticamente en una hoja de cálculo de Excel para su posterior análisis.

Sin embargo, el sistema de instalación de baterías no ha cubierto el 100% de sus expectativas. Aunque la rama de carga ha sido lograda con éxito, varios problemas relacionados con el inversor y la sincronización han impedido la integración de la rama de descarga. Este inconveniente impidió que las baterías pudieran ser totalmente analizadas, pero el trabajo realizado a su vez ha permitido detectar aquellos puntos donde se encontraba el error.

4. Conclusiones

Analizando el trabajo realizado y los resultados obtenidos, y comparándolos con los objetivos iniciales del proyecto, podemos concluir que la mayor parte de los requisitos iniciales han sido correctamente cumplidos. Investigación, modificaciones y ajustes finales en cada uno de los subsistemas han dado como resultado una red eléctrica a pequeña escala con baterías integradas.

Aunque se ha puesto especial esfuerzo en la correcta compleción del proyecto, se podrían introducir algunas mejoras: integrar un inversor personalizado o construir uno propio, crear un sistema de control para la carga y descarga automática de las baterías dependiendo de la potencia consumida por las cargas o añadir inductores y condensadores a la red.

La principal dificultad que hemos encontrado al realizar el presente proyecto es que, frente a la simulación por ordenador, donde se fijan unas variables a priori, en el modelo físico que hemos desarrollado intervienen variables impredecibles que en todo caso alteran el normal funcionamiento del mismo; sin embargo, esto es imprescindible cuando queremos llevar a la práctica un ambicioso trabajo del que resulten ventajas en el uso futuro de la energía.

5. Referencias

[1] Jefferson W. Tester, Elisabeth M. Drake, Michael J. Driscoll, Michael W. Golay, William A. Peters. “Sustainable Energy. Choosing Among Options”. Second edition. 2012. Massachusetts Institute of Technology.

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Collaborating Entity: Boston University.

ABSTRACT

Keywords: Energy storage, batteries, electricity demand

1. Introduction

Energy is undoubtedly one of the essential needs of a modern society and its use has expanded rapidly as both population and per capita consumption have grown. Projections of energy demand over the next hundred years forecast a sharp increase in world energy consumption, which will come due in large part to the development of emerging economies. In order to meet these needs, a new generation of renewable energy technologies and an increase in efficiency of energy production and use result essential.

A key solution to this challenge is energy storage, which addresses four major needs: dispatchability, responding to fluctuations in electricity demand; interruptibility, reacting to intermittent energy supplies; efficiency, recovering wasted energy for reuse; and regulatory-driven needs, meeting national, regional, state and local performance requirements, while expanding distribution and transmission capacity. [1]

Energy can be stored in a wide variety of forms: potential, kinetic, thermal, chemical and electrical. Currently, there are several promising technologies, some already implemented and others still under development. Significant research is done in order to increase their capacity, reduce their charging time and increase their lifetime while reducing the maintenance costs.

Pumped hydropower, compressed air energy storage (CAES), flywheels, supercapacitors, superconducting magnetic energy storage (SMES) and batteries are some of the technologies used for energy storage. The most popular and technologically matured storage option, batteries, is the main subject of this project.

The project aims to build a scaled down power grid with battery storage integrated, in order to test different battery chemistries such as Li-Ion, Lead Acid or Nickel-Cadmium.

It has been developed in parallel with a real battery installation carried out by Braintree Electric Light Department, a utility company located in Braintree, Massachusetts, US, and customer of the present project.

2. Methodology

The mock grid, one-phase AC system, works at $10V_{rms}$ and 60Hz, standard frequency in the US. The grid comprises four different subsystems: generation and distribution, variable load, battery installation system and data acquisition and display, shown in Figure 1. In this figure, red and black arrows represent the flow of power, blue arrows indicate the spots of the grid where measurements are taken and green arrows refer to the external connections of the grid.

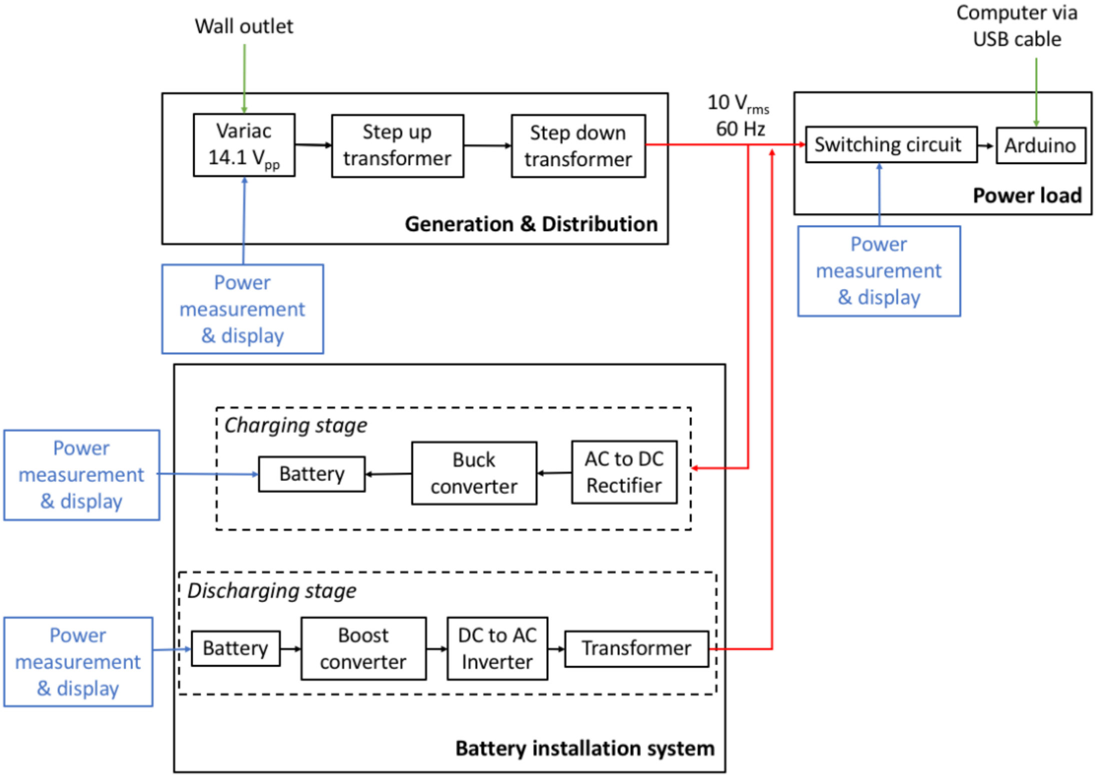

Figure 1. Block diagram of the project.

The main objective of each of the four subsystems is the following:

-The generation system, models BELD’s power plants by using a Variac transformer, and the transmission and distribution lines by stepping up and down the voltage with two different transformers.

-The variable load system, whose main function is to model the electricity demand curve of the grid, changing the total resistance of the circuit.

-The battery installation system, which will either charge or discharge electrical power to the loads. It will provide power to the grid in times of peak demand and will charge during times of low demand.

-Finally, the data acquisition and display system will gather data in the important spots of the grid (generation, batteries and loads) for further analysis and will feature live characterization readings.

Special emphasis will be made in modeling the demand curve of the mock power grid, principal axis of this document.

The ultimate objective of the variable load is to model the typical electricity summer demand curve of New England. Throughout the period of the day, the demand for electricity fluctuates from low in the morning to high in the late afternoon into the evening and back down again at night.

This has been accomplished using TRIACs (triodes for alternating current) acting as switches for AC. The circuit designed has six different steps of power and six high-power 30Ω resistors, being the maximum power consumed 20W, and the maximum current 2A.

The board Arduino Uno is used to program the summer demand curve. In order to isolate the microprocessor, which can only stand a current of 40mA, from the rest of the circuit, optocouplers are used.

The project has been finished by building a wood base supporting all the components except for the Variac, and a plexiglass enclosure in order to increase the safety of the user.

3. Results

Focusing first on the variable load, the summer demand curve of New England was successfully simulated and a printed circuit board (PCB) was designed, fabricated and tested.

The code programmed in order to make the load follow the demand curve is user-friendly and enables anyone interacting with the grid to simulate a different demand curve. Although there were no requirements related to the simulation time (time it takes to simulate one demand curve), it can be easily modified according to the user's own criteria.

According to the complete project. The major part of the subsystems was correctly executed.

The generation and distribution subsystem provides a $10V_{rms}$, 60Hz waveform to the mock grid and simulates the transmission lines by stepping the voltage up and down.

The data acquisition and display system effectively displays in real time voltage, current and power in significant spots of the grid, using LCD screens. In addition, it stores the results obtained for future analysis in an excel file, using the software Processing.

However, the battery installation subsystem has not covered all its expectations. Although the charging stage was successfully accomplished, several problems related to the DC-AC inverter and the synchronization have impeded the integration of the discharging stage in the grid. Due to this inconvenient, batteries could not be totally tested and analyzed, but, at the same time, the work done has allowed us to detect the erratic points.

4. Conclusion

Analyzing the work done and the obtained results, and comparing them with the initial objectives of the project, we can conclude that the major part of the initial requirements has been completely accomplished. Significant research, modifications and final adjustments in each of the subsystems have led to a small scale AC power grid with batteries integrated.

Although special effort was put in the correct completion of this project, several improvements could be made: installing a customized or designing our own inverter, making the batteries charge and discharge automatically depending on the power being consumed by the loads or adding inductors and capacitors in the grid.

The main difficulty we have found during the fulfillment of the present project is that, unlike computer simulations, where variables are fixed previously, in the physical model developed, several unpredictable variables intervene altering the normal operation of it. However, this results essential when putting into practice an ambitious project with considerable advantages in the future use of energy.

5. References

[1] Jefferson W. Tester, Elisabeth M. Drake, Michael J. Driscoll, Michael W. Golay, William A. Peters. "Sustainable Energy. Choosing Among Options". Second edition. 2012. Massachusetts Institute of Technology.

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Part I: Report

CHAPTER I: INTRODUCTION

1.1. Description Of The Problem

Energy is undoubtedly one of the essential needs of a modern society. The living standards and the degree of industrialization that a particular society experiences are closely associated to the scale of energy use. The high quality of life enjoyed by the developed nations today is due in large part to the availability of plentiful and affordable fossil fuels over the last century. Countries energy policies have become more relevant thorough the years and energy use has expanded rapidly as both population and per capita consumption have grown.

The relationship between the growth in population and energy consumption over time is shown in Figure 1. World population increases at a rate of about 1.09% [1] per year and it has tripled since the late 1930s. In 1700, world population was 600 million; in 2000, it was over 6 billion and it reached 7 billion in 2011.

As a consequence of the growth in world population, energy demand has increased as well. The energy utilization rate throughout the ages can only be estimated in a rough manner. In the year 10^6 BC, the energy utilization rate was around 100 W/capita, similar to what is consumed by a light bulb. In the year 8,000 BC, with primitive agriculture, it ascended to 800 W/capita. In the year 1600 AC, it reached 6,000 W/capita due to the developments in industry. Today, the energy utilization rate varies significantly depending on the country. In the US, it is approximately 11,000 W/capita.

Projections of energy demand over the next hundred years are uncertain, but the graph in Figure 1 gives an idea of the sharp increase in world energy consumption in the next decades, which will come due in large part to the development of emerging economies such as China, India and Brazil.

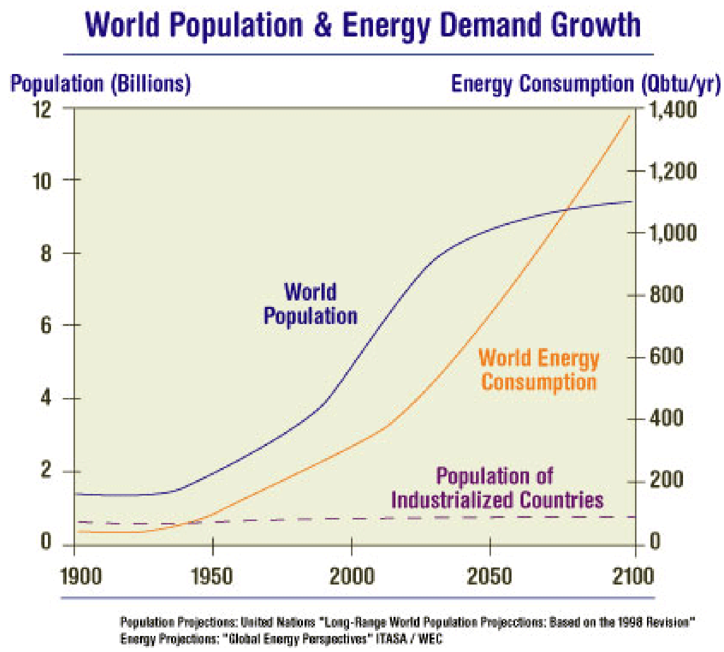


Figure 1. World population and energy demand growth over time. [2]

More and more development suggests even higher future needs for energy. The most available and affordable sources of energy in today's economic structure are fossil fuels (about 85% of all commercial energy is derived from them [3]). However, public concerns regarding the negative environmental impact of burning fossil fuels have encouraged engineers and scientists to develop reliable alternative energy resources. Efficiency improvements and new technologies are part of the solution. Still, as major challenges require major changes, society has to invest in innovative technologies if we wish to address the challenge of stabilizing greenhouse gas emissions without severe economic consequences.

The rapid depletion of nonrenewable resources, the severe impacts of emissions on the global environment and global instabilities that affect the security of supplies are some of the areas where concerns about the sustainability of present energy-use practices are now arising.

The concept of sustainability was defined by Brutland in 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3]. It is a state of global being yet to be realized. The dilemma needed to be solved is how to maintain and extend energy-derived benefits for present and future generations while sensibly administrating the planet's natural resources.

To achieve a more sustainable energy future, our society needs to develop a rich set of energy technology and technology-intensive policy options. Some of the options proposed include:

-increase efficiency of energy production and use,

-reduce energy consumption,

-nuclear options that can win and retain public acceptance,

-the means to use fossil fuels in a climate-friendly way,

-a new generation of renewable energy technologies.

Focusing on this last issue it is evident that, at present, renewables are a small part of the energy supply, as they only represent 9.59 % [4] of the world energy consumption. However, their importance is growing.

The three most expanded renewable energy technologies are hydro power, wind and solar. Hydroelectric energy is limited to about 6.79 % of the world's energy consumption because of the limited water resources suitable for generating electricity. Both solar and wind energy are becoming more cost competitive but their variability requires either an energy storage device or a backup alternate energy supply. Nevertheless, when they are generating energy, they are reducing the total demand for fossil energy.

Renewable energy types such as solar and wind are variable on a daily basis. What this means is that the times when energy can be captured and converted efficiently do not always correspond to periods of high demand. This causes mismatches between supply and demand, which can lead to blackouts or even total system collapse.

To illustrate this idea, a certain electric grid with solar panels and wind turbines installed can be considered. Figure 2 shows the power demand of the grid, as well as the solar and wind power curves during a typical day.

In the case of wind energy, there are certain times of the day, more specifically at night, when wind speeds are stronger and the power generated by wind farms is higher than the power demanded in the grid. In this case, a large part of the injected power of wind would be useless, due to the lack of demand. On the contrary, when the power demand is extremely high, but the wind speed is not favorable, power from another source would be required in order to meet the demand.

In the case of solar energy, the peak of the solar power curve is shifted from that of the power demand of the grid and there are hours in the day where the solar power curve is higher than the power demand, having again an excess of energy in the grid in a time when it is not needed.

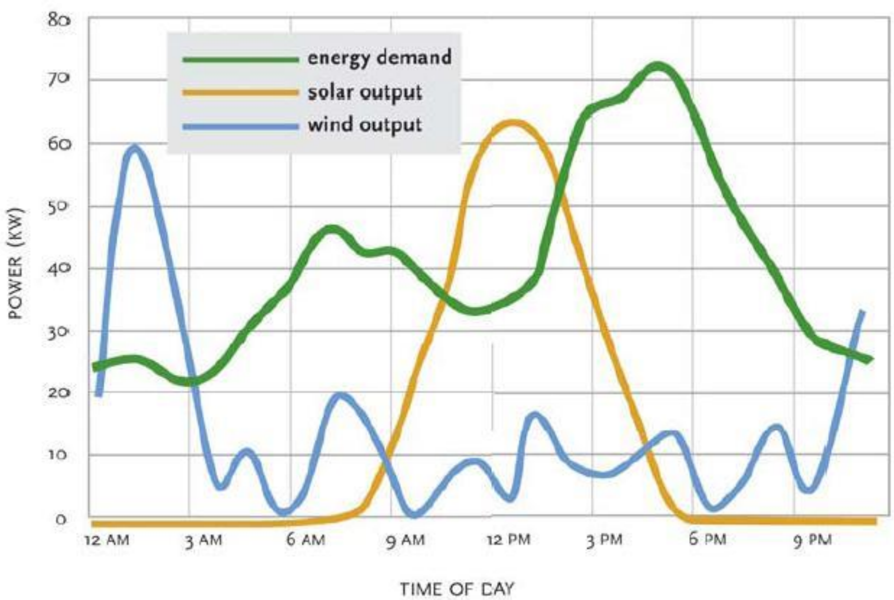


Figure 2. Power demand and solar and wind energy generation curves. [5]

The solution to this problem would be to store energy when solar or wind power outputs surpass the energy demand and to inject it in the grid during the peak demand hours.

It can be deducted from this example that for nondispatchable renewable systems to play a major role in supplying primary energy, robust energy-storage systems are needed. Having cost-effective, high-efficiency storage system with low losses available for electricity highly increases the attractiveness of these renewable energy types.

1.2. Importance of Energy Storage in the Electric Grid

The traditional infrastructures for electrical energy have evolved based on large continuous output source locations (baseload plants) which feed transmission and distribution networks to bring energy to end-use locations. To deal with the usual fluctuations in demand, dispatchable energy sources are connected to the grid and operated as needed. In addition, to meet peak energy demand, combinations of energy storage, pricing incentives to shift demand to off-peak times, and more expensive "peak-shaving" energy sources are used.

Energy storage permits decoupling of energy supply and demand periods, which is desirable for both economic and technical reasons. Economically, demand for energy and power has significant variation, both diurnally and seasonally. To maintain the capacity to meet peak demand periods without energy storage would require more quick-start generators, which can be translated to high capital investment. From a technical perspective, some types of renewable energy cannot be captured and converted when the demand requires energy. As it has been illustrated above, solar and wind energy are intermittent on a daily and seasonal basis, requiring storage technologies to function most effectively.

Storage addresses four major needs [3]:

1) Dispatchability: responding to fluctuations in electricity demand;
2) Interruptibility: reacting to intermittent energy supplies;
3) Efficiency: recovering wasted energy for reuse;
4) Regulatory-driven needs: meeting national, regional, state and local performance requirements, while expanding distribution and transmission capacity.

In order to outline the benefits of energy storage in the electric grid, an in-depth analysis of the typical demand curves is required.

It is worth mentioning that thanks to engineers the power system that we enjoy today is undoubtedly the most reliable and efficient complex system ever built by man. Its complexity is highly based in its unpredictability, which constitutes as well one of the key problems to deal with.

Electricity demand fluctuates on several cycles daily and weekly due to variations in industrial and domestic loads, and seasonally due to weather and average temperature changes. There is more power used in the winter for heating, and in the summer for air conditioning. The variation with time during the day is also generally greater in the summer than in the winter.

The use of energy also varies with the day of the week in many cases. Whereas it is easy to understand that there is a daily pattern of energy use, the needs are not the same every day of the week because many activities are different on weekends than they are during workdays. This can be observed in Figure 3, which shows the typical weekly load curve of an electric utility.

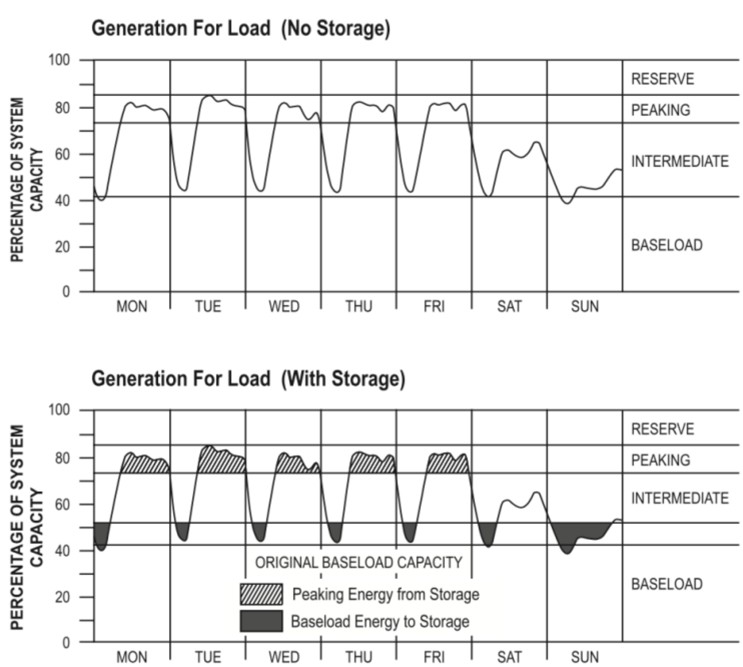


Figure 3. Typical weekly load curve of an electric utility. [3]

These significant variations result in a serious problem for the electric utility firms that both supply and manage the transmission and distribution electric power grid.

Electric utilities supply this power to the grid from a number of different sources. They are often two or three different technologies, depending upon the load level. The least expensive, but most contaminating, is the use of coal or oil in large base-load facilities. Therefore, utilities try to cover as much as possible of the need from such sources. However, they are not very flexible, requiring from 30 to 60 minutes to start up.

In addition, utilities typically have a modest amount of operating reserve, which is additional capacity that is available to the system operator within a certain amount of time, to meet the demand if a generator fails or there is another disruption in the supply.

This operating reserve can be divided into two types. One, called spinning reserve, is extra generating capacity that can be made available by a relatively simple modification of the operation of the major turbines. The other is supplemental, or non-spinning, reserve. This term describes capacity that is not currently connected to the system, but that can be brought online after only a short delay. It may involve the use of fast-start generators, or importing power from other interconnected power systems. Generators used for either spinning reserve or supplemental reserve can generally be put into operation in around 10 minutes.

Furthermore, there are additional secondary source technologies that are more flexible, but significantly more expensive, employed to handle any need for extra capacity. In some cases, these involve the use of gas turbine power.

One method to reduce the magnitude of the variations in energy demand is to use energy storage technologies to absorb electrical energy when it is available and inexpensive, and to supply it back into the grid system when the demand is higher, as shown in Figure 3.

The crosshatched and shaded areas on the figure illustrate how electric energy could be stored during periods of low demand (shaded areas) and supplied from a suitable storage reservoir during peak demand periods (crosshatched areas). The nominal cycle time for shifting electric power to and from the storage system typically occurs during a 24-hour period. This would result not only in an increase in the grid efficiency, but also it will help stabilizing it.

Into these major variations in the energy demand, there are also many short-term transients. These transients can produce rotor angle instability, leading to oscillations and an unstable operating condition. Voltage instability can also occur when the load and the associated transmission system require a large amount of reactive, rather than real, power. This can result in a sudden and drastic voltage drop. Short-term (usually less than 5 minutes) power outages can also occur and these can be significantly expensive.

A different type of technology is necessary to handle this problem, which is currently solved by making small adjustments in the frequency. However, fast-reaction high power storage mechanisms are ideal for this application.

In conclusion, the potential use of storage technologies in many applications and recent deployment initiatives for renewable and distributed energy resources have reactivated interest in storage technologies because of two main reasons:

1) Recovery of wasted energy also enables energy storage technologies to increase efficiency.
2) The value of intermittent renewable energy sources increases substantially if they can be dispatched when needed and if they have self-contained storage systems that make this possible.

The final motivation for developing and deploying energy storage systems comes from regulatory policies that promote more efficient, reliable, and secure energy supply systems. Deregulation and restructuring of the electric power industry will lead to new opportunities for energy storage, particularly when it enhances power quality or reliability or eliminates a need to expand the transmission and distribution infrastructure.

1.3. Braintree Electric Light Department

The customer of the present project, Braintree Electric Light Department, better known as BELD, is a local utility company located in Braintree, Massachusetts, US.

With an experience of more than 110 years, it supplies electric service to approximately 14,000 residential and business customers in the town of Braintree and operates generation, transmission and distribution facilities.

BELD service comprises around fourteen square miles, including 148 miles of overhead lines and 88 miles of underground lines. They operate three electric distribution substations and two 115 kilovolt transmission interchange substations. BELD’s connection to two separate 115kV NStar transmission lines, part of the ISO New England electric grid, provides them with easy access to power supply sources throughout the Northeast.

Apart from receiving power from many units within New England, BELD currently owns and operates four different power plants and bids these plants into the ISO New England market system. These power plants include [6]:

-A 96 MW combined-cycle power plant (Potter II)
-The two Thomas Watson 58 MW quick-start simple-cycle turbines
-A 2 MW diesel unit

It is worth mentioning that the Thomas A. Watson Generating Station is one of the most modern and efficient plants in the United States and it was named one of the fourteen best power plants in the world in the January-February 2010 edition of Diesel & Gas Turbine Worldwide magazine [7].

Engineers at BELD are highly concerned about energy storage and its benefits in the electric grid, therefore they have decided to invest in energy storage, more specifically in batteries. They are developing a 2 MW/4.2 MWh lithium-ion battery storage project. The energy storage system will be installed at one of BELD’s substations, which will reduce both energy and transmission capacity costs for BELD and its ratepayers. The project also aims to demonstrate the ability of energy storage to enable more intermittent renewable generation and defer traditional distribution system investment in addition to advancing an innovate community storage model. This project is unique in that it will also pilot a community storage-as-a-service model to help reduce participating customers' peak coincident charges.

In collaboration with Boston University, BELD sponsored our team for making a physical simulation of an electric grid with battery storage integrated, in parallel with the real battery installation project. The final deliverable is a small-scale, physical grid network with various battery installations, that includes real time data acquisition so that the user can experiment and analyze the data collected.

1.4. Brief description of the project

Briefly, the aim of this project is to build a small-scale, physical electric grid with battery storage, in order to analyze how batteries can help with peak shaving, increase the efficiency of the grid and provide it with more stability. A simple visualization of the overall project is represented in Figure 4.

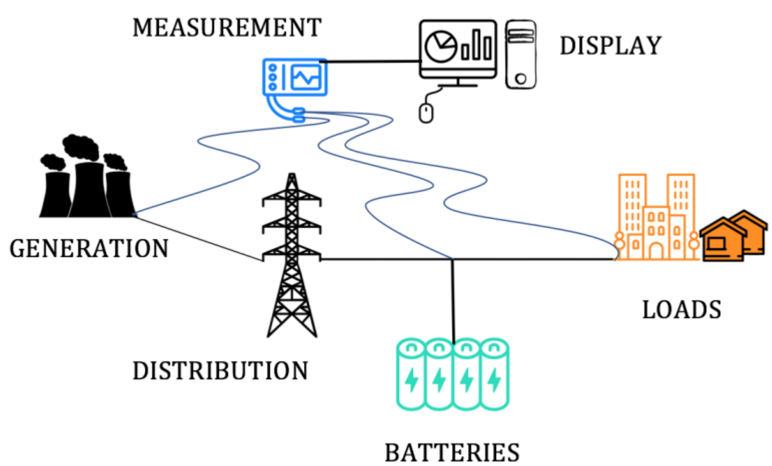


Figure 4. Visualization of the mock power grid

The project can be divided into four main subsystems: the generation and distribution, the battery installation system, the variable load, and the data acquisition and display.

-The generation system will model the generation power plants of BELD using a Variac transformer, connected to the wall outlet. Next, voltage will be stepped up and then stepped down to feed the loads, modeling the transmission and distribution lines.

-The main function of the variable load system is to model the electricity demand curve of the grid, modifying the total resistance of the circuit.

-The battery installation system will either charge or discharge electrical power to the loads. It will provide power to the grid in times of peak demand and will charge during times of low demand.

-Finally, the data acquisition and display system, will gather data in the important spots of the grid (generation, batteries and loads) for further analysis and will feature live characterization readings.

The overall project will be put into a compact container so that it can be easily moved for further testing. Although this document focuses on modeling the electric demand curve of the mock power grid, we will briefly review the different subsystems of the project and their operation.

CHAPTER II: STATE OF THE ART

2.1. Storage Technologies

After highlighting the importance of energy storage in the last section, this chapter goes through different storage technologies, their working principle, main applications and state of development.

The far-reaching road to the ideal energy storage technology started in 1800, when the Italian physicist Alessandro Volta invented the first energy storage system in the form of batteries. Since then, and until a few years ago, little was done to invent different and more effective systems.

Currently, there are several promising technologies. Some of the largest energy storage technologies are owned and/or operated by energy suppliers. Smaller ones are primarily related to energy users. Some of them are already implemented and others are still under development to increase their capacity, reduce their charging time and increase their lifetime while reducing their maintenance costs.

Energy can be stored in a wide variety of forms. This chapter covers potential, kinetic, thermal, chemical and electrical energy storage methods, which are the most important storage mechanisms for the major areas of application.

2.1.1. Potential energy storage

Pumped hydropower and compressed-air energy storage (CAES) are the two main storage systems that employ potential energy.

Pumped hydropower

In pumped hydropower systems, the dominant mean of electricity storage for daily load shifting, a reservoir containing water at an elevated location represents stored potential energy that can be recovered by lowering it in the earth's gravitational field.

In a typical cycle, when electric capacity exceeds demand during an off-peak period, the generator of the hydroelectric system runs as a motor, reversing the rotation of the turbine and the flow of water. The excess electrical power is used to pump water up to the storage reservoir. During high-demand periods, the water flows downward through the hydro turbine generator to produce additional power as needed.

Pumped hydro facilities are also used for spinning reserve and operating reserve applications. They typically produce hundreds of megawatts for up to 10 hours.

One of its major advantages is that the flow through the turbines can be turned on and off in response to the current need. This is not instantaneous, however, there is a startup time for the turbines of the order of a few minutes.

The main disadvantages are the high cost of the dams and the fact that the development of additional pumped hydro facilities is very limited, due to the scarcity of further cost-effective and environmentally acceptable sites. Countries with more mountainous terrains have an obvious advantage.

Whereas the efficiency of large-scale water-driven turbines can be quite high, even over 95%, the efficiency of the dual cycle reversible storage system typically is about 80%. There are other losses, of course, such as water evaporation from one or both of the reservoirs, leakage around the turbine, and losses due to friction of the moving water.

The list of countries with more pumped hydropower capacity is led by China, with 32 GW, followed by Japan (28.3 GW), United States (22.6 GW) and Spain (8 GW) [8].

Compressed-air energy storage

CAES systems utilize the compressive energy associated with pressurized air contained either in a closed underground reservoir consisting of natural or mined rock or salt cavities or in porous aquifers that are geologically contained. The large compressibility of air is utilized to produce power by expansion in a gas turbine at a relatively high efficiency. Charging of the reservoir is accomplished by high-efficiency compression, typically using the turbine expander operating in reverse.

Although currently there are only a few CAES installations operating worldwide (there were only two CAES systems in operation in 2011, one in Germany and one in Alabama, US), their potential is large, particularly if new lower-cost technologies appear for mining cavities in rock and salt. Several other CAES systems are in various stages of development at this time.

2.1.2. Kinetic energy storage

The most common form of kinetic energy storage is achieved using mechanical flywheels, with rotational energy being transferred to and from the device. A flywheel is essentially an electric machine with three distinctive features: high speed, large inertia and minimum losses. When energy needs to be stored, the machine operates as a motor and the energy is stored in its rotating mass, which can be a solid cylinder or disk, in the form of kinetic energy. When the energy is needed, the machine operates as a generator converting the stored kinetic energy into electrical energy.

The amount of stored energy increases if the mass of the rotor increases, the radius of the rotor increases, or the speed of rotation increases. Therefore, the flywheel has a heavy mass and is rotating at very high speeds (typically 20,000-100,000 rpm). Flywheels can have a wide variety of shapes. One of the most common optimization strategies is to use a disk design in which the stress is the same in every point.

The main disadvantage of the flywheel system is safety. The high speed may increase the tensile strength of the rotor beyond its limit and this may shatter the rotor causing an explosion. Also, failure in the magnetic bearing can cause the rotor to hit the enclosure causing explosion. This is why flywheel systems are often placed inside strong containment or are buried in ground vaults. In addition, other issues that should be taken into account are the frictional losses associated with the rotation of the flywheel itself and the need to add and extract power at high efficiency over a range of rotational speeds.

Flywheels are a very good solution to applications that involve handling high power, and therefore energy transients.

2.1.3. Thermal energy storage

There are two primary mediums used for thermal storage. One involves sensible heat stored in the heat capacity of single-phase materials by changing their temperature, while the other involves the latent heat associated with changing the phase of a material at a fixed temperature and pressure.

Sensible heat involves adding energy to a material by simply heating it to a higher temperature. This added energy is the product of the specific heat and the temperature change. The sensible heat can be transferred to another, cooler material, or to the environment, by radiation, convection or conduction. Therefore, this is a method for storing energy in the form of heat, and transferring it again.

One of the applications of this type of storage is controlling the temperature in living or working spaces. In some cases, the amount of storage material can be quite large, and this results in the use of relatively simple and inexpensive materials. Each of them has some advantages and some disadvantages. Some of the material characteristics that should be considered are the specific heat of the material, the cost, the range of temperatures and the thermal conductivity.

The main disadvantage of this method is that there are always losses, no matter how well the system is insulated. The rate of heat loss to the surroundings is proportional to the surface area and also to the temperature difference, but the total amount of thermal energy storage is proportional to the volume of any storage container.

Latent heat storage involves phase transitions with no change in the chemical composition. Latent heat is absorbed or supplied at constant temperature, rather than over a range of temperatures, as it is with sensible heat. Isothermal latent heat systems are generally physically much smaller than sensible heat systems of comparable capacity.

Latent-heat storage systems have some advantages, in that thermal energy can be supplied or removed at essentially constant temperature, which is desirable for many applications.

A useful application of thermal energy storage is large-scale solar installations that use molten-salt storage systems to extend the daily dispatch time. In addition, there are many end-use applications in which thermal storage is the most appropriate and economic option. Some examples are solar water heating, or making ice using off-peak electricity for refrigeration-based building air-conditioning systems.

2.1.4. Chemical energy storage

Another type of energy storage involves reversible chemical reactions in which there is a change in the chemical species present. A considerable amount of energy is contained in the chemical bonds that hold atoms in place within molecules. Breaking these bonds selectively, such as during the oxidation of fossil or biomass fuels as they are combusted, can release a large amount of energy at high temperatures.

The proposed application of chemical energy storage that is expected to play a major role in future energy systems is hydrogen. Hydrogen is an important energy carrier, and when used as a fuel, can be considered as an alternate to the major fossil fuels. It has the potential to be a clean, reliable, and affordable energy source, and has the advantage that the product of its combustion with oxygen is water, rather than carbon dioxide or carbon monoxide, which are greenhouse gases.

There are many applications in which hydrogen can be utilized. It has been demonstrated that hydrogen can be used directly in internal reciprocating combustion engines, requiring relatively minor modifications, if it is raised to a moderately high pressure, as well as in turbines and process heaters.

It can also be used in hydrogen/oxygen fuel cells to directly produce electricity. Again, the only product is water. The energy efficiency of fuel cells can be as high as 60%. On the other hand, fossil fuel systems are typically about 34% efficient. When high temperature fuel cells are used, it is possible to obtain electricity and also to use the heat generated in the fuel cell, related to its inefficiency, for heating purposes. This is called cogeneration, and it is possible to obtain total energy efficiencies up to 80% [9].

In addition, hydrogen can have an enormous impact in the transportation sector. Electrically powered vehicles have the advantage that electric motors can have energy efficiencies of about 90%, whereas typical internal combustion engines are about 25% efficient. On the other hand, fuel cells now cost about 100 times as much as equivalent internal combustion engines of comparable power. However, a reduction in cost can be expected with mass production and further development of fuel cells.

Undoubtedly, deploying hydrogen on a large scale, particularly for use in the transportation and building sectors, raises the need to develop infrastructure to produce, distribute and store hydrogen in a safe, economic manner.

2.1.5. Electrical energy storage

There are three major mechanisms for storing electrical energy: electrostatic, electromagnetic and electrochemical. The main technology for each storage mode is supercapacitors for electrostatic energy storage, superconducting magnetic energy storage (SMES) systems for electromagnetic energy, and batteries for electrochemical energy storage.

Supercapacitors

Capacitors store electrical energy in the form of confined electrostatic charges in a device consisting of two conductive plates separated by a dielectric medium. Recovery of the stored energy is achieved by connecting the conducting plates to a suitable load.

Capacitors have the ability to be charged and discharged quickly, on the order of seconds or less, which makes them useful for responding to power interruptions of short duration. Given that the power density of capacitors is inherently large, they have been used for mitigating power interruptions for many years in stationary utility applications over a range of scales. However, the specific energy densities of early generation capacitors were low, making them unattractive for energy storage applications. The appearance of "supercapacitors" that utilize advanced materials that greatly increase the effective surface area of the capacitor's electrodes per unit mass has changed performance metrics in a manner that results in significant gains in energy storage capacity. They are attractive for regenerative braking and other power needs in electric and hybrid vehicles.

This storage mechanism is most applicable to situations in which there is a requirement for the storage of modest amounts of energy under very transient conditions, for relatively short times and sometimes at high rates. Such applications, therefore, emphasize fast kinetics and high power, rather than the amount of energy that can be stored. A very long cycle life is also generally very important. However, the amount of energy that can be stored by supercapacitors is generally much less than what can be stored by chemical and electrochemical methods.

Superconducting magnetic energy storage (SMES)

In SMES systems, electro-magnetic energy is stored and retrieved directly and with negligible losses using direct current owing through superconducting coils to generate a magnetic field.

Resistive losses in the SMES unit are low, as are other losses associated with required AC to DC conversion rectifier, inverter, control system and general power conditioning. To achieve superconductivity conditions will require some level of cryogenic refrigeration to maintain low temperatures. An additional feature that must be taken into account is that superconductor materials have to be maintained below a material-specific critical temperature. The maintenance of the required low temperature requires also energy. In addition, superconducting materials lose their superconductive property if the value of the surrounding field is above the critical field.

SMES has many attractive features for utility-scale electric power applications. In principle, large amounts of energy can be stored for long periods and utilized when needed at extremely high rates with overall cycle efficiencies of 95% or more. One of the disadvantages of such large units is their high total capital costs. To offset this, new technology is under development that could lead to micro-SMES units that would be less capital-intensive.

Although SMES technology was demonstrated at a small scale in the northwestern US and micro-SMES units became available in 2001, SMES is not yet ready for widespread development. Long-term performance testing and a number of economic issues need to be resolved.

Batteries

In batteries, electrical energy is stored in the electrodes in the form of chemical reactants that have a strong affinity for one another, there is a difference in chemical potential between the electrodes. However, these electrodes are separated by an ionically conductive medium, the electrolyte, which is usually a liquid solution, solid conductive polymer or gel, or ceramic host media. Because the electrolyte acts as a filter that allows the passage of ionic, but not electronic species (is an electronic insulator), chemical reaction between reactants in opposite electrodes can occur only if there is a path for electrons to go. Then, a reduction/oxidation (redox) reaction takes place at the electrode/electrolyte interfaces. One reaction involves electron production (oxidation at the anode) and the other reaction involves electron consumption (reduction at the cathode).

The intensity of the driving force for the reaction is expressed as the voltage, and the rate at which the reaction can proceed is expressed by the current. Since such reactions necessarily produce a DC current, for utility applications it is normally converted to AC form using a suitable power inverter. During charging, the action of electric current forced through the battery converts the products of the spontaneous discharge reaction into the original reactants.

Batteries can be used for a very wide range of applications, from assisting the very large-scale electrical grid down to tiny portable devices used for many purposes. Some of their applications are: electric and hybrid-electric vehicles, aerospace applications such as satellites, launchers or aircraft; load-leveling, renewable energy storage and portable small-to-medium size electronic devices.

Two of the most recent applications worth to mention where batteries play a leading role are the Vehicle-to-Grid and Tesla Powerwall. The Vehicle-to-Grid is a system in which plug-in electric vehicles, such as battery electric vehicles return electricity to the grid during the peak demand hours.

On the other hand, Tesla Powerwall is a rechargeable lithium-ion battery used for home energy storage, which stores electricity for solar self-consumption, time of use load shifting, backup power, and off-the-grid use. During the day, solar panels produce more energy than what is consumed by a typical home. Tesla Powerwall stores this excess of energy and allows the use of it when needed.

The following tables and figures illustrate important characteristics of the energy storage technologies described above, such as maturity, energy and power ranges, overall efficiency and capital cost.

Table 1 compares schematically the characteristics of the main energy storage technologies.

Energy Storage Technology Characteristics

Characteristic	Pumped Hydro	CAES[a]	Flywheels	Thermal	Batteries	Supercapacitors	SMES[b]
Energy range	1.8×10^6–36×10^6 MJ	180,000–18×10^6 MJ	1–18,000 MJ	1–100 MJ	1,800–180,000 MJ	1–10 MJ	1,800–5.4×10^6
Power range	100–1,000 MW_e	100–100 MW_e	1–10 MW_e	0.1–10 MW_e	0.1–10 MW_e	0.1–10 MW_e	10–1,000 MW_e
Overall cycle efficiency[c]	64–80%	60–70%	~90%	~80–90%	~75%	~90%	~95%
Charge/discharge time	Hours	Hours	Minutes	Hours	Hours	Seconds	Minutes to hours
Cycle life	≥ 10,000	≥ 10,000	≤ 10,000	>10,000	≤ 2,000	>100,000	≥ 10,000
Footprint/unit size	Large if above ground	Moderate if under ground	Small	Moderate	Small	Small	Large
Siting ease	Difficult	Difficult to moderate	N/A	Easy	N/A	N/A	Unknown
Maturity	Mature	Early development	Early development	Mature	Lead-acid mature, others under development	Available	Early R&D stage, under development

Sources: Jensen and Sorensen (1984); Schoenung et al. (1996); Boes, Goldstein, and Nix (2000).
[a] CAES = compressed-air energy storage.
[b] SMES = superconducting magnetic energy storage.
[c] For 1 full charge-discharge cycle.

Table 1. Energy Storage Technology Characteristics. [3]

Figure 5 shows the characteristic times for energy storage technologies. Both flywheels and batteries have the widest range of times, which makes possible their utilization in a larger number of applications, including power quality applications, stability applications, enhanced load following, load leveling, peak reduction, spinning reserve, reliability and renewable energy.

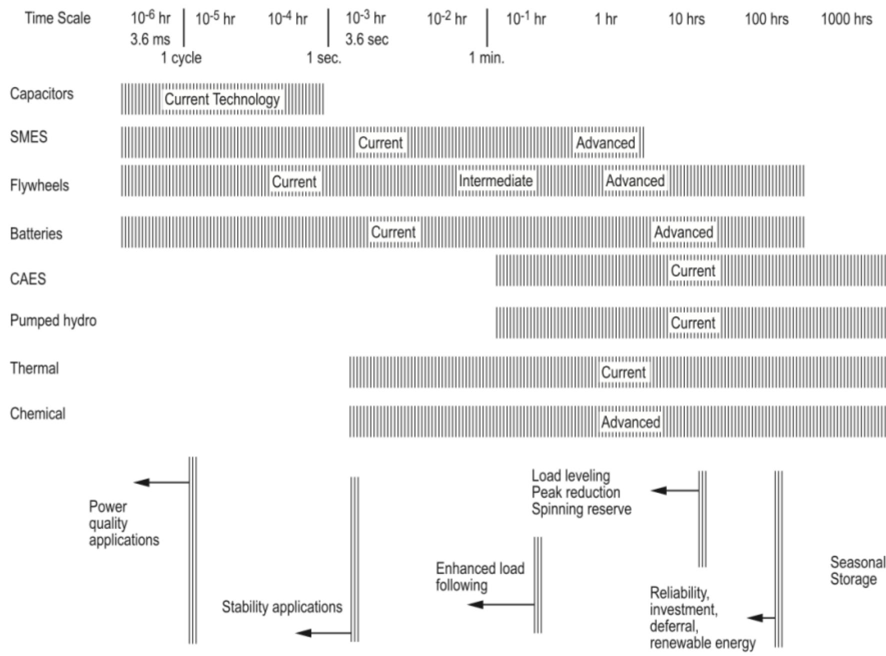


Figure 5. Characteristic times for energy storage. [3]

Figure 6 shows the power density versus the energy density of different storage technologies.

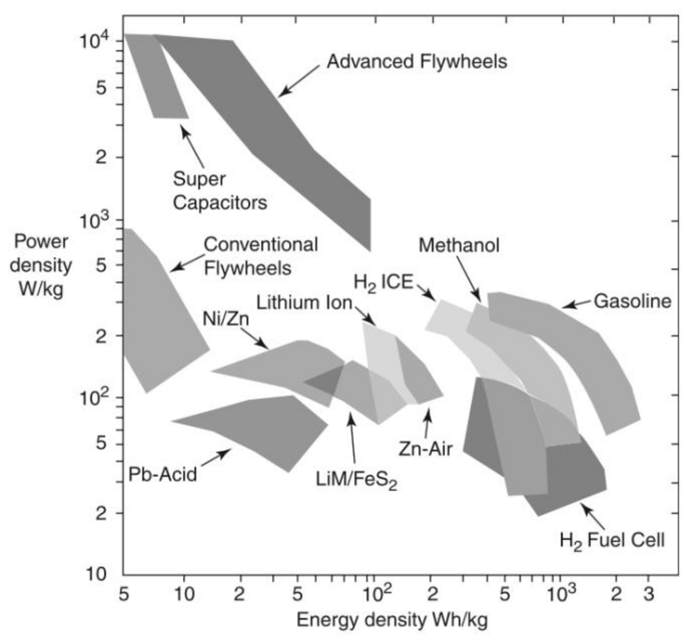


Figure 6. Power density and energy density of main storage technologies. [3]

Table 2 shows capacity and capital cost ranges for electrical storage applications. As it can be observed in the table, batteries are the more economic storage technology in terms of cost per kW.

Estimated Capital Costs for Representative Energy Storage Systems for Supplying Electric Power

System	Typical Size Range (MW_e)	$/$kW_e$	$/$kW_e$h
Pumped hydropower	100–1000	600–1000	10–15
Batteries:			
Lead-acid	0.5–100	100–200	150–300
Nickel–metal hydride	0.5–50	200–400	
Lithium ion	0.5–50	200–400	
Mechanical flywheels	1–10	200–500	100–800
Compressed-air energy storage (CAES)	50–1,000	500–1,000	10–15
Superconducting magnetic energy storage (SMES)	10–1,000	300–1,000	300–3,000
Supercapacitors	1–10	300	3,600

Sources: Turkenburg et al. (2000); Schoenung et al. (1996); Boes, Goldstein, and Nix (2000).

Table 2. Estimated Capital Costs for Representative Energy Storage Systems for Supplying Electric Powers. [3]

Choosing a specific energy storage technology highly depends on the application. For instance, for transportation applications, low power and energy density are required. On the other hand, for utility or building applications, the size or weight of the storage system is usually not a limiting factor.

Nonetheless, there are several common performance factors that apply for all applications. These include:

-life time: maximum number of charge and discharge cycles,

-overall efficiency,

-depth of discharge per cycle,

-cost per unit of power or energy stored.

The most popular and technologically matured storage option, batteries, is the main subject of this project.

2.2. BATTERIES FOR UTILITY GRID APPLICATION

There are several types of large-scale energy storage applications that have unique characteristics, and therefore require storage technologies that are significantly different from the smaller systems that we are used to. These include utility load leveling and solar and wind energy storage. As it has been illustrated in the first chapter, they play critical roles in the transition away from fossil fuels' dependence.

The crucial factors that need to be taken into account in large and complex systems are the cost per unit energy storage (per kWh), the efficiency of the energy storage cycle, that has a large influence upon operating costs, and the lifetime of the critical components. Investors generally expect large systems to be in operation for 25 years or more. In addition, special attention needs to be paid to safety matters.

It has been demonstrated, thanks to a significant number of projects described in Table 3, that battery storage systems effectively stabilize the electric grid and aid renewable integration by balancing supply and demand in real time. This type of energy storage acquires special importance in densely populated urban areas, where traditional storage techniques such as pumped hydroelectric energy storage and compressed-air energy storage are often not feasible.

The principal roles played by battery energy storage in utility applications are the following [10]:

1) Leveling the load, providing backup electricity, and ensuring grid safety and stability. Batteries can help balance electricity supply and demand on several time scales (seconds, minutes or hours).

2) Improving power quality via frequency/voltage regulation. Fast-ramping batteries are particularly well suited to help maintain the grid's electric frequency on a second-to-second basis.

3) Diversifying generation portfolios, reducing expensive fuel consumption, and promoting renewable penetration.

4) Enhancing the safety and reliability of power supply. Batteries can provide back-up power during outages or support the grid reliability. In addition, they can help keep power flowing when a microgrid is temporarily electrically separated from the rest of the grid.

5) Increasing the efficiency of electricity generation and transmission, and therefore deferring expansion of the power system infrastructure. Local pockets of growing electricity demand sometimes require building expensive new grid infrastructure which is very costly. Installing batteries at strategic locations, at much lower cost, enables utilities to manage growing demand while deferring large grid investments.

6) Lowering the operational cost for power generation while saving electricity expenses for end customers. Shifting portions of electricity demand from peak hours to other times of the day reduces the amount of generation capacity needed to be online, which results in lower wholesale electricity prices. In addition, end-use consumer demand charges can be reduced by using on-site energy storage during peak demand times.

7) Mitigating system fluctuations at low and high frequencies

8) Accelerating the synergy between electric vehicles (EVs) and the electric grid

2.2.1. Battery storage in the world

Although operational electrochemical storage, with 1.64 GW installed, only represents 0.96% of the world storage capacity (171.05 GW) and 0.028% of the world installed capacity (5699.4 GW) [11], battery storage has grown significantly over the last few years.

Electrochemical storage has surpassed the 1.5 GW mark from a few hundred megawatts just a few years back. When comparing the installed capacity from 1996 to 2018 in Figure 7, it can be realized that installations of battery storage are growing sharply and their importance has increased thorough the last decade.

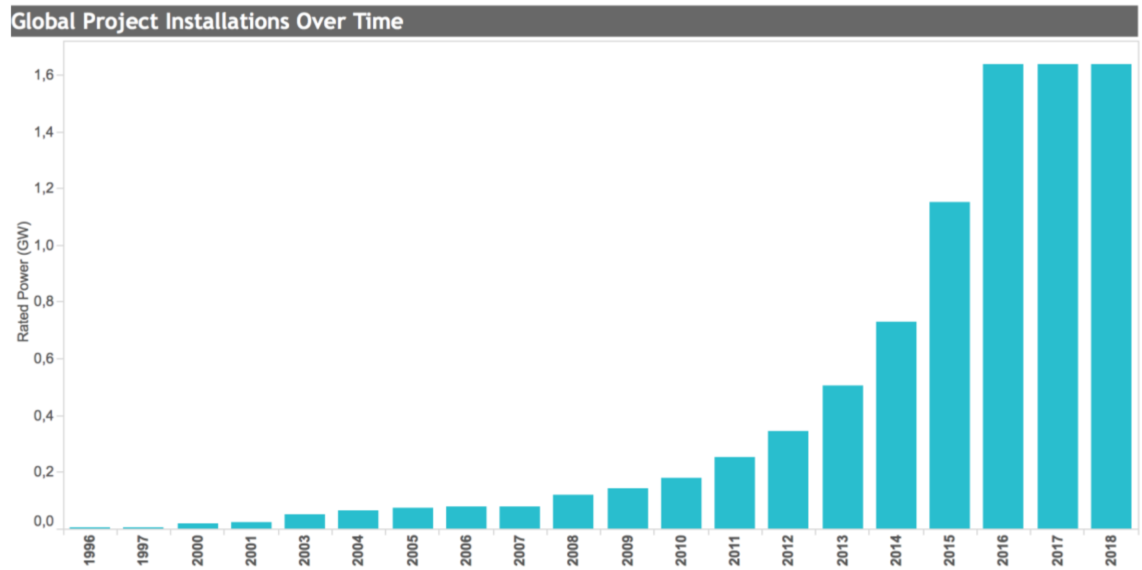


Figure 7. Global electrochemical operational project installations over time. [11]

Electrochemical energy storage technologies are mainly concentrated in North America, East Asia and Europe. In total, around 85% of installed projects exist in these regions.

The leading countries in electrochemical energy storage installed are the United States with 36.6% of the total electrochemical energy storage installed in the world, South Korea, with 17.7%, Japan, with 15.5% and Germany with 7.4% [11].

This uneven distribution of projects around the world means that there is significant room for growth outside of the main markets. The opportunity is particularly pronounced in many developing countries where power systems are less advanced.

Table 3 summarizes the ten biggest battery installations in the world. Some of them are already online while others are still under construction and are expected to be functioning in the next few years.

Project Name	**Location**	**Energy**	**Type of Battery**	**Year of installation**
Dalian VFB – UET /Rongke Power	China	200MW/4h	Vanadium Redox flow	Expected to come online in 2020
Hyundai & Korea Zinc energy storage system	South Korea	150MW	Lithium Ion	Expected to come online in 2018
Long Beach Energy Project	California, US	100MW/4h	Lithium Ion	Expected to come online in 2020
Tesla Powerpack Project	South Australia	100MW/1.29h	Lithium Ion	2017
Notrees Wind Energy Storage Project	Texas, US	36MW/0.67h	Lead acid	2013
Santa Rita Jail Smart Grid	California, US	32MW/0.25h	Lithium-Ion	2012
Battery Energy Storage System (BESS)	Alaska, US	27MW/0.25h	Nickel-Cadmium	2003
Primus Power Wind Firming Energy Farm	California, US	25MW/3h	Zinc chlorine redox flow	2012
Anchorage Area Battery Energy Storage System	Alaska, US	25MW/0.6h	Lithium-Ion	2012
Angamos	Chile	20MW/0.33h	Lithium-Ion	2011

Table 3. Battery energy storage systems for grid applications. [10]

2.2.2. Requirements for the ideal battery

For batteries to be effectively used in high power applications, they must have ideally several key features:

- Slow loss of charge: The battery needs to maintain its charge for extended period of time.
- Cost effective: Batteries are still expensive to operate and some are expensive to maintain.
- High charge/discharge efficiency: Losses during the charging and discharging processes need to be minimized. Efficiencies higher than 90% is attainable.
- Long cycle life: Durability and long cycle life are very important to reduce the overall cost.
- No memory effect: Charging a partially charged battery should not reduce the amount of energy that can be extracted from the battery.
- Safe to operate: Some batteries with low charging/discharging efficiencies generate high temperatures. Other batteries need to reach high temperatures to start their functions. These high temperatures can cause overheating problems or even explosions.

2.2.3. Main battery chemistries for utility grid applications

Unfortunately, our world is not ideal and although significant improvement has been made in the batteries field, there is still much to do.

Rechargeable batteries are today's most widespread electrical energy storage devices. Representative commercial-scale technologies currently used in the electric power industry include lead-acid batteries, nickel-metal-hydride (NiMH) batteries, lithium-ion (Li-ion) batteries, sodium sulphur (NaS) batteries and vanadium redox flow batteries (VRBs). These technologies normally exhibit different characteristics, with various sizes and built-in chemical components. Table 4 summarizes the main attributes of each.

Type	Lead-Acid	NiMH	Li-ion	NaS	VRB
Energy density (Wh/kg)	25-30	60-120	75-200	150-240	10-30
Power density (W/kg)	75-300	250-1,000	500-2,000	150-230	85-50
Cycle life (100% depth of discharge)	200-1,000	180-2,000	1,000-10,000	2,500-4,000	>12,000
Capital cost (US$/kWh)	100-300	900-3,500	300-2,500	300-500	150-1,000
Round-trip efficiency (%)	75-85	~65	85-97	75-90	75-90
Self-discharge	Low	High	Medium	-	Negligible

Table 4. Main attributes of representative batteries. [10]

Li-ion and VRB have experienced remarkable advances over recent years. Until 2014, the NaS battery was the leading option in the electric power sector. However, since then, the battery storage landscape has been gradually shifting from the NaS battery to its counterparts, Li-ion and redox flow batteries. This is due to the significant performance improvements and cost reductions achieved by these batteries. Particularly, the cost of Li-ion batteries is expected to fall to $100/kWh in 2025 (in 2010, it was $1000/kWh, ten times higher) [12]. The installed Li-ion battery capacity is projected to increase rapidly, so it is expected to become the dominant battery storage technology for the future. Flow batteries also show increasing popularity in utility-scale energy storage.

The main battery chemistries for utility grid application are the following:

-Lead acid battery

The lead-acid battery is the oldest rechargeable battery. In this battery, the positive and negative electrodes are separately made up of lead dioxide and metallic lead, which are immersed in a diluted sulphuric-acid electrolyte. There are two main types, flooded lead-acid and sealed valve-regulated lead-acid (VRLA) solutions.

The main advantages of using lead-acid batteries are energy efficiency, low self-discharge rate, and low up-front cost. Nonetheless, their further promotion for commercial use suffers from some obvious technical drawbacks, including low depth of discharge (<20%), low life cycle, low energy density, and slow charging rate.

-NiMH battery

Work on the commercialization of small metal hydride electrode cells began in Japan's Government Industry Research Institute laboratory in 1975 [13]. The active metal of the positive electrode in the charged state is nickel oxyhydroxide. The negative active material, in the charged state, is hydrogen in the form of a metal hydride. This metal alloy is capable of undergoing a reversible hydrogen absorbing-desorbing reaction as the battery is charged and discharged.

Its main advantages are its sealed construction, minimal environmental problems, rapid recharge capability, long cycle life and long shelf life in any state of charge.

It suffers from several technical downsides, such as high self-discharge rate, limited service life and low Coulombic efficiency (about 65%). Moreover, its ability to tolerate fast charging and overcharge is very low. Particularly during fast charging, massive amounts of heat may be generated, and hydrogen buildup may cause cell rupture, leading to considerable capacity decay.

-Li-ion battery

The Li-ion battery is an advanced rechargeable battery first commercially developed by Sony in the early 1990s [10]. Lithium-ion batteries are comprised of cells that employ lithium intercalation compounds as the positive and negative materials. As a battery is cycled, lithium ions exchange between the positive and negative electrodes.

Compared to other types of batteries, Li-ion batteries have the advantages of high energy density, high efficiency, long cycle life, environmental friendliness, broad temperature range of operation, low self-discharge rate, rapid charge capability, high rate and high-power discharge capability and no memory effect.

Some of the challenges Lithium-ion batteries face are safety concerns, degradation at high temperature, need for protective circuitry, capacity loss or thermal runaway when overcharged, venting and possible thermal runaway when crushed.

Commercial applications of Li-ion battery technologies are expected to require a substantial price reduction before they fit into large-scale utility applications widely.

-NaS battery

The NaS battery was pioneered by the Ford Motor Company with the goal of powering early-model electric cars in the 1960s [14]. This battery is composed of a molten sulphur anode, a molten sodium cathode and solid beta alumina ceramic electrolyte. In the course of discharge operation, sodium ions move through the electrolyte and merge with the sulphur to form sodium pentasulphide. Because this compound is immiscible with the remaining sulphur, a two-phase liquid mixture appears in the cathode. When the available free sulphur is completely consumed, single-phase sodium polysulphides are gradually generated with increasing sulphur content. The reversed process corresponds to charge operations.

The intriguing potential of the NaS battery comes from its ability to provide high energy density and round-trip efficiency (70-90%), long lifetime, and deep, fast discharge. Its ability to work at high temperatures allows operation within some hot, harsh environments.

The main disadvantages are the high temperatures, which are quite dangerous, as the battery can rise up to 2,000ºC. In addition, if pure sodium is exposed to air and moisture, it will spontaneously burn, and if the electrolyte is broken, it can lead to short-circuits and exothermic reactions.

-Redox Flow battery

The modern RFB was developed by the U.S. National Aeronautics and Space Administration in the 1970s [13]. A RFB is a type of energy storage device consisting of separate power and energy modules. The power module is the stack, which provides energy conversion between chemical and electrical energy. The stack typically comprises multiple cells to meet power demand, each with positive and negative half-cells separated by an ion-exchange membrane. The electrolyte tanks constitute the energy module, where chemical energy is stored in the liquid electrolyte. Energy conversion occurs when liquid electrolytes are pumped from the tanks to cells, where the electrochemical reaction happens in the electrodes. The ion-exchange membrane prevents the electrolytes for mixing and transports charged ions to from an inner pathway between the positive and negative half-cells.

Compared with other rechargeable batteries, commercial rapidly deployable batteries (RDBs) currently have lower energy density. However, they show several distinct advantages.

RFBs show several distinct advantages in comparison with other rechargeable batteries, such as the decoupling between power and energy capacity, which makes these batteries easy to scale up, long cycle span, excellent safety and reliability and very high response speed. However, they have low energy density.

CHAPTER III: PROJECT DEFINITION

This chapter covers the objectives and requirements of the project, as well as the work methodology.

3.1. Objectives And Requirements

Several objectives were established in order to be able to estimate afterwards the accomplishments of the project.

The main objectives of the project are the following:

- Build a physical small-scale mock grid with battery storage installed
- Compare different battery chemistries in terms of efficiency, lifetime, and other significant characteristics
- Show how the use of battery storage can reduce costs with peak-shaving and help with the reliability of the grid
- Ultimately, either this project or future continuations of it, will help determine the optimal battery chemistry for BELD.

In order to meet these objectives, some engineering requirements must be satisfied. These have been classified into four different categories:

Electrical requirements:

-The mock grid will work in AC

-The grid frequency must be 60 Hz ± 5% (standard grid frequency in the US)

-The transmission and distribution lines must be modeled by stepping up and down the voltage

-The electricity demand will be modeled using some type of variable resistors

-The variable load needs to be able to represent different demand curves to test the batteries in different scenarios.

-Different battery chemistries should be tested

-DC sources should be converted to AC

-The initial conditions of the system should be replicated for each experiment with different battery chemistries

-The inverter must be bidirectional

Data acquisition and display requirements:

-The overall grid should be monitored to know the current, voltage and power in the generation, batteries and loads.

-Current, voltage and power should be displayed in real time in significant spots of the grid.

-The data will be automatically displayed after a test.

-Data of each experiment must be stored for further analysis

Physical requirements:

-The project will be a physical small-scale mock grid

-The interface needs to be user-friendly

-The overall project should be put into some type of enclosure

-The utility grid model should be able to fit through a standard door

Safety requirements:

-The voltage must range between 0-30V ± 5%

-The maximum current in the grid should not exceed 3A.

-Some type of electrical security system should be implemented

3.2. Work methodology

The conceptual approach to solve our customer's problem is a physical representation of the grid as well as performing empirical experiments to determine the best battery chemistry regarding discharge, reliability and overall efficiency of the charge and discharge processes.

However, this was not the only option. Initially, we thought of using computer simulation to determine the most efficient and cost-effective battery configuration. We considered the alternative of running computer simulations to meet the objectives of the project. We would have used programs such as PSS/E (Power Transmission System Planning Software) developed by Siemens. To analyze the possible transitional regimes, we would also have modeled the system in a Simulink workspace.

This alternative was abandoned as our customer had a physical representation in mind when he decided to sponsor our project. Furthermore, as the physics involved in a system this complex are not straightforward we decided that the best alternative was to try the concepts in a real environment so we would not state assumptions that could affect the results significantly.

As previously mentioned, our final approach is a physical representation of the power grid. The project was divided into four main lines of work: Generation, Batteries, Variable load and Data acquisition and display. The tasks in these subsystems were accomplished simultaneously. When the four subsystems were completed, the whole system was integrated and tested.

Generation

Task 1. Generation

A Variac, variable AC power transformer 0-130V shall be connected to the wall. It shall provide 10 V_{rms} to the grid.

Task 2. Transmission and distribution

A step-up transformer should be connected after the Variac. It shall have a ratio 1:5, and step the voltage up to 70.7 V_{pp}. Another transformer should be connected after this last one, with a ratio of 1:5. It shall step down the voltage again to 10 V_{rms}. These transformers should model the transmission lines of Braintree electric grid, and provide 14.14 V_{pp} ± 5%, 60 Hz ± 5%.

Battery Installation

Task 3. Bidirectional DC-DC converter

A bidirectional DC-DC converter shall be designed and tested. It shall limit the amount of current entering the battery. The design should be tested with different battery configurations.

Task 4. Bidirectional AC-DC converter

A bidirectional AC-DC converter shall be designed, fabricated and tested. It shall convert the AC voltage of the grid (10 V_{rms}) to DC. A filter should be placed after the transformer.

Task 5. Battery Control System

A control system for the batteries shall be designed, implemented and tested. It shall control the MOSFET's switching frequency for both the AC-DC converter and the DC-DC converter. A microcontroller with fast pulse width modulation (PWM) should be used.

Task 6. Integration

Battery installation, bidirectional DC-DC converter, bidirectional AC-DC converter and control system shall be assembled.

Task 7. Testing

The complete system including battery installation, bidirectional DC-DC converter, bidirectional AC-DC converter and control system shall be tested with different battery configurations. Firstly, it should be tested with a single 3.7V battery. Then, it should be tested with other possible configurations, such as two 3.7V batteries in series, two batteries in parallel or a 2x2 array configuration.

Variable load

Task 8. Scaled-down demand curve

A typical summer demand curve in New England should be scaled-down to appropriate voltage and current for the grid.

Task 9. Switching control system

A switching control system shall be designed and implemented. A microcontroller should control the switching times of the TRIACs, using fast pulse width modulation (PWM) in order to achieve the average resistance needed.

Task 10. Power load testing

The circuit should be tested. The equivalent resistance shall model the typical scaled-down summer demand curve of New England.

Task 11. Power load PCB design

A printed circuit board for the power load shall be designed and fabricated using the software Altium.

Data acquisition and display

Task 12. Voltage measurement

A circuit able to measure the current shall be designed, implemented and tested. The read values shall be saved using a microcontroller. The circuit should be able to measure the current in important spots of the grid: generation, batteries and loads, with a maximum error of ± 5%.

Task 13. Current measurement

A reliable circuit able to measure the current shall be created, implemented and tested. A current sensor shall be used to measure the current, and a microcontroller should save the read values. The circuit shall measure the current in every spot of the grid: generation, batteries and loads, with a maximum error of ± 5%.

Task 14. Power measurement and display

A code calculating the power based on the voltage and current measures shall be programmed in a microcontroller. A display of the power, voltage and current in real time in different spots of the system (generation, batteries and loads) shall be implemented.

Task 15. Voltage and current sensors PCB design

Printed Circuit Boards shall be designed and fabricated for both voltage and current sensors using the software Altium.

Final integration

Task 16. Generation and loads

Firstly, the variable load shall be integrated with the generation and distribution system.

Task 17. Data acquisition and display system

Next, the data acquisition and display system should be integrated with the grid.

Task 18. Synchronization circuit

A synchronization circuit should be designed, implemented and tested to connect the output voltage of the DC-AC converter to the grid.

Task 19. Batteries

The battery installation system should be integrated with the grid, using the synchronization circuit.

Testing

Task 20. System testing

An in-depth analysis should be made to figure out which battery installation results optimal (most efficient and cost effective) for Braintree. Different battery chemistries shall be tested: Lithium-Ion, Lead Acid and Nickel Cadmium. Different battery configurations should be tested. The analysis should include how these batteries can contribute to peak-load-shaving and a comparison between the characteristics of the different battery chemistries such as rate of discharge or lifetime.

CHAPTER VI: PROJECT DEVELOPMENT

This chapter goes through the significant research, modifications and improvements in each subsystem of the project, until the final touch. The components used, their specific characteristics and operating mode will be explained. Special detail will be made when describing the variable load subsystem.

Figure 8 shows the detailed block diagram of the project. As stated in the introduction chapter, it comprises four main subsystems: the generation and distribution, the variable load, the battery installation system and the data acquisition and display, blue in the figure. In this figure, red and black arrows represent the flow of power, blue arrows indicate the spots of the grid where measurements are taken and green arrows refer to the external connections of the grid.

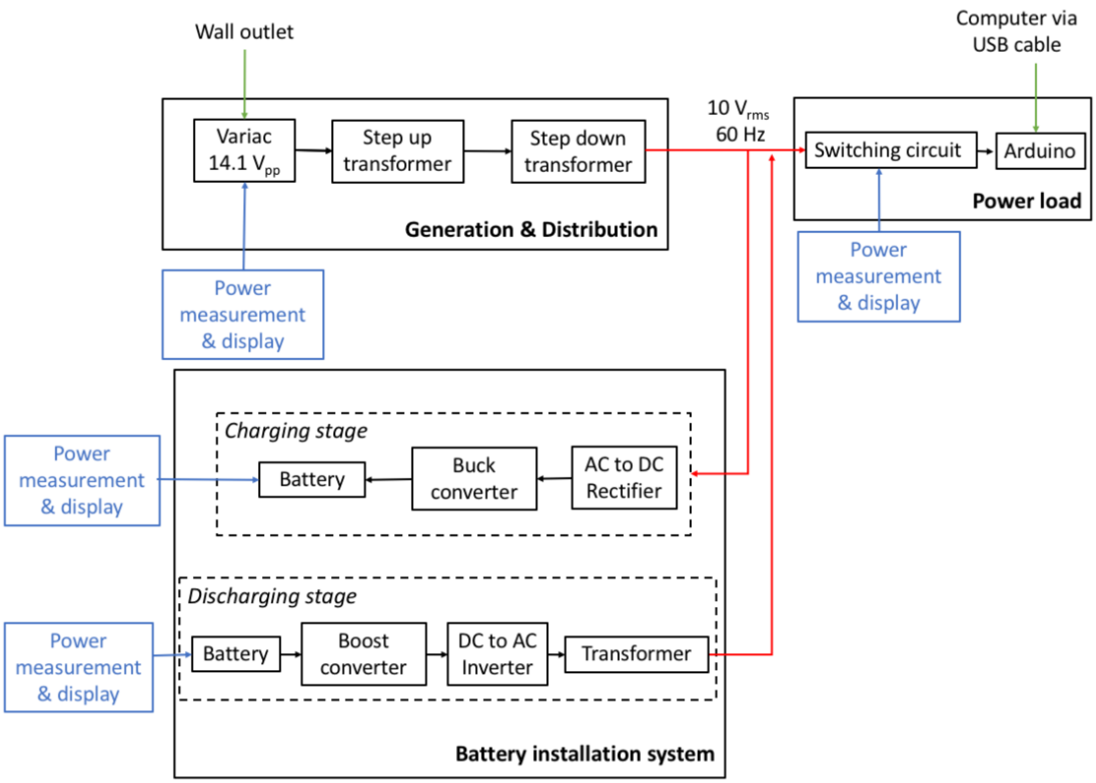


Figure 8. Block diagram of the project

4.1. Generation and Distribution System

The main objective of the generation system is to provide 10 V_{rms} to the grid. In this project only one phase will be used for simplicity. BELD has four generators, of 78 MVA, 23 MVA, 68 MVA and 68 MVA. In total, they sum 273 MVA. In addition, BELD has renewable sources that supply intermittent power to the grid.

The first attempt to model the generation was to use four different motor-generators modeling the four real generators of BELD (base load) and a solar panel or its equivalent circuit modeling the renewable sources (intermittent load).

Focusing on the base load, it was realized that having four different motor-generators highly increased the complexity of the grid and it was not significant for the main objective of the project, which was integrating the battery system. That is the reason why the decision of having just one motor-generator supplying the base load, with its apparent power rating scaled down, was taken. This motor-generator would model the available capacity of the grid.

The principal idea for modeling the generation involved using a DC motor powered by a DC power supply which is connected to the wall outlet, followed by an alternator and a variable transformer. However, this method is highly inefficient. The variable transformer after the alternator was used to fix the voltage of the grid with it.

An additional problem was that the frequency needed to be controllable, in order to put in phase the base load and the solar source, that were modeled separately. One of the requirements of the project was to maintain the frequency constant at 60Hz. In order to achieve this, the speed of the DC motor needed to be controllable. As, in a DC motor, $w_{mec}=K*V_{cc}$, we can control w_{mec} by adjusting V_{cc}. This can be done using a chopper circuit, which works the following manner: a transistor opens and closes at regular time intervals, modifying the average value of the output voltage. This control allows to keep the frequency steady and hopefully the changes in the voltage will be small enough to ignore them. If this was not the case, a voltage controller would be included.

In order to measure the speed and, therefore, the frequency, an optical encoder could be used. When the frequency is over an upper or lower limit, Arduino would send a signal to the chopper and it would change the input voltage of the DC motor.

During the process of stabilizing the speed, the voltage would change with the following equation:

$$U = K \cdot w_{mec} \cdot I_{exc} - x_j \cdot i$$

The original schematic illustrating the intended functioning of the base load generation system is showed in Figure 9.

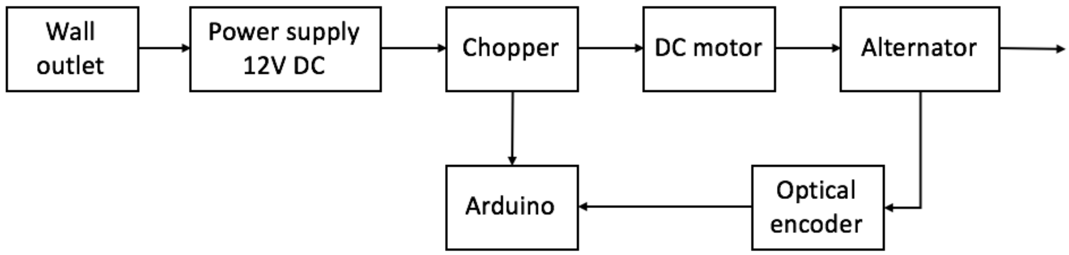


Figure 9. Original schematic of base load generation

On the other hand, the solar source should supply intermittent energy to the grid, modeling the variability of renewable energy such as solar and wind. There were two main options to model the solar source.

Option 1 involved an actual solar panel with a light bulb that changed its light intensity with the help of a microcontroller. The main advantage of this option was its close similarity with a real solar panel.

Option 2 involved modeling the solar panel using an electric circuit. This circuit consisted of a current source in parallel with a diode. The current source models the solar irradiance in the panel.

To account for electrical losses, resistances of the collector traces and the external wires as well as the resistance of the crystal itself are included. The wires and traces can be represented by a series resistance (R_s), while the internal resistance of the crystal can be represented by a parallel resistance (R_p). The series resistance is in the range of a few milliohms and the parallel resistance is in the range of a few kiloohms. Figure 10 shows the complete circuit design that models a solar panel.

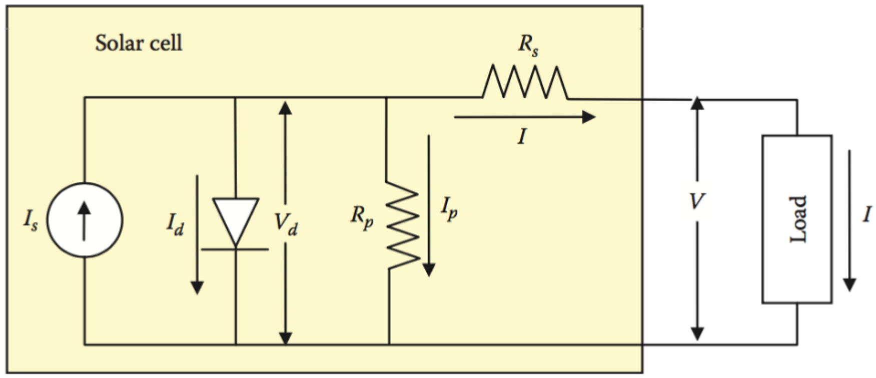


Figure 10. Electric circuit modeling a solar panel. [15]

Although modeling both the base load and the renewable sources was the first idea, this completely changed after the feedback we received. We then realized that the project should mainly focus on three parts: the battery installation, the loads and the data acquisition. Energy generation could be easily simulated and there was no need to build solar panels or to include motor-generators.

Therefore, we shifted to a less complex method, which also satisfied the objective of the power generation. We used a variable AC power transformer 0-130V, 3A (Variac) connected to the wall outlet, which could provide 14.14 V peak to peak to the grid, and simulated all the power plants of BELD.

In order to model the transmission and distribution lines, two Class-2 4VZF5 step-down transformers were used. The secondary winding of one of them was connected right after the Variac and stepped up the voltage to 70.7 V_{pp} (5:1 ratio), modeling the high voltage transmission lines. The primary winding of this transformer was connected to the primary winding of the second step-down transformer. Therefore, the output from the secondary winding of the second step-down transformer is 14.14 V_{pp}, which was the desired voltage for the power lines in the mock grid. Figure 11 illustrates the schematic of the generation and transmission system.

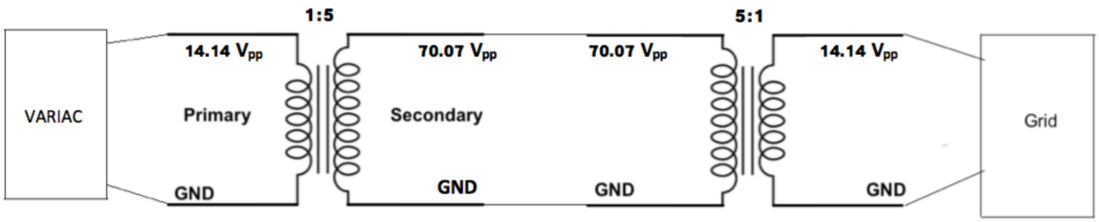


Figure 11. Schematic used to model the generation and transmission system.

The generation system was tested using a Lecroy Wavesurfer Oscilloscope. The frequency of the waveform and the peak to peak voltage after each of the transformers were measured and corresponded to the expected values. Figure 12 illustrates the AC output voltage waveform of the second transformer.

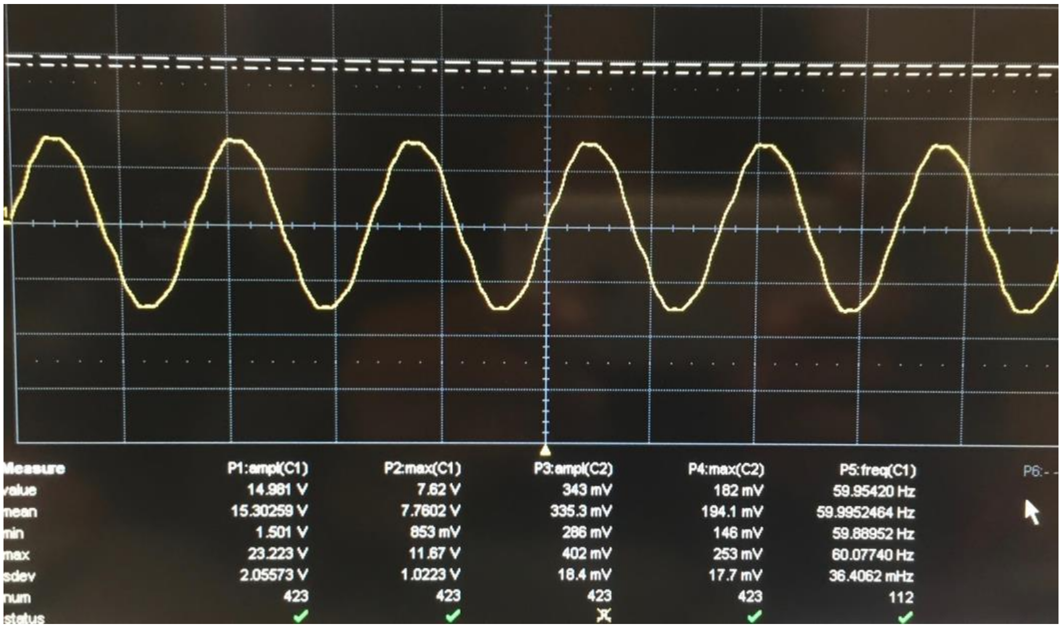


Figure 12. Output voltage of the second transformer.

4.2. Battery installation system

The heart of this project, but also the most complex part is the battery installation system. The batteries need to be able to discharge and charge on the command of the operator. Originally, the battery installation system was going to be done through bidirectional converters where the current would be able to channel in both directions, to and from the battery.

Two bidirectional converters were needed to achieve this, the DC-DC and DC-AC converters. The bidirectional DC-DC was designed. Its schematic is shown in Figure 13. A 7.4V battery pack would be able to discharge current whenever the battery voltage was higher than a reference voltage of 5V.

The control scheme, labeled in the orange box, is a comparator circuit that compares the voltages between the battery and a reference voltage. We are using two 3.7V batteries in series such as the 18650 3.7V Lithium-ion battery (7.4V battery pack), and its voltage cannot be below 5V due to the decrease in the lifetime of the battery. The reference voltage was therefore set at 5V. Whenever the battery of the voltage was below the threshold, the charge controller, in the green box to the right will turn on to charge the batteries. The same scenario in reverse is done when the battery voltage is above the reference voltage.

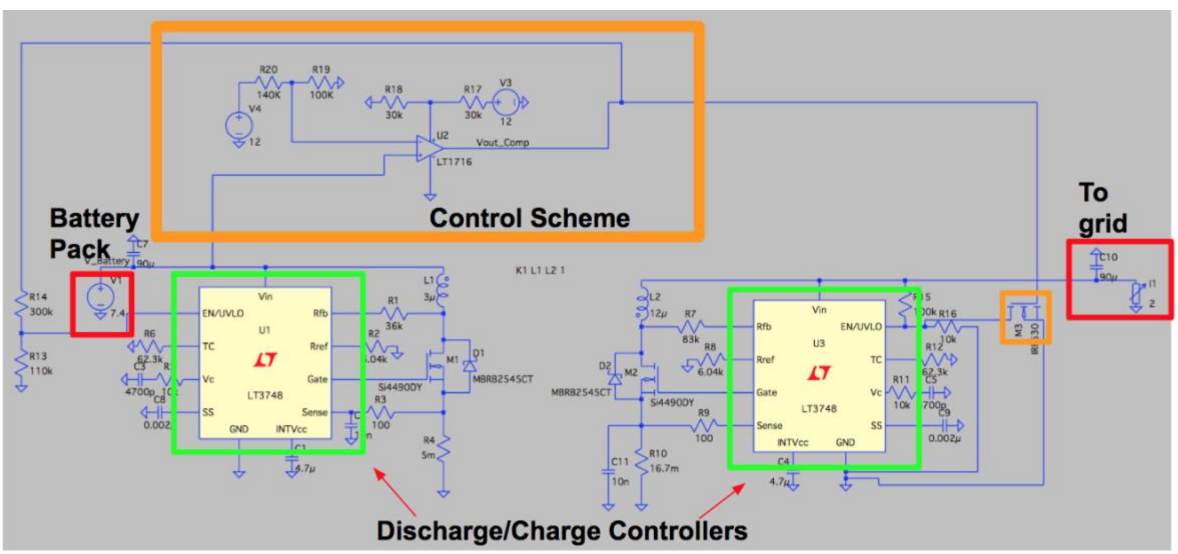


Figure 13. Breakdown of the bidirectional DC-DC converter

This design was simulated using the software LTSpice.

The results of the simulation are shown in Figure 14. The figure on the left represents the voltage in the batteries in the charging mode. Ideally, it should be 8.4, as each battery requires a charging voltage of 4.2V. The figure on the right represents the output voltage of the DC/AC converter when the batteries are discharging.

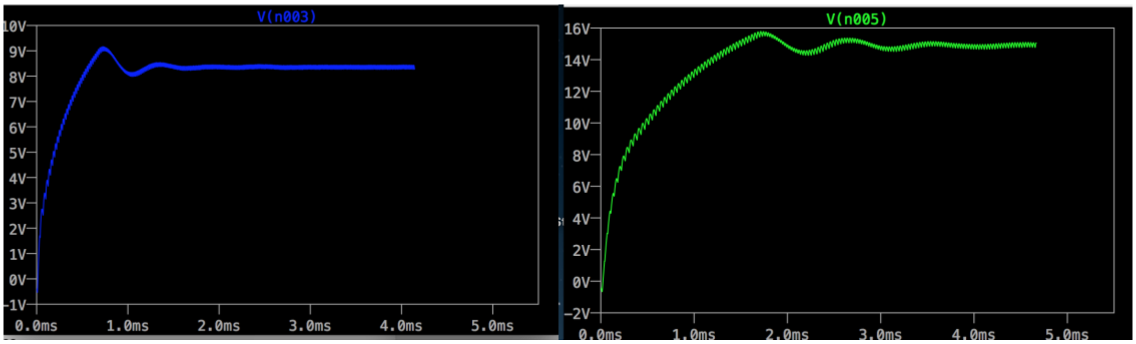


Figure 14. Simulation results for charging mode (left) and discharging mode (right)

Although the results are very close to the ideal values, both voltages presented some ripple. In the case of the charging mode, the ripple was 0.20V, 2.38% of the total voltage. In the discharging mode, the voltage ripple was 0.34V, 2.27% of the total voltage. As both voltage ripples are small enough, the simulation was considered successful.

A printed circuit board (PCB) was designed using the software Altium, an electronic design automation software package for printed circuit boards. However, the PCB could not be finally tested, as it presented some errors. The main error was that the pads were made very small for soldering and that the clearances were extremely narrow, risking in a short to the ground plan.

As for the DC-AC converter, it presented an ambitious challenge. These bidirectional systems are only sold in high powered applications such as electric vehicles and power grid applications. Our systems had low voltages ranging from 7.4V to 15V, which made it very difficult to find a bidirectional DC-AC converter with these specifications. Designing it from scratch posed a challenge.

After taking into account the long fabrication time the new PCB of the bidirectional DC-DC system would require and the complexity of the DC-AC system, we decided to look for a different alternative.

The new solution was to make two different stages: one for charging and another for discharging. As the operator, the user would be able to turn each of these stages when the system made some type of notification from either a LED or a LCD screen.

The schematic used for the charging stage is shown in Figure 15. The AC voltage from the grid needs to be converted into DC such that the batteries can charge. This will be achieved using a rectifier circuit. The DC voltage goes into the battery management system, which can vary the voltage depending on the battery configuration (two batteries in series, two batteries in parallel, etc.).

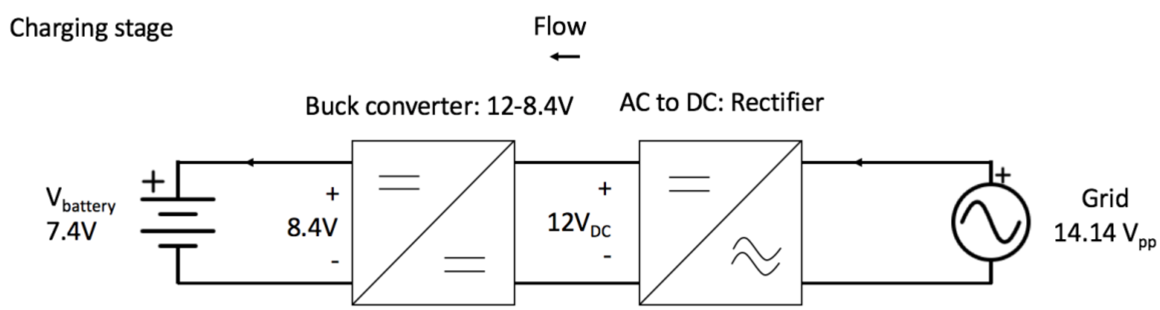


Figure 15. Charging stage of the battery installation system.

On the other hand, whenever the batteries need to be discharged their voltage output needs to be converted into grid voltage at 60Hz. This is done by boosting up the voltage of the lower battery cells into $12V_{DC}$ so that an inverter can be enabled to convert the DC voltage in AC. This is followed by a step-down transformer to make the amplitudes of the inverter's output voltage and the grid voltage equal. Therefore, it would result in two independent power sources in the grid: on one hand the Variac, and on the other hand, the batteries. Figure 16 shows the schematic of the discharging stage.

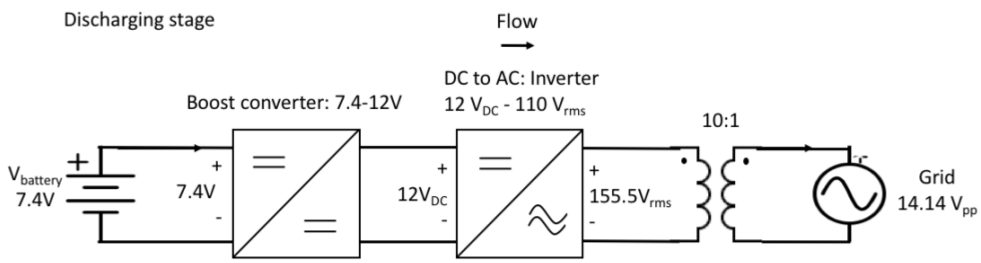


Figure 16. Discharging stage of the battery installation system.

In order to boost the voltage of the battery up, a boost converter XL6009 module was used. Its main characteristics are summarized in Table 5. The reasons why this module was used were primarily its high efficiency and appropriate voltage ranges for the grid. In addition, the output voltage ripple was almost imperceptible.

Input voltage	4.2-32V
Output voltage	5-52V
Maximum input current	4A
Transfer efficiency	94%
Output ripple	50mV
Operating temperature	-40ºC ~ +85℃

Table 5. Specifications boost converter XL6009

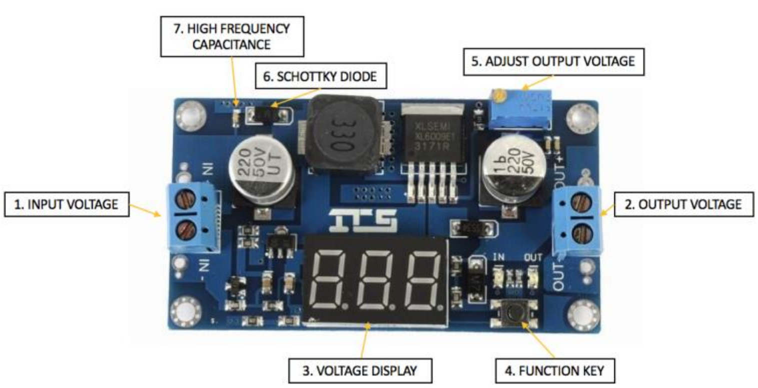


Figure 17. Boost converter XL6009 module

The main components of this module, shown in Figure 17 , are the following:

1. Input voltage header.
2. Output voltage header.
3. Voltage display.
4. Function key:
    a. Short press: input/output display options.
    b. Moderate press: Enter the fine-tuning state and increase or decrease the offset (the default is 0).
    c. Long press: state of low power consumption, the digital tube and the lights are out. Click the button again to restore normal display.
5. Potentiometer to adjust output voltage.
6. Schottky diode, that provides protection of reverse connection.
7. High frequency capacitance to eliminate electric spark.

The main function of this module is to boost the voltage from 7.4V of the battery pack, to 12 V DC. This task was successfully accomplished.

After the boost converter, the 12V DC needed to be converted into AC voltage. For that reason, an inverter was bought. A car inverter was chosen because of its low voltage input, which made it appropriate for our discharging stage. The inverter model was MRZ3011HU. Its specifications are included in Table 6.

Rated power	300W
Input voltage	11V-15VDC
Output voltage	110VAC ± 10V, 60Hz ± 1Hz
Overload protection	350W-380W
Size	161*97*58mm
Weight	320g+-15g
Protection	low battery shutdown low voltage protection overload protection short circuit protection over temperature protection surge protection.

Table 6. Specifications MRZ3011HU power inverter.

This inverter was activated using a ON/OFF switch, as shown in Figure 18. A 3-prong plug with a two inputs header in the other side was connected to the inverter, and the DC side wire was cut, in order to connect it to the boost converter.

Figure 18. MRZ3011HU power inverter. [16]

As the output voltage of the inverter was 110 V_{rms}, a 10:1 transformer was used to get approximately 10V_{rms}, the standard voltage of the mock grid.

The overall circuit was tested, simulating the 7.4V of the battery pack with an Agilent triple DC power supply E3631A. An approximately pure sine wave of 10V_{rms} and 60Hz was the output of the discharging branch.

4.3. VARIABLE LOAD

The variable load system is the main focus of this project. The ultimate objective of the power load is to model the typical electricity summer demand curve of New England in the mock grid. The idea was to achieve this using some type of variable resistors.

The first attempt was to use a DC motor moving a variable resistor or potentiometer. The motor needed to be controlled precisely, so that the total resistance of the circuit was controlled. This option was rapidly discarded, as the idea of precisely controlling a DC motor would require a unique senior design project due to its complexity.

4.3.1. Digital potentiometer

Doing some research, the next idea was to use a digital potentiometer, which is a digitally-controlled component that mimics the analog functions of a potentiometer. It is usually built from a resistor ladder integrated circuit. Every step on the resistor ladder has its own switch which is able to connect this step to the output terminal of the potentiometer. The selected step on the ladder determines the resistance ratio of the digital potentiometer. The main advantage of the digital potentiometer is the big number of steps it can perform (the most common resolution is 8 bits, which equals 256 steps).

However, digital potentiometers have a major drawback which was not compatible with the scaled-down mock grid: they are constrained by a current limit in the range of tens of milliamperes, and the project required at least 1A to have a significant amount of power consumed.

4.3.2. AC light dimmer

After that, the idea of an AC light dimmer was seriously taken into consideration. A light dimmer is a device used to control the brightness of light, by controlling the current going into it and, therefore, the power consumed. The objective was to be able to control the average power in a 12V light bulb using a microcontroller.

In order to achieve this, the circuit in Figure 19 was built. This circuit can be separated in two different parts, the zero-crossing detector, which consists of a 4N35 and resistors to limit the current, and the AC load driver circuit, which comprises a TRIAC and an optocoupler (IL420).

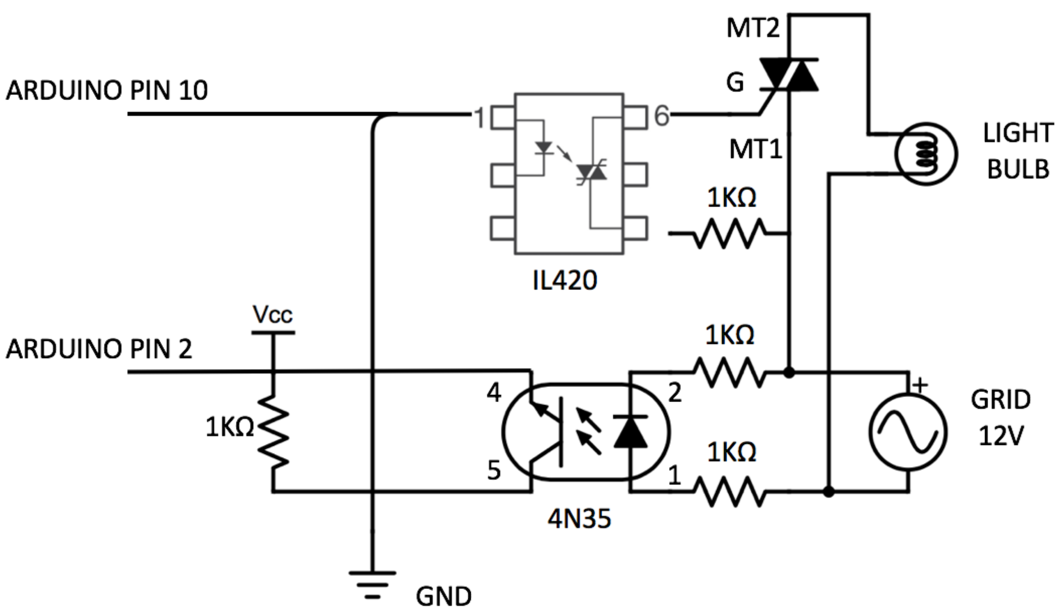


Figure 19. AC light dimmer circuit.

The functioning of these components will be briefly described in order to gain a better understanding of the circuit.

A TRIAC, triode for alternating current, is an electronic component that conducts current in either direction when triggered. This bidirectionality makes them convenient switches for alternating current. Although they are capable of large currents and large blocking voltages for use in high-power applications, switching frequencies cannot be as high as when using other devices such as MOSFETs, used in DC.

For the TRIAC to begin to conduct, it must have a gate current applied, known as the gate threshold current, which is generally a few milliamperes. After conduction is established, the gate signal is no longer required to maintain the current. The TRIAC will continue to conduct as long as the current remains positive and above a minimum value called the holding current.

Figure 20 shows the circuit symbol for a TRIAC, which has three different terminals: main terminal 1 (MT1), main terminal 2 (MT2) and the gate. The TRIAC used was an NTE5645, which has a gate threshold current, I_{GT}, of 50 mA, and a holding current, I_H, of 50 mA.

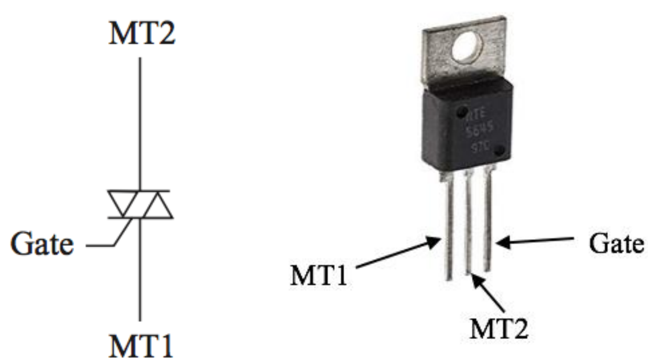


Figure 20. Circuit symbol for a TRIAC and NTE5645 TRIAC

The component used for controlling the TRIAC was Arduino Uno, which is an electronic board based on the microcontroller ATmega328. It has 14 digital inputs/outputs, of which 6 can be used as PWM (pulse width modulation) outputs and other 6 are analogic inputs. In addition, it includes a ceramic resonator of 16 MHz, a USB connector, a feeder connector, a ICSP header and a reset button.

The main characteristics of Arduino Uno are included in Table 7.

Microcontroller	ATmega328
Voltage	5V
Input voltage (recommended)	7-12V
Input voltage (limits)	6-20V
Digital I/O Pins	14 (pins 3, 5, 6, 9, 10 and 11) are PWM outputs
Analogic inputs	6
DC Current per I/O Pin	40mA
Clock speed	16 MHz

Table 7. Specifications Arduino Uno board

Figure 21 shows the main components of the board Arduino Uno.

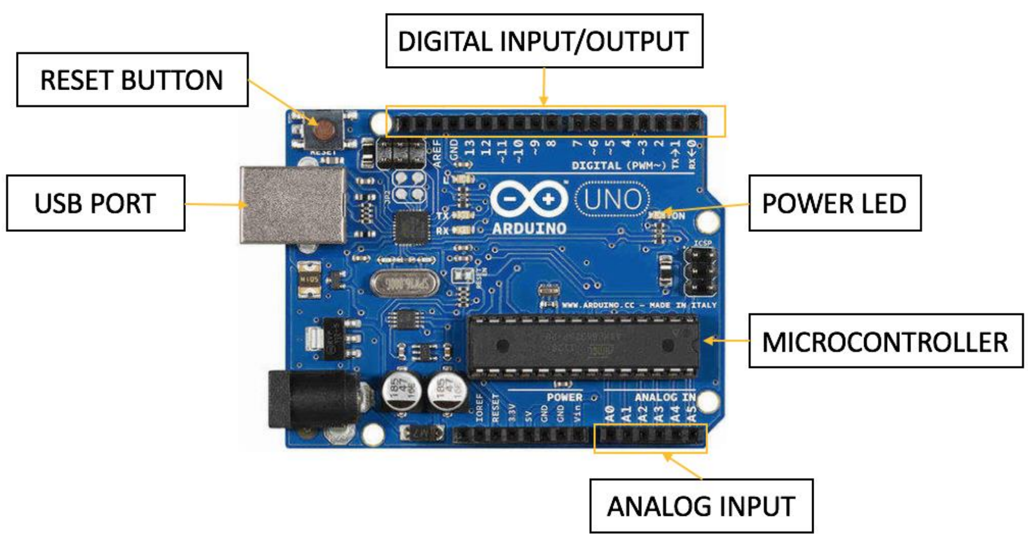


Figure 21. Arduino Uno microcontroller

To protect the microcontroller from being damaged by high voltage, an optocoupler is placed in between the Arduino microcontroller and the TRIAC to isolate the high voltage side of loads and low voltage side of the microcontroller, whose current limit is 40mA. The optocoupler used is a IL420. As PWM control is being used, the IL420 driving the TRIAC needs to be connected to a PWM Arduino pin. In this case the selected one is pin 10. Figure 22 shows the optocoupler used.

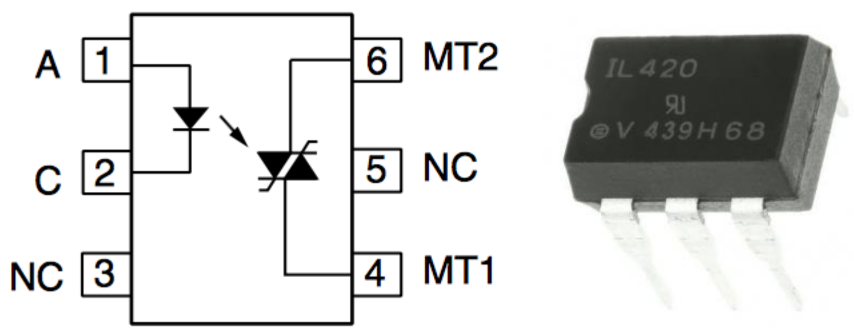


Figure 22. Optocoupler IL420

The zero-crossing detector is necessary to identify when the sinusoidal supply voltage goes through zero. This could avoid unpredictable time for TRIAC conduction or, in other words, during what part of the sinusoidal wave the TRIAC is ON and leads to unpredictable power consumption. The pulses generated by the zero-crossing detector act as interrupt signals to the Arduino microcontroller. Arduino microcontroller is then firing a pulse to the TRIAC.

By controlling the time delay between the zero-crossing point and the TRIAC's gate triggering, power delivered to the AC load is controlled smoothly and effectively. The zero-crossing detector used was a 4N35, as shown in Figure 23.

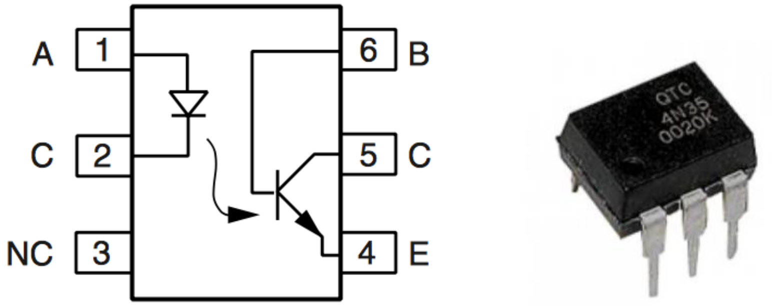


Figure 23. Zero-crossing detector 4N35

The load used, shown in Figure 24, was a Philips 12V, 100W halogen light bulb, dimmable and with an average life of approximately 4000 hours.

Figure 24. 12 V light bulb

After having described the main components of the circuit, its theory of operation will be explained in detail.

The zero-crossing detection circuit provides a 5V pulse every time the AC signal crosses zero volts. This can be detected with the Arduino Uno and it can use interrupts to time the trigger circuit precisely in synchronization with these zero-crossing events. The method for power control is shown in Figure 25.

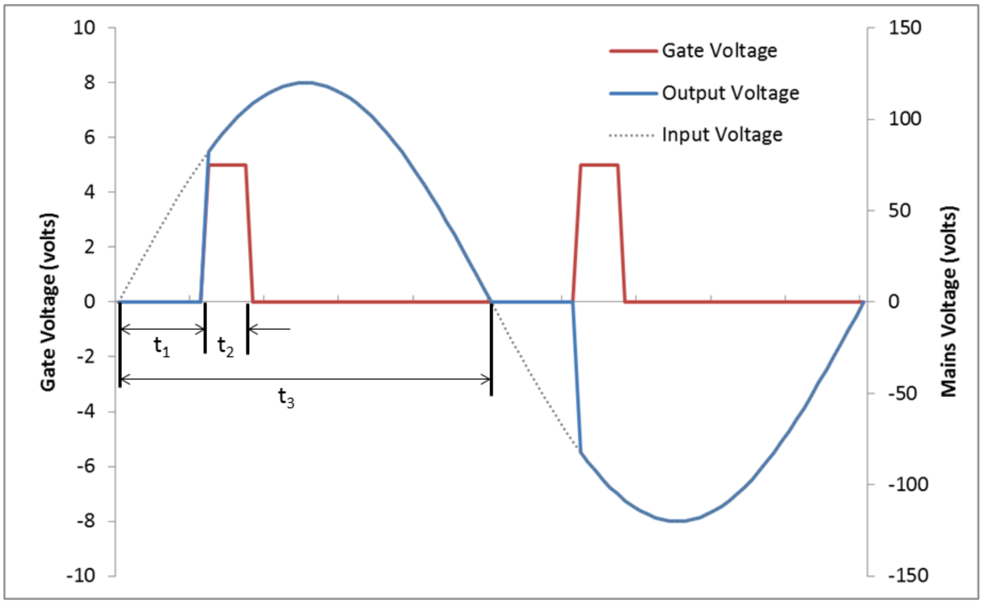


Figure 25. AC light dimmer method for power control. [17]

Once a zero crossing is detected, the TRIAC remains off for a controlled amount of time (t_1 in the figure). The longer this time is, the less power the AC circuit receives. Once the off-time, t_1 has elapsed, the microcontroller turns on the TRIAC by applying a voltage to the gate (shown in red in the figure). Once the TRIAC has been turned on, it will remain on even after the gate voltage has been removed. It will turn off if the gate voltage is zero the next time the AC wave crosses zero. Because of this, we do not need to take care to turn the TRIAC off when the AC signal crosses zero again. All we need to do is to ensure that the TRIAC gets turned off inside of the period of ½ wave (t_3).

The duration of the gate pulse (t_2) is determined by a minimum requirement of the TRIAC. If this pulse is too short, the TRIAC will not fire. In this case, the duration of the gate pulse was 10 microseconds, which is time enough for the TRIAC to fire. Once the second zero crossing occurs, since there is no voltage on the gate, the TRIAC remains off until triggered again in the next ½ cycle. The net result here is that parts of the wave have been chopped out resulting in lower average power. This is essentially how PWM control of an AC wave can be accomplished.

Interrupts and the Arduino timer will be used to precisely control the timing of the TRIAC gate. Basically, the way an interrupt works is that when some event happens (it can be either internal or external to the microprocessor), the microprocessor immediately stops what it is doing to service the interrupt. This allows the microprocessor to handle very time sensitive events.

To understand the time intervals, we need to look at the AC signal and the Arduino clock. The AC signal in the US is 60 Hz. What this means is that the AC signal crosses zero, reaches peak positive voltage, crosses zero, reaches peak negative voltage and returns to zero 60 times each second. The period, length of time this process takes, is 1/60 or 0.0167 seconds (16.7 milliseconds). A half cycle, the time between two zero-crossings, occurs in 8.33 milliseconds, t_3 in Figure 25.

The Arduino clock runs at 16 MHz, which is 16,000,000 cycles per second: one clock cycle takes 0.0625 microseconds. A single half cycle of the 60 Hz AC signal contains 133,333 clock cycles. This is important because the time intervals will be determined by clock counts in the Arduino code, not by seconds.

Table 8 shows the digital pins usable for interrupts for different types of boards. For Arduino Uno digital pins 2 or 3 can be used. In this case, digital pin 2 will be used.

BOARD	DIGITAL PINS USABLE FOR INTERRUPTS
Uno, Nano, Mini, other 328-based	2, 3
Mega, Mega2560, Mega ADK	2, 3, 18, 19, 20, 21
Micro, Leonardo, ther 32u4-based	0, 1, 2, 3, 7
Zero	All digital pins, except 4
MKR1000 Rev.1	0, 1, 4, 5, 6, 7, 8, 9, A1, A2
Due	All digital pins
101	All digital pins (Only pins 2, 5, 7, 8, 10, 11, 12, 13 work with CHANGE)

Table 8. Digital pins with interrupts in different types of boards. [18]

The appropriate function for using interrupts is called AttachInterrupt. It contains three different parameters. The first one is the pin number, written as digitalPinToInterrupt(pin), the second one is the interrupt service routine (ISR) to call when an interrupt occurs (this function must take no parameters and return nothing), and the last parameter is the mode, that defines when the interrupt should be triggered. There are four constants predefined as valid values for the mode:

- LOW to trigger the interrupt whenever the pin is low,
- CHANGE to trigger the interrupt whenever the pin changes value
- RISING to trigger when the pin goes from low to high,
- FALLING for when the pin goes from high to low.

In this case, RISING will be used, as the interrupt should be triggered when pin 2 goes from low to high.

The code used for testing the AC light dimmer reduces the brightness of the light bulb every ten milliseconds, until it is completely off. It comprises three different parts:

1) Definition of variables, outputs and attachInterrupt
2) Zero-cross function. It calculates the dim time, which is t_1 in Figure 25, fires the TRIAC, waits for 10 microseconds and stops triggering the TRIAC.
3) Loop. It increases the dim time every 10 milliseconds until the light bulb is completely off.

```
// Program: AC light dimmer [17]
// Description: An AC light dimmer controls the brightness of a light bulb
// Author: Teresa Jiménez-Castellanos Vida
// Date: January 10th, 2018

// Define the Arduino pin connected to the load
int AC_LOAD = 10;     // Output to IL420 pin 1
int dimming = 128;  // Dimming level (0-128) 0=ON, 128=OFF
// 128 steps (arbitrary number)

void setup()
{
  pinMode(AC_LOAD, OUTPUT);// Set AC Load pin as output
  attachInterrupt(digitalPinToInterrupt(2), zero_cross_int, RISING);  //
Choose the zero cross interrupt number from table X
}

void zero_cross_int()  //function to be fired at the zero crossing to dim
the light
{
  // Firing angle calculation: 1 full 60Hz wave =1/60=16.666ms
  // Every zero-crossing thus: (60Hz)-> 8.33ms (1/2 Cycle)
  // 10ms=10000us, 8.33ms=8333
  // (8333us - 8.33us) / 128 = 65

  int dimtime = (65*dimming);    // For 50Hz =>75
  delayMicroseconds(dimtime);    // Wait till firing the TRIAC
  digitalWrite(AC_LOAD, HIGH);   // Fire the TRIAC
  delayMicroseconds(10);   // TRIAC On. Propagation delay
  digitalWrite(AC_LOAD, LOW);    // No longer trigger the TRIAC
}

//Increase 1 step each 10ms. Range should be tested

void loop()  {
  for (int i=5; i <= 128; i++){
    dimming=i;
    delay(10);
   }
}
```

The light dimmer was successfully achieved.

4.3.3. Final design

Although the AC light dimmer effectively accomplished the requirements of the load system, it had a major drawback: its dissimilarity with the loads in the real power grid, where there are loads connected and disconnected depending of the actual time of the day.

As stated before, the prime objective of the load system is to model the electricity demand curve of New England in the mock grid. Throughout the period of the day, the demand for electricity fluctuates from low in the morning to high in the late afternoon into the evening and back down again at night. After the AC light dimmer was functioning, we shifted to show a similar trend by connecting and disconnecting different loads, thus modifying the total power consumed.

The basic circuit of the load subsystem consists of six resistors and six switches. Opening and closing the switches, enables us to change the total power consumed.

We used six 30 Ω, 10 W, high power resistors. The current and power in each resistor was calculated and resulted to be lower than the limits, as the following calculations show:

-Maximum current across each resistor

$$P = I^2 \cdot R$$

$$I_{max} = \sqrt{\frac{P}{R}} = \sqrt{\frac{10}{30}} = 0.58\ A$$

-Current across each resistor and power dissipated by each resistor in the mock grid:

$$I_{1\ resistor} = \frac{V}{R} = \frac{10}{30} = 0.333A\ < 0.58\ A \rightarrow OK$$

$$P_{1\ resistor} = V \cdot I = 10\ V\ \cdot 0.333\ A = 3.33\ W < 10W \rightarrow OK$$

The circuit, shown in Figure 26, has 6 different steps of power, each one of 3.33W, resulting in a maximum power consumed of 20W. The maximum current across the circuit is 2A, which is lower than the maximum current allowed (3A).

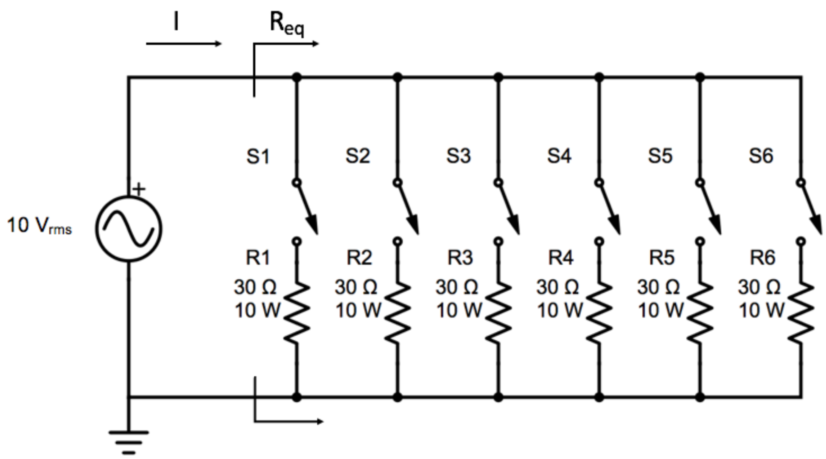


Figure 26. Basic diagram of the load subsystem.

This circuit enables us to connect up to six resistors at the same time. Table 9 shows the equivalent resistance seen by the source, the total current across the load system, and the total power consumed in each case.

Number of resistors connected	$R_{equivalent}$ (Ω)	Total current I (A)	Total power consumed P (W)
0	0	0	0
1	30	0.333	3.33
2	15	0.667	6.66
3	10	1.000	10.00
4	7.5	1.333	13.33
5	6	1.667	16.66
6	5	2.000	20.00

Table 9. Electrical characteristics depending on the number of resistors connected.

Two versions of the circuit in Figure 26 were built, one for DC, as an option B if the overall grid did not work in AC, and another for AC.

The DC circuit is shown in Figure 27. The circuit consists of six 30Ω resistors, each one with its own MOSFET, connected in parallel. Each MOSFET gate is connected to a different PWM digital pin in Arduino.

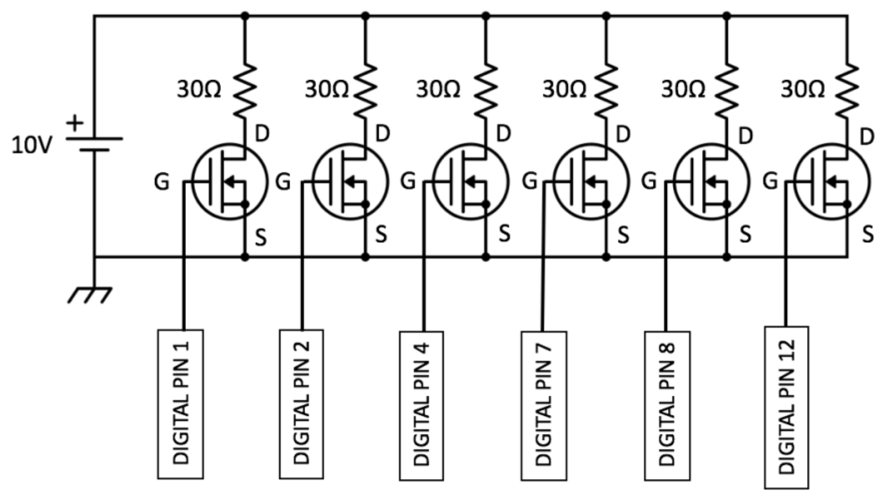


Figure 27. DC circuit for power load

The main component of this circuit was the MOSFET IRF520, which acts as a switch in DC. The principal advantage of this MOSFET is that it was already soldered on a module that had two phases. A primary, low power phase, which is connected to Arduino, and a secondary, high power phase, which is connected to the load. The MOSFET IRF520 has a maximum voltage of 24V, and a maximum current of 4A, which are higher values than what we expected in the circuit.

Figure 28 shows the MOSFET module, as well as its inputs. The load is connected in the V+ and V- terminals, and the power supply (in this case the grid) is connected in the VIN and GND terminals. The SIG pin should be connected to the digital pin in Arduino. When it is HIGH, a red LED will turn on. VCC should be connected to the 5V pin in Arduino, and GND to the ground pin in Arduino.

Figure 28. MOSFET IRF520 module. [19]

This circuit was successfully built on a breadboard and tested using an Agilent triple DC power supply E3631A.

As MOSFETs only work for DC, for the AC version of the circuit TRIACs were used instead of MOSFETs. The circuit consists of six different 30Ω high power resistors as well, each one controlled by a different TRIAC NTE5645 driven by the optocoupler IL420. Each optocoupler is connected to a different pin in Arduino. The schematic of the circuit is shown in page 66.

Some LEDs were included to know if a certain resistor was connected or disconnected. A green LED next to the resistor will light up if the load is connected. There are three 5 millimeters LEDs, which model the base load (their corresponding resistors are always connected) and three 3 millimeters LEDs, which model the intermittent load. 330 ohms resistors were added to protect the LEDs from being burned.

The calculation of the value of these resistors is the following:

The maximum current is the same for both 5mm and 3mm LEDs, 20mA.

$$V_{cc} - V_{f\ LED} = I \cdot R_{min}$$

$$V_{CC} = 5V$$

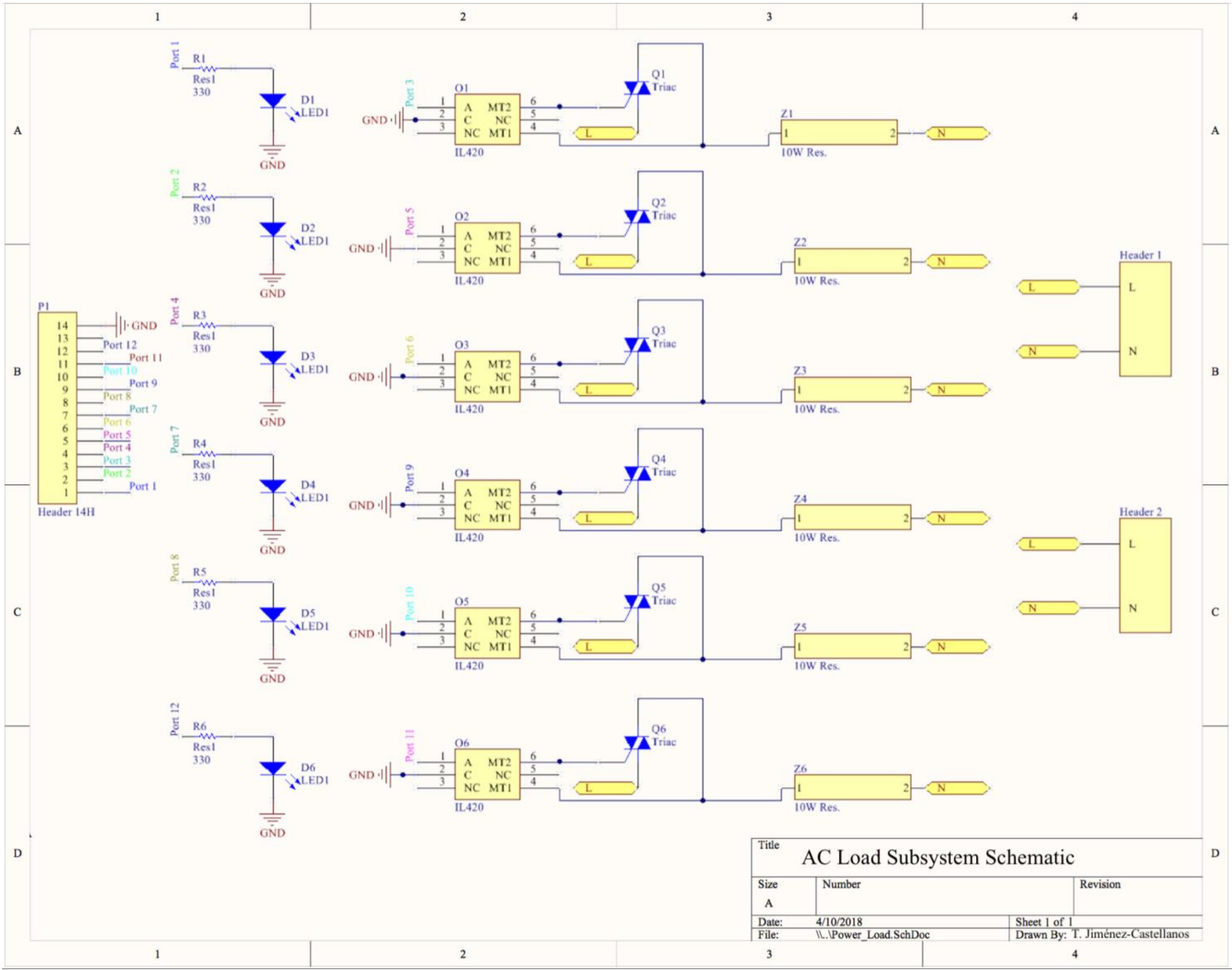
$$V_{f\ LED} = 2.4V$$

$$I_{MAX} = 20\ mA$$

$$5 - 2.4 = 0.02 \cdot R_{min}$$

$$R_{min} = 130\ \Omega$$

The resistors used were 330Ω.


AC Load Subsystem Schematic
Size A
Date: 4/10/2018
File: \\..\Power_Load.SchDoc
Sheet 1 of 1
Drawn By: T. Jiménez-Castellanos
Header 14H
Header 1
Header 2
IL420
10W Res.
Triac
LED1
Res1 330
GND

4.3.4. Scaled-down demand curve

The load system aims to model a typical summer demand curve. This was accomplished by first scaling down a real summer electricity demand curve in New England from July 6th, 2010. (Figure 29).

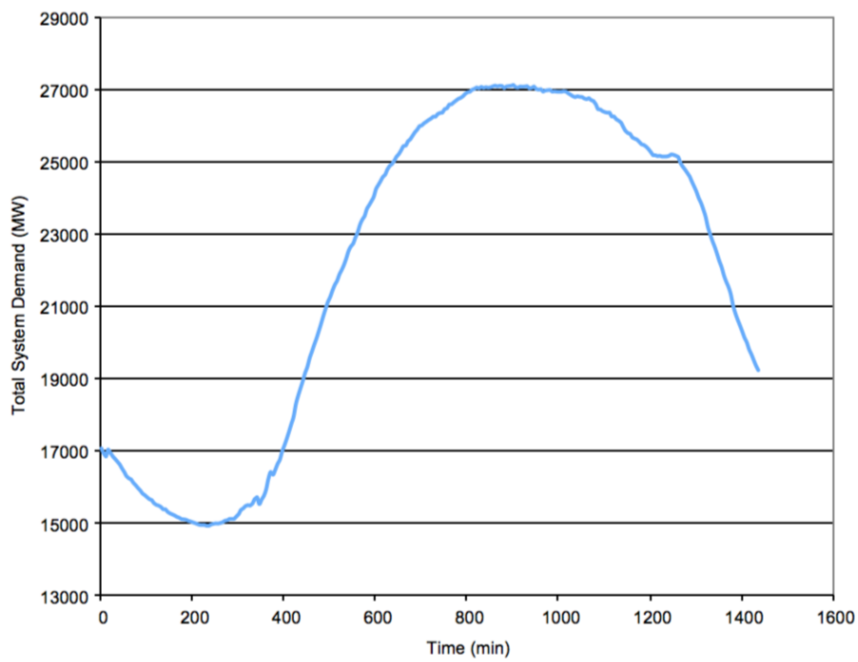


Figure 29. Typical summer demand curve of New England [20]

In order to scale it down, the day has been divided into 24 intervals of 1 hour each. The average power has been calculated in each interval, and scaled down taking into account that the maximum power of the actual demand curve (27,111MW) corresponds to 20W, which is the maximum power consumed by the loads. Then, the average power has been rounded to the nearest power that the load circuit can achieve. Finally, the number of resistors that need to be connected in each interval has been calculated.

Table 10 shows the results obtained:

Hour	Power 1 (MW)	Power 2 (MW)	Average power (MW)	Scaled down average power (W)	$P_{equivalent}$ (W)	Number of resistors connected
0	17,086	16,259	16,672.5	12.299	13.333	4
1	16,259	15,527	15,893.0	11.724	13.333	4
2	15,527	15,127	15,327.0	11.307	10.000	3
3	15,127	14,985	15,056.0	11.107	10.000	3
4	14,985	15,269	15,127.0	11.159	10.000	3
5	15,269	15,950	15,609.5	11.515	10.000	3
6	15,950	17,959	16,954.5	12.507	13.333	4
7	17,959	20,523	19,241.0	14.194	13.333	4
8	20,523	22,526	21,524.5	15.879	16.666	5
9	22,526	24,238	23,382.0	17.249	16.666	5
10	24,238	25,425	24,831.5	18.318	16.666	5
11	25,425	26,182	25,803.5	19.035	20.000	6
12	26,182	26,729	26,455.5	19.516	20.000	6
13	26,729	27,049	26,889.0	19.836	20.000	6
14	27,049	27,111	27,080.0	19.977	20.000	6
15	27,111	26,994	27,052.5	19.957	20.000	6
16	26,994	26,881	26,937.5	19.872	20.000	6
17	26,881	26,582	26,731.5	19.720	20.000	6

18	26,582	25,954	26,268.0	19.378	20.000	6
19	25,954	25,264	25,609.0	18.892	20.000	6
20	25,264	25,126	25,195.0	18.587	20.000	6
21	25,126	23,473	24,299.5	17.926	16.666	5
22	23,473	21,029	22,251.0	16.415	16.666	5
23	21,029	19,242	20,135.5	14.854	13.333	4

Table 10. Results of scaling down the summer demand curve

Figure 30 shows the scaled down summer power demand curve of our circuit, versus the time of the day in hours.

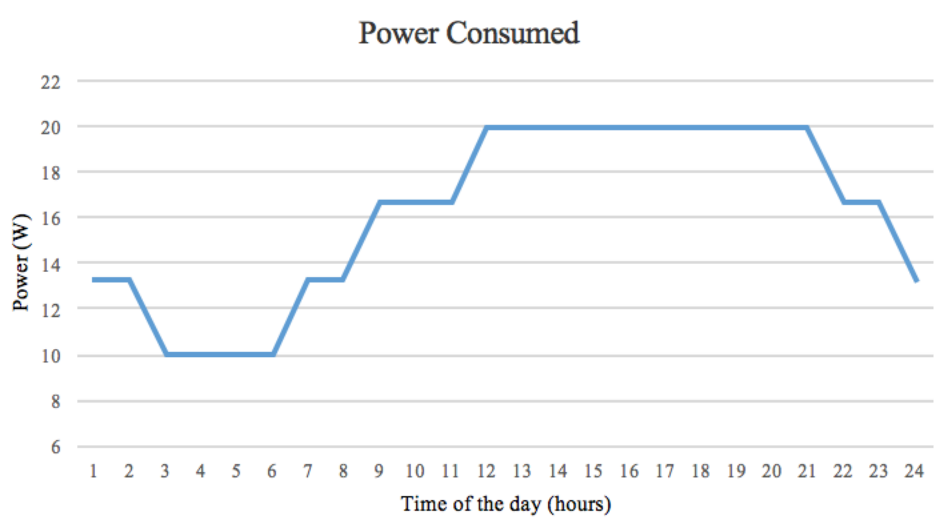


Figure 30. Summer demand curve followed by the power load circuit

Although our customer requirement was to model the summer demand curve, almost any electricity demand curve can be easily simulated. Part II, chapter I of the present document shows the instructions for modifying the demand curve.

4.3.5. Programming the demand curve

The demand curve in Figure 30 was programmed in Arduino. This microcontroller controls both the LEDs and the TRIACs. When a TRIAC is fired, its correspondent LED is shining. The code was divided in the 24 hours of the day, and in each hour a certain number of TRIACs were fired in order to connect a certain number of resistors, according to Table 10.

3 different versions of the code have been proposed depending on the simulation time:

- 3 minutes
- 6 minutes
- 30 minutes

However, the simulation time can easily be modified. The instructions for doing this are included in Part II, chapter I of the present document.

An example of the 30 minutes code is the following:

```
// Program: Summer demand curve simulation 30 minutes
// Description: A typical New England summer demand curve is simulated
// Author: Teresa Jiménez-Castellanos Vida
// Date: March 19th, 2018

int AC_LOAD_1 = 3;
int AC_LOAD_2 = 5;
int AC_LOAD_3 = 6;
int AC_LOAD_4 = 9;
int AC_LOAD_5 = 10;
int AC_LOAD_6 = 11;
int LED_1 = 1;
int LED_2 = 2;
int LED_3 = 4;
int LED_4 = 7;
int LED_5 = 8;
int LED_6 = 12;
float time;

void setup()
{
  pinMode(AC_LOAD_1, OUTPUT);
```

```
 pinMode(AC_LOAD_2, OUTPUT);
 pinMode(AC_LOAD_3, OUTPUT);
 pinMode(AC_LOAD_4, OUTPUT);
 pinMode(AC_LOAD_5, OUTPUT);
 pinMode(AC_LOAD_6, OUTPUT);

 pinMode(LED_1,OUTPUT);
 pinMode(LED_2,OUTPUT);
 pinMode(LED_3,OUTPUT);
 pinMode(LED_4,OUTPUT);
 pinMode(LED_5,OUTPUT);
 pinMode(LED_6,OUTPUT);

 time=75000;
}

 void loop(){
   // 0-1 hr
   digitalWrite(AC_LOAD_1, HIGH);
   digitalWrite(LED_1, HIGH);
   digitalWrite(AC_LOAD_2, HIGH);
   digitalWrite(LED_2, HIGH);
   digitalWrite(AC_LOAD_3, HIGH);
   digitalWrite(LED_3, HIGH);
   digitalWrite(AC_LOAD_4, HIGH);
   digitalWrite(LED_4, HIGH);
   digitalWrite(AC_LOAD_5, LOW);
   digitalWrite(LED_5, LOW);
   digitalWrite(AC_LOAD_6, LOW);
   digitalWrite(LED_6, LOW);
   delay(time);

   //1-2 hr
   delay(time);

   //2-3 hr
   digitalWrite(AC_LOAD_4, LOW);
   digitalWrite(LED_4, LOW);
   delay(75000);

   //3-4 hr
   delay(time);

   …

}
```

The code consist mainly of turning on and off the gate of the TRIACs, as well as the LEDs corresponding to each resistor. The complete code and a detailed explanation of how to select the variable “time” is included in Part II, chapter I.

The circuit was first built on a breadboard and tested. Figure 31 shows the circuit on the breadboard and its main components, the TRIACs, the optocouplers, the high power resistors and the LEDs. The green and yellow wires connect the circuit to Arduino Uno.

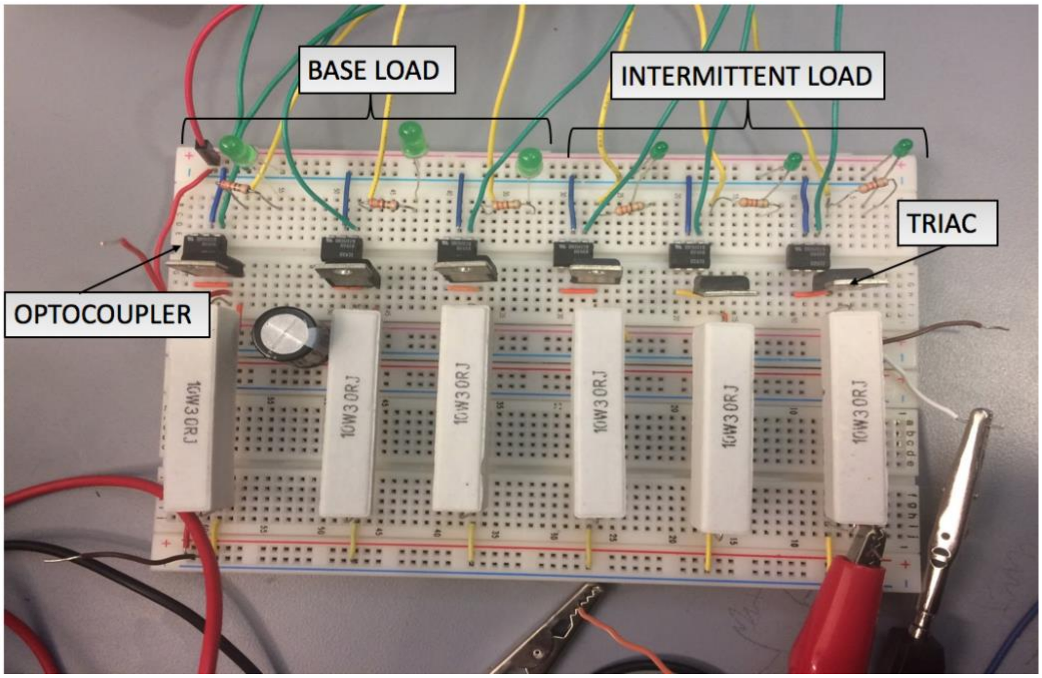


Figure 31. Load circuit built on a breadboard

4.3.6. Testing results

Firstly, the circuit was tested using a B&K Precision 1653A AC Power Supply, 150V, 2A.

The testing had the following steps:

1) It was checked that the TRIACs were functioning by measuring the voltage in the gate and in their terminals, when the correspondent Arduino pin was HIGH. If a TRIAC was not functioning, it usually was because it had been burned. In this case, the TRIAC was replaced.

2) It was checked that there was voltage across the resistor when the TRIAC had been triggered. If this was not the case, the connections were carefully inspected.

3) After the circuit was functioning properly. It was checked that the voltage was $10V_{rms} \pm 5\%$ in the loads.

The testing results for this last step are included in Table 11:

Nº resistors	$V_{source\ pp}$ (V)	$V_{load\ pp}$ (V)	I_{load} (A)	I_{total} (A)	P_{load} (W)	P_{total} (W)	Error (%)
3	15.76	15.35	0.362	1.085	3.927	11.781	2.60
4	15.66	15.08	0.355	1.422	3.790	15.160	3.70
5	15.08	14.35	0.338	1.691	3.432	17.160	4.84
6	14.24	13.68	0.322	1.935	3.119	18.714	3.93

Table 11. Testing results % of error in voltage

As the error was in all cases below 5%, the test was accepted as successful.

Once the AC circuit was successfully functioning, a printed circuit board (PCB), shown in Figure 32, was designed to achieve a more professional finished circuit. The software used was Altium. Some considerations taken into account when designing the PCB were the following.

-Due to the significant amount of connections, two layers were used. The top layer is red in Figure 32 and the bottom layer is blue.

-As numerous pins needed to be connected to ground, a rectangular polygon connected to ground was created (red rectangle in Figure 32)

-Traces were designed as thick as possible due to the considerable amount of current.

-Traces connecting the loads to the generation were the thickest, as the highest value of current goes through them

-Special attention was paid when drawing the traces in the three TRIAC's terminals, in order to avoid connecting accidentally two of them, as well as when drawing the traces for the live and neutral wires, in order to avoid a possible future short-circuit.

-The design was as organized and tidy as possible

-Each component had its own designation. The letters used were T for TRIACs, Z for high power resistors, O for optocouplers, L for LEDs, and R for resistors

-A big header was placed in the left for the connections to Arduino. Each input had its own designation referring to the Arduino pin it should be connected to.

-Two-inputs headers were used for connecting the live, designed with L, and neutral, designed with N, wires of the grid.

-The PCB dimensions were 101.6 x 152.4 mm

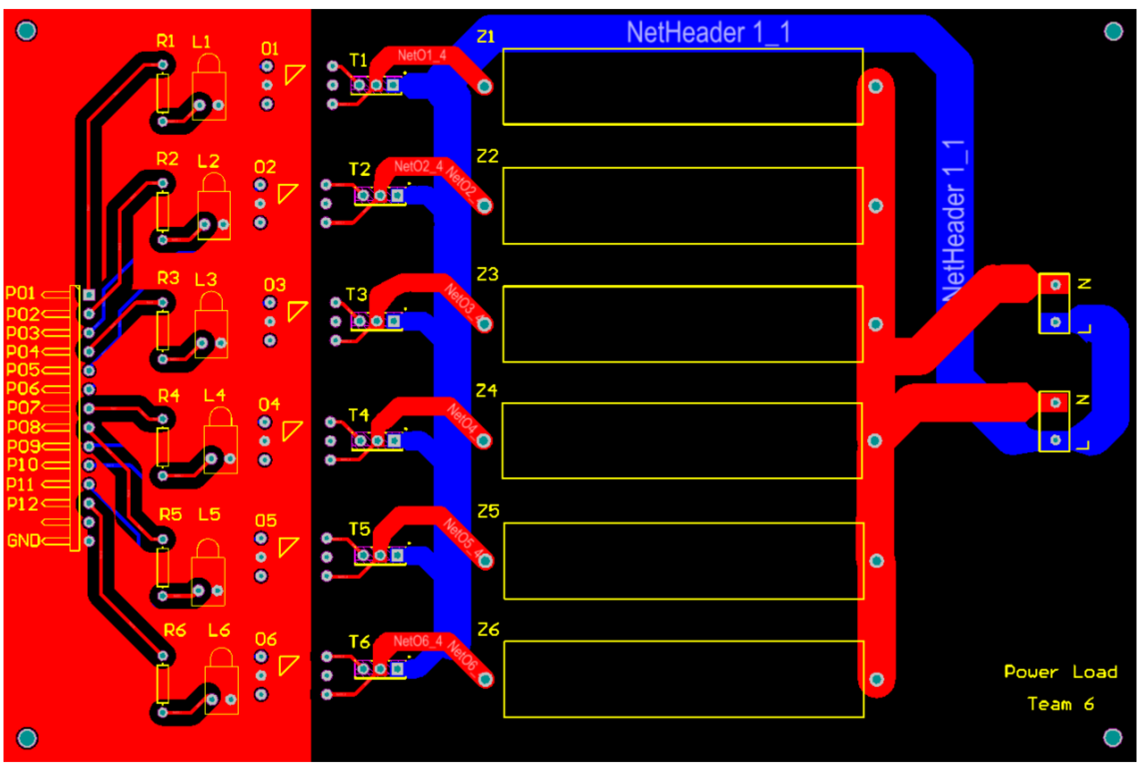


Figure 32. PCB layout of the AC power load circuit

After designing the PCB, it was sent to fabrication. Once it was received, all the components were meticulously soldered and it was made sure that the overall circuit was functioning.

Figure 33 shows the finished PCB with all the components.

Figure 33. Finished PCB power load

4.4. DATA ACQUISITION AND DISPLAY

The data acquisition and display subsystem has two main objectives. The first one, is to model live characterization of important features in the grid. In other words, voltage, current and power should be displayed in real time in the generation, the loads and the battery installation.

To achieve that, two different circuits have been built. The first one, to measure the voltage. It consists of resistors of different values and operational amplifiers. As Arduino can only read from 0 to 5V, not accepting negative voltages, the function of this circuit is first to add a DC offset to the voltage sine wave of the grid, and then to reduce the voltage so that Arduino can read it.

The second circuit is able to measure AC current and consists mainly of a current sensor, that is clipped to the correspondent wire.

Both values of voltage and current are sent to Arduino, which calculates then the power as voltage times current. After that, a LCD screen is connected to Arduino and displays in real time voltage, current and power in significant spots of the grid. Each LCD screen includes a potentiometer, which enables the user to regulate the bright of the screen.

As displaying the reading on a screen in live time is not sufficient to examine the behavior of the batteries, the second objective involves storing the data collected into an excel file for further analysis. This has been accomplished using the software Processing, which enables the user to get a vector of the measurements, in order to analyze the data and extract conclusions about the battery performance.

4.5. INTEGRATION

Due to the significant number of subsystems this project has, the integration between them results essential. This integration was carried out following several tasks described in the methodology section before.

The first step was to integrate the generation and transmission with the variable load subsystem. It consisted of replacing the AC power supply used to test the load system, with the Variac and the two transformers described in the sections before. The voltage in the generation as well as the voltage in the variable load is shown in Figure 34.

Figure 34. Output voltage of the generation system (yellow) and voltage in the loads (pink)

As the output voltage of the generation was $14.14V_{pp}$ and the voltage of the variable load was $13.52V_{pp}$, the voltage drop was 4.4%, less than the 5% required. Therefore, the first part of the integration was correctly accomplished.

The second step was to add the data acquisition and display system to the grid. It consisted of connecting different voltage and current sensors in significant spots of the grid. In addition, LCD screens were also connected to have a real-time display. This step was achieved successfully, as shown in Figure 35, where an LCD screen shows the voltage, current and power of the variable load.

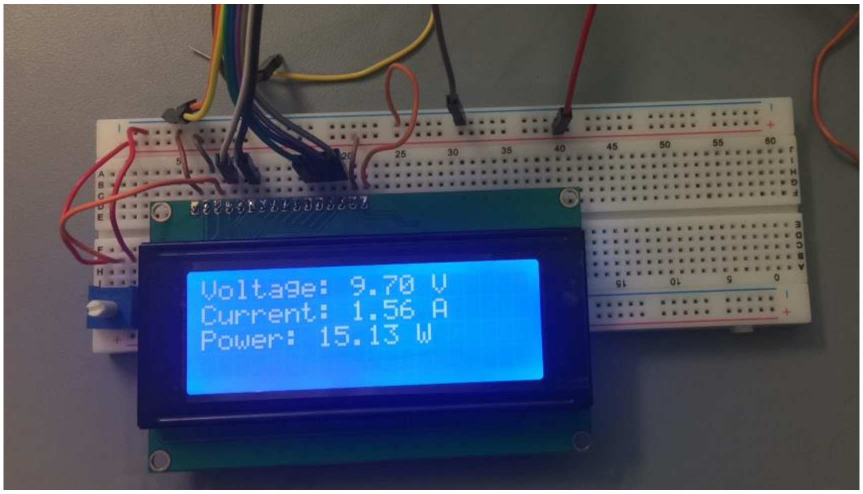


Figure 35. LCD screen displaying grid characteristics in real time

Finally, the last step was to integrate the batteries. As batteries work in DC, a synchronization circuit was built to put in phase the DC-AC inverter output with the grid voltage. The circuit consisted of two different switches and a red LED. Its schematic is shown in Figure 36.

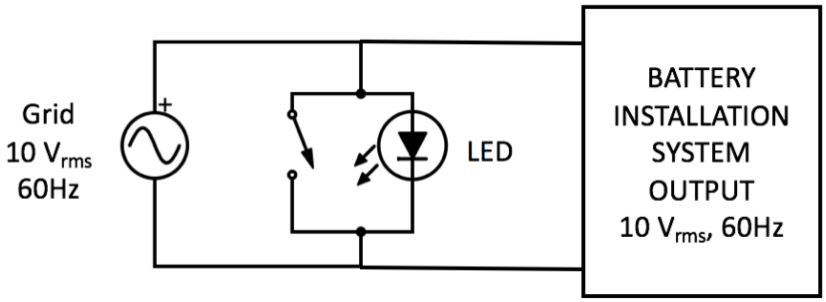


Figure 36. Synchronization circuit

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. With the switch open, the red LED will illuminate. It will start to turn on and off at a determined frequency.

2. When the LED is completely OFF (or dimmest), the switch should be closed.

   a. This is made even easier using an oscilloscope with two probes. The user should connect a probe to both inputs of the synchronization circuit and look at the waveforms. The switch needs to be closed when the waveforms are in phase. This method also is more visually demonstrative of the synchronization process.

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

Firstly, the synchronization circuit was tested using two different Agilent Function Generators 33120A, that generated sinusoidal waveforms with the same amplitude and slightly different frequencies, however it did not work as expected. In the oscilloscope, it could be observed the point when the two waveforms were in phase. However, when the switch was pressed, the waveform started to change its amplitude. After significant research, we realized that in order to put two generators in phase, at least one should be a spinning generator, which could change the rotating speed to slightly modify the frequency. As our grid did not include any spinning generators, an alternative was investigated in order to integrate the batteries with the grid.

We then tried using a grid-tie inverter, which converts direct current into alternating current suitable for injecting into the power grid, but it did not accomplish what we were looking for, as it only worked when connected to the 120V of the wall outlet but not when connected to the $10V_{rms}$ of our grid. As this type of inverters are normally used for connecting solar panels to the grid, they are usually designed to be connecter either to 120V, 60Hz or to 230V, 50Hz.

Therefore, a possible solution would be to build a customized inverter, consisting mainly of a H-Bridge PWM switching circuit. However, the complexity of building such inverter would require a project focused only in its construction and testing.

4.6. Enclosure and final details

The project was finished using electrical power cable wires, a red one for the live wire and a black one for the neutral wire. These connectors are able to handle 5A, which is a higher value than the maximum current of the grid (2A). For components that needed to be connected and disconnected depending on the experiment, such as the batteries, male and female XT60 connectors were used to make the connections more professional and easier for the user.

The various subsystems needed to be assembled in an organized way in a compact, easy to transport enclosure with easy access to the batteries such that they can be swapped when the user decides. For these reasons, the overall project was placed on a rigid base made out of wood, with dimensions 75x60 cm. Every component except for the Variac, which was outside the board due to its significant size and weight, was stuck to the wood base.

In order to safeguard the users from the exposed voltage leads of the circuitry and power supplies of the system, a plexiglass cover was built to isolate the components from the user for precaution. A hole was made in the back of it so that the user could swap the batteries when the experiment finished. In addition, a 3A circuit breaker was connected to protect the grid from high currents. Figure 37 shows the final aspect of the project.

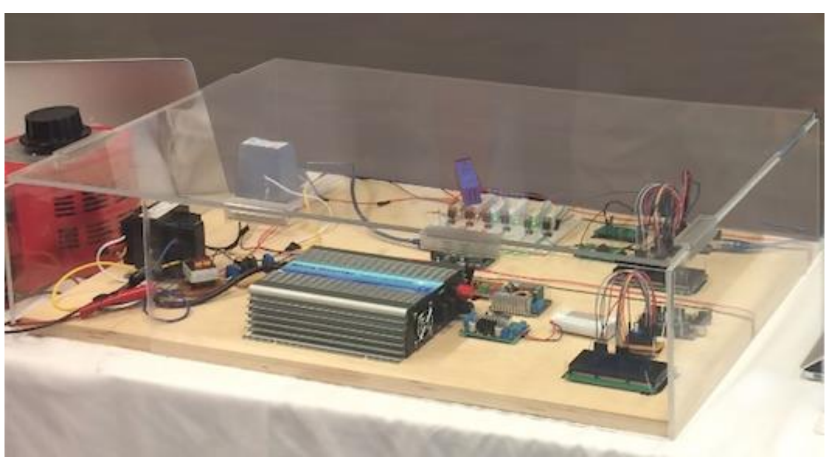


Figure 37. Final project with enclosure

CHAPTER V: ANALYSIS OF RESULTS

In order to analyze the results, the initial objectives and requirements of the project will be considered. Firstly, this section will focus on the load subsystem. Then, the complete project will be examined.

The load subsystem has been successfully accomplished due to several reasons. The main objective, which was simulating the summer electricity demand curve in New England has been achieved. Not only has the summer demand curve been programmed, but also the code has been made simple to interact with such that the user can easily simulate a different demand curve.

Although there were no requirements related to the simulation time, the code has been programmed in a flexible way, so the user can modify the simulation time according to his own criteria. Almost any simulation time can be chosen, however, the minimum time proposed is 3 minutes, in order to have time enough to observe what is happening in the grid. Other times proposed are 6 minutes and 30 minutes.

The final PCB of the power load has been completed, giving the load subsystem an appropriate and professional finish. In addition, the LEDs included turn out to be of great help for the user to know when each resistor is connected or disconnected.

The requirements affecting the load subsystem and their grade of accomplishment are summarized in Table 12:

Requirement	Grade of accomplishment
The electricity demand will be modeled using some type of variable resistors	Completed Six different steps of power have been designed

The variable load needs to be able to represent different demand curves to test the batteries in different scenarios.	Completed The code can easily be modified to represent a different demand curve
The voltage must range between 0-30V ±5%	Completed The grid voltage is $10V_{rms}$ ± 5%
The maximum current in the grid should not exceed 3A.	Completed The maximum current of the grid is 2A

Table 12. Load system requirements and grade of accomplishment

On the other hand, according to the complete project, around 85% of it has been successfully accomplished.

The generation and distribution subsystem achieves its main objective. It provides a $10V_{rms}$ waveform to the mock grid and simulates the transmission lines by stepping the voltage up and down.

The data acquisition and display system effectively displays in real time voltage, current and power in significant spots of the grid. In addition, it stores the results obtained for future analysis in an excel file.

The battery installation subsystem has not fulfilled all the requirements. The original bidirectional DC-DC and DC-AC converters had to be modified moving to two different branches for charging and discharging. The charging stage has been completely accomplished. However, the problems with the DC-AC inverter and the synchronization described in the section above, have impeded the integration of the discharging stage in the grid. Due to this inconvenient, batteries could not be totally tested and analyzed.

The rest of requirements of the project are the following:

Requirement	**Grade of accomplishment**
The mock grid will work in AC	Completed. The Variac provides AC voltage to the grid
The transmission and distribution grid must be modeled by stepping up and down the voltage	Completed Two different transformers step up and down the voltage
Different battery chemistries should be tested	Not accomplished Due to several problems in the integration, batteries could not be finally tested
DC sources should be converted to AC	Partially accomplished DC voltage of the batteries was converted to AC, but not integrated with the grid.
The initial conditions of the system should be replicated for each experiment with different battery chemistries	Completed The same system conditions can be used for different battery chemistries
The inverter must be bidirectional	Modified Two different branches for charge and discharge
The overall grid should be monitored to know the current, voltage and power in the generation, batteries and loads.	Completed The grid characteristics are measured using voltage and current sensors
Current, voltage and power should be displayed in real time in significant spots of the grid.	Completed LCDs display measurements in real time

The data will be automatically displayed after a test.	Completed The software Processing allows to display the data collected after the experiment
Data of each experiment must be stored for further analysis	Completed The software Processing allows to store the data
The project will be a physical small-scale mock grid	Completed The project is a physical scaled down $10V_{rms}$ mock grid
The interface needs to be user-friendly	Completed Appropriate connectors and interactive components make the mock grid easy to use
The overall project should be put into some type of enclosure	Completed A wood base supports the project and a plexiglass enclosure covers it
The utility grid model should be able to fit through a standard door	Completed The dimensions of the project are 75x60 cm
Some type of electrical security system should be implemented	Completed A circuit breaker has been connected to prevent the grid from high currents

Table 13. Project requirements and grade of accomplishment

CHAPTER VI: BUDGET

Due to the considerable number of components used in this project, the budget has been divided in the four subsystems: generation and distribution, loads, battery installation and data acquisition and display (Table 14). Shipping costs are included in the price of each item. Although not all of the items included in the budget were used in the finished project, all of them were necessary for its realization.

LOAD SUBSYSTEM			
Item	**Quantity**	**Unit price**	**Total price**
NTE 56050 TRIAC	1	12.36	12.36
IRF520 MOSFET	6	2.83	17.00
IRF520 Driver	6	3.26	19.57
100 W, 12 V light bulb, Philips	1	9.99	9.99
100 W, 12V halogen light bulb, Sunlite	1	6.23	6.23
IL420, optocoupler, Vishay	7	4.80	33.60
10 pieces, 30 Ω, 10 W ceramic resistors	2	20.64	41.27
TRIAC NTE 5645	7	8.20	57.40
Optocoupler 4N25, Phototransistor	1	5.75	5.75
Optoisolator NTE 3220	1	7.51	7.51
MOSFET IRF510	7	1.00	7.00
Green 5mm/3mm LED	6	0.40	2.40
Printed circuit board	5	6.69	33.45
TOTAL	$253.53		
GENERATION AND DISTRIBUTION			
Item	**Quantity**	**Unit price**	**Total price**
4VZF5 Cls 2 Transformer, Open, Foot	2	35.72	71.45
Philmore TR121 12VCT 1A Power Transformer	1	13.67	13.67
Variac variable AC Power Transformer 0-130V	1	73.99	73.99

TOTAL	$159.11		
BATTERIES INSTALLATION			
Item	**Quantity**	**Unit price**	**Total price**
MBRB2545CT (Diode)	3	1.59	4.77
LT3748	4	7.43	29.72
IRFH6200 (Power Mosfet)	2	1.75	3.50
LT1716	2	2.50	5.00
NMOSFET	1	1.00	1.00
Iher	1	1.00	3.00
NMOS	1	1.00	1.00
Solder Kit	1	20.00	20.00
EK 307 Kit	1	19.99	19.99
Tape	1	6.90	6.90
Ferrit Core	1	5.80	5.80
Clamp, U Shaped Clip	1	1.36	1.36
Coil Former Vertical	1	1.16	1.16
Solder	1	10.00	10.00
Copper Wire	1	9.46	9.46
ANBES Soldering Iron Kit Electronics, 60W	1	19.99	19.99
DC-DC converter PCB	5	8.34	41.72
DROK DC Buck Converter	1	10.99	10.99
DROK LTC1871 3.5-30V DC Boost Converter	1	15.95	15.95
eBoot 5 Pack Boost Converter Module XL6009	1	12.59	12.59
DROK LM2596 Buck Converter DC-DC 4-32V	1	8.89	8.89
Car Inverter	1	11.80	11.80
BESTEK Pure Sine Wave 300W Power Inverter	1	43.99	43.99
Enkey 150W Car Inverter 12V DC-110V AC	1	11.80	11.80
Grid Tied Inverter	1	94.00	94.00
Lithium Ion Battery	1	13.29	13.29

1600 mAh BBTY0651101 Phone Battery	1	8.99	8.99
orlov 50pcs 18650 Battery Holder	1	11.99	11.99
10PCS 3.7V 5000mAh 18650 Batteries	1	15.99	15.99
UPG UB645 Sealed Lead Acid Batteries 2 packs	1	15.25	15.25
2 of GEILIENERGY 8 Pieces Set AA NiCd	2	3.94	7.89
AuBreey 5PCS/LOT 2S 3A Li-ion 7.4v 8.4V	1	6.99	6.99
18650 5000mah Li-Ion batteries	1	15.99	15.99
Battery Protection Circuit	5	1.40	7.00
Circuit breaker, 3A, NTE	1	12.99	12.99
Battery Switch Scheme PCB	1	20.47	20.47
TOTAL	$531.22		
DATA ACQUISITION AND DISPLAY			
Item	**Quantity**	**Unit price**	**Total price**
Current sensor and voltage sensor PCB	10	3.14	31.37
RioRand LCD Screen	5	11.62	58.11
Uxcell SCT-013-005	4	28.58	114.33
Arduino Uno board	1	10	10
Current Sensors	1	9.34	9.34
TOTAL	$223.15		
Total Hardware Expenses	$1,167.01		

Table 14. Budget

Table 15 contains the equipment used for testing purposes. This equipment was facilitated by Boston University Senior Project and Electronics laboratories.

Equipment	Specifications
Agilent triple DC power supply E3631A	80W, 0 - 6V, 5A / 0 - ±25V, 1A
Agilent Function Generator 33120A	15 MHz
B&K Precision 1653A AC Power Supply	150V, 2A
Lecroy Wavesurfer Oscilloscope	500 MHz
Agilent MSO6012A mixed signal oscilloscope	100 MHz
Agilent 34401A Digital multimeter	1000V max voltage input, 3A max current input
MPJA 15845-TL Soldering station	-

Table 15. Equipment used for testing purposes

Two were the principal funding sources of this project. On one hand, Boston University reimbursed each senior design project with $500 for purchased items.

On the other hand, this project was awarded a $5,000 Technical Design Project scholarship from the American Public Power Association's Demonstration of Energy and Efficiency Developments (DEED) program. The grant also included $3,000 in travel funds which were used to showcase our work at the Association's Engineering & Operations Technical Conference, which was held April 29th - May 2nd in Raleigh, North Caroline.

CHAPTER VII: CONCLUSION

7.1. CONCLUSION

The load subsystem, main axis of this project, has been effectively accomplished. Although the design has been modified several times during the transition of the course, it finally achieved all its objectives and requirements, resulting in an appropriate PCB connected to a microcontroller able to simulate different power demand curves. The main characteristic of the resulting circuit is its flexibility, allowing the user to modify both the power steps of the demand curve and the simulation time.

According to the overall project, the major part of the subsystems has been completed successfully. Our mock grid provides AC power to the variable load and voltage, current and power are displayed in real time in significant spots of the grid. In addition, data can be stored for further analysis. The battery installation system is the one that has not covered all its expectations. Although special effort was put in the integration of the batteries, we did not manage to successfully operate the discharging stage due to the problems with the inverter. With the lessons learned while working on this project and future work, batteries could be completely integrated in the grid and tested in depth.

The main difficulty we have found during the fulfillment of the present project is that, unlike computer simulations, where variables are fixed previously, in the physical model developed, several unpredictable variables intervene altering the normal operation of it. However, this results essential when putting into practice an ambitious project with considerable advantages in the future use of energy.

7.2. Recommendations For Future Improvements

Although significant accomplishments have been achieved with regards to this project, several features could be added in order to develop a more sophisticated power grid with battery storage. This section goes through the major modifications that could be made in each of the subsystems of the project.

In the generation and distribution subsystem, the transmission lines could be modeled with inductors, resistors and capacitors and these values could be made adjustable to study how the line behaves depending on its inductance, resistance and capacitance.

In the load subsystem, the variable loads are purely resistive loads. Inductors and capacitors could be added to simulate a more realistic load, by making the phase shifts disproportionate to the grid leading to compensation techniques.

In the data acquisition and display system, a circuit able to measure the power factor in the loads could be designed and fabricated, and important battery characteristics could be measured such as the rate of charge/discharge, the state of charge (battery capacity as a percentage of maximum capacity), charge/discharge efficiency and memory effect, reduction of the amount of energy that can be extracted when charging a partially charged battery.

The battery installation system is the part that needs the biggest amount of work. On one hand, a grid-tie inverter able to make the batteries discharge power to the grid should be either bought or build.

On the other hand, a control system to make the batteries charge and discharge automatically could be implemented, instead of a LED notifying the user to charge or discharge them. A proposed way to do this is to use two diodes and two MOSFETs in the configuration of Figure 38. When batteries should charge, MOSFET number 2 is ON and diode 2 is conducting (case represented in the figure). On the other hand, when batteries should discharge, MOSFET 2 is OFF, and MOSFET 1 is ON and diode 1 is conducting.

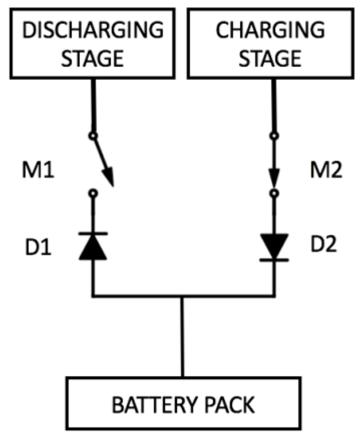


Figure 38. Proposed switching circuit for charging and discharging

As the power being consumed by the load is being measured with Arduino, a program could be written to charge or discharge the batteries, triggering one or the other MOSFET, depending on the value of the power consumed that Arduino is calculating.

Finally, as a complement to the physical simulation, a computer simulation could be designed and its results could be compared with the actual results of the physical mock grid.

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Part II: Annexes

CHAPTER I. DEMAND CURVE CODE

The demand curve has been programmed to be easily customizable. Both the power steps in the curve and the simulation time (time it takes to simulate one demand curve) can be selected.

In order to modify the demand curve, the switching of the TRIACs must be changed, by writing digitalWrite(AC_LOAD_P, HIGH or LOW), where P is the correspondent AC load number, in each simulated hour of the code.

According to the simulation time, three times have been proposed: 3 minutes, 6 minutes and 30 minutes. Once this time has elapsed, the demand curve will start again from the beginning. The instructions for modifying the simulation time are the following:

3 minutes code: The variable time in the code should be set to 7,500.

6 minutes code: The variable time in the code should be set to 15,000.

30 minutes code: The variable time in the code should be set to 75,000.

X minutes code: The variable time in the code should be set to Y, where Y is:

$$Y\ (miliseconds) = \frac{X\ minutes}{24} \cdot 60 \cdot 1000$$

The programmed code is the following:

```
                    AC LOAD - SIMULATION X MINUTES

int AC_LOAD_1 = 3;
int AC_LOAD_2 = 5;
int AC_LOAD_3 = 6;
int AC_LOAD_4 = 9;
int AC_LOAD_5 = 10;
int AC_LOAD_6 = 11;
int LED_1 = 1;
int LED_2 = 2;
int LED_3 = 4;
int LED_4 = 7;
int LED_5 = 8;
int LED_6 = 12;
float time;

void setup()
{
  pinMode(AC_LOAD_1, OUTPUT);
  pinMode(AC_LOAD_2, OUTPUT);
  pinMode(AC_LOAD_3, OUTPUT);
  pinMode(AC_LOAD_4, OUTPUT);
  pinMode(AC_LOAD_5, OUTPUT);
  pinMode(AC_LOAD_6, OUTPUT);

  pinMode(LED_1,OUTPUT);
  pinMode(LED_2,OUTPUT);
  pinMode(LED_3,OUTPUT);
  pinMode(LED_4,OUTPUT);
  pinMode(LED_5,OUTPUT);
  pinMode(LED_6,OUTPUT);

  time=Y;
 }


  void loop(){

    // 0-1 hour
    digitalWrite(AC_LOAD_1, HIGH);
    digitalWrite(LED_1, HIGH);
    digitalWrite(AC_LOAD_2, HIGH);
    digitalWrite(LED_2, HIGH);
    digitalWrite(AC_LOAD_3, HIGH);
    digitalWrite(LED_3, HIGH);
    digitalWrite(AC_LOAD_4, HIGH);
    digitalWrite(LED_4, HIGH);
    digitalWrite(AC_LOAD_5, LOW);
    digitalWrite(LED_5, LOW);
    digitalWrite(AC_LOAD_6, LOW);
    digitalWrite(LED_6, LOW);
    delay(time);
```

```
//1-2 hour
delay(time);

//2-3 hour
digitalWrite(AC_LOAD_4, LOW);
digitalWrite(LED_4, LOW);
delay(time);

//3-4 hour
delay(time);

//4-5 hour
delay(time);

//5-6 hour
delay(time);

//6-7 hour
digitalWrite(AC_LOAD_4, HIGH);
digitalWrite(LED_4, HIGH);
delay(time);

//7-8 hour
delay(time);

//8-9 hour
digitalWrite(AC_LOAD_5, HIGH);
digitalWrite(LED_5, HIGH);
delay(time);

//9-10 hour
delay(time);

//10-11 hour
delay(time);

//11-12 hour
digitalWrite(AC_LOAD_6, HIGH);
digitalWrite(LED_6, HIGH);
delay(time);

 //12-13 hour
delay(time);

 //13-14 hour
delay(time);

 //14-15 hour
delay(time);

 //15-16 hour
delay(time);
```

```
    //16-17 hour
    delay(time);

    //17-18 hour
    delay(time);

    //18-19 hour
    delay(time);

    //19-20 hour
    delay(time);

    //20-21 hour
    delay(time);

    //21-22 hour
    digitalWrite(AC_LOAD_6, LOW);
    digitalWrite(LED_6, LOW);
    delay(time);

    //22-23 hour
    delay(time);

    //23-24 hour
    digitalWrite(AC_LOAD_5, LOW);
    digitalWrite(LED_5, LOW);
    delay(time);

}
```

CHAPTER II. USER MANUAL

This user manual has four different parts: a software report, where the software needed for this project is detailed: where to download it and the steps that must be followed to run the programs; a hardware report, which describes the interaction between the user and the physical components of the project, as well as the instructions to operate them; an abnormal conditions section, which solves some of the main problems when running the project and finally safety issues that should be taken into account by the user.

Software Report

Only two subsystems of the mock grid use software. These are the power load and the data acquisition and display subsystems.

Power Load

The program for the power load system is run using Arduino, version 1.8.4. It is open source and can be downloaded from https://www.arduino.cc/en/Main/OldSoftwareReleases#previous. The installation procedures are as follow:

-For Windows:

1. Get the version 1.8.4 from the website: https://www.arduino.cc/en/Main/OldSoftwareReleases#previous. You can choose between the Installer (.exe) and the Zip packages. We suggest you use the first one that installs directly everything you need to use the Arduino Software (IDE), including the drivers. With the Zip package, you need to install the drivers manually.
2. When the download finishes, proceed with the installation and allow the driver installation process when you get a warning from the operating system.
3. Choose the components to install
4. Choose the installation directory

5. The process will extract and install all the required files to execute properly the Arduino Software (IDE)

-For Mac OS X:

1. Get the version 1.8.4 from https://www.arduino.cc/en/Main/OldSoftwareReleases#previous website. Select Mac OS X. The file is in Zip format; if you use Safari it will be automatically expanded. If you use a different browser you may need to extract it manually.
2. Copy the Arduino application into the Applications folder.

The next procedure is to connect Arduino UNO to the computer and run the code:

1. Before you can move on, you must have installed the Arduino Software (IDE) on your PC (see installation procedures above).

2. Connect your Arduino Uno board with a USB printer cable. The green power LED (labelled PWR) should go on. The USB connection with the PC is necessary to program the board and not just to power it up. The Uno automatically draw power from either the USB or an external power supply.

3. Install the board drivers:

   - If you used the Installer, Windows (from XP up to 10) will install drivers automatically as soon as you connect your board.
   - If you downloaded and expanded the Zip package or, for some reason, the board wasn't properly recognized, please follow the procedure below.

     1. Click on the Start Menu, and open up the Control Panel.
     2. While in the Control Panel, navigate to System and Security.
     3. Next, click on System.
     4. Once the System window is up, open the Device Manager. Look under Ports (COM & LPT). You should see an open port named "Arduino

UNO (COMxx)". If there is no COM & LPT section, look under "Other Devices" for "Unknown Device".

5. Right click on the "Arduino UNO (COMxx)" port and choose the "Update Driver Software" option.

6. Next, choose the "Browse my computer for Driver software" option.

7. Finally, navigate to and select the driver file named "arduino.inf", located in the "Drivers" folder of the Arduino Software download (not the "FTDI USB Drivers" sub-directory). If you are using an old version of the IDE (1.0.3 or older), choose the Uno driver file named "Arduino UNO.inf". Windows will finish up the driver installation from there.

4. Open the sketch (the code for the power demand curve simulation is provided in the previous chapter)

5. Select the board type and port. You'll need to select the entry in the Tools > Board menu that corresponds to your Arduino or Genuino board. In our case, we have to select Arduino Uno.

6. Select the serial device of the board from the Tools | Serial Port menu. This is likely to be COM3 or higher (COM1 and COM2 are usually reserved for hardware serial ports). To find out, you can disconnect your board and re-open the menu; the entry that disappears should be the Arduino or Genuino board. Reconnect the board and select that serial port.

7. Compile and upload the program

Now, simply click the "Upload" button in the environment. Wait a few seconds - you should see the RX and TX LEDs on the board flashing. If the upload is successful, the message "Done uploading." will appear in the status bar.

A few seconds after the upload finishes, you should see some of the green LCDs in the power load PCB turning on. If they do, you have gotten the code running correctly.

Data Acquisition

The data acquisition subsystem uses both Arduino and Processing software. The Arduino installation procedure can be found in the power load section above. As for the Processing software, the installation procedure is as follows:

Visit http://processing.org/download and select the Mac, Windows, or Linux version, depending on what machine you have.

- On Windows, you'll have a .zip file. Double-click it, and drag the folder inside to a location on your hard disk. It could be Program Files or simply the desktop, but the important thing is for the processing folder to be pulled out of that .zip file. Then double-click processing.exe to start.

- The Mac OS X version is also a .zip file. Double-click it and drag the Processing icon to the Applications folder. If you're using someone else's machine and can't modify the Applications folder, just drag the application to the desktop. Then double-click the Processing icon to start.

- The Linux version is a .tar.gz file, which should be familiar to most Linux users. Download the file to your home directory, then open a terminal window, and type: `tar xvfz processing-xxxx.tgz` (Replace xxxx with the rest of the file's name, which is the version number.) This will create a folder named processing-2.0 or something similar. Then change to that directory: `cd processing-xxxx` and run it: `./processing`

In order for the Processing code to run correctly two libraries need to be installed: “Grafica” and “Arduino (Firmata)”. To install a library open Processing, select Sketch > Import library and search the name of the library, in this case “Grafica” and “Arduino (Firmata)”. Once the library is selected just click install.

The steps after installation are connecting the Arduino to your computer and running the programs in Arduino and Processing. This can be done as follows:

1. Connect the Arduino, upload a program and run the program "Measurement_AC" and "Measurement_DC" (a guide on how to connect Arduino to your computer and run a program can be found in the power load section of this document).

2. Open Processing, open the sketch "Display and storage", compile it and run it (clicking the "Upload" button in the environment). It is important to notice that the Arduino program has to be run first. While this program is running the user should run the Processing program. An error will show up if you invert the order.

3. Save the data in Excel: After the test is finished a .csv file will be created in the folder where the "Display and storage" is located. The user has to import the file as follows:

   a. Open Excel

   b. 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.

   c. The user should now have the file in the right format so it can be saved normally in Excel. Select File > Save as

Generation

The main power supply providing current to the resistive loads is the Variac. In order to operate it, 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 $10V_{rms}$, the black knob on the top of the Variac must be set to $14.14V_{AC}$, until we make sure the LCD screen that displays the voltage and current of the source indicates $10V_{rms}$.

Power Load

The load subsystem requires almost no user interaction, as it has been designed to follow the demand curve automatically. However, several steps must be followed to connect the PCB correctly before running the code.

The power load system consists of a PCB that is connected to Arduino. The PCB has three main headers: the biggest one (header number one), with 14 inputs, is for the connection to Arduino, the two small ones (headers number two and three), with two inputs each are for connecting the power and the measurement (voltage sensor) PCB. Figure 39 shows the three different headers.

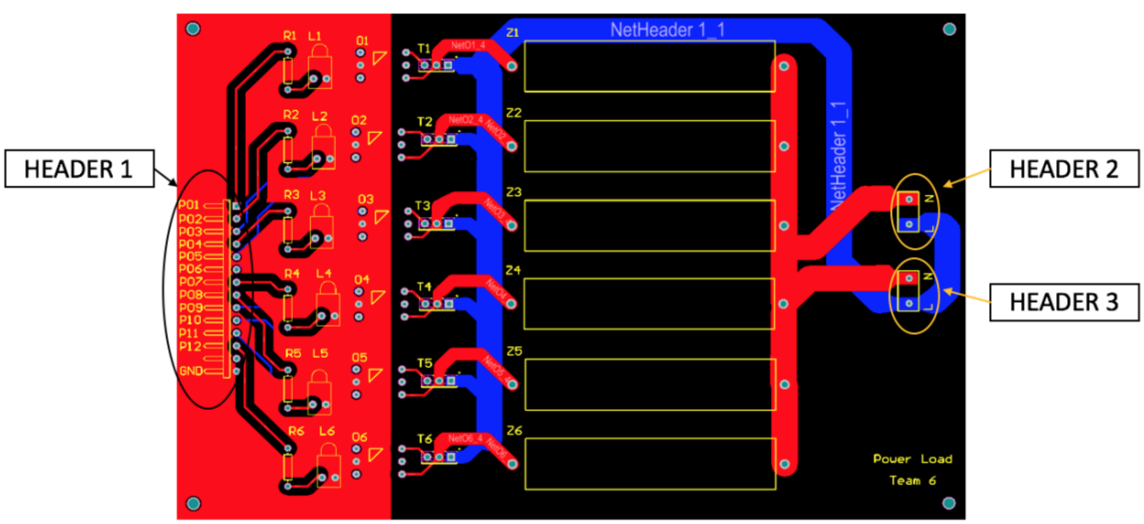


Figure 39. Power Load PCB headers

The connections of each spot of the big header to Arduino are specified in Table 16:

Header 1 inputs	Arduino UNO pin
1	Digital output 1
2	Digital output 2
3	Digital output 3
4	Digital output 4
5	Digital output 5
6	Digital output 6
7	Digital output 7
8	Digital output 8
9	Digital output 9
10	Digital output 10
11	Digital output 11
12	Digital output 12
14	GND

Table 16. Connections Power Load PCB – Arduino Uno

Header number two is connected to the output of the second transformer of the grid, which will power the loads. The red wire should be connected to the L (live) input of the header, and the black wire should be connected to the N (neutral) input.

Header number three is used to connect the data acquisition system to measure the current and voltage consumed by the load in each instant of time. As in the last header, the red wire should be connected to the L input of the header, and the black wire should be connected to the N input.

When all the connections are done, the user needs to connect the USB to Arduino and run the appropriate program as explained in the software section. Once the program is running, the user needs to make sure that some of the LEDs have turned on and that the current of the LCD near the load changes at the same time a new LED is turned on or off.

Data Acquisition

For the power measurement, there are two circuits: the voltage and current sensor, that will be used to calculate the power at significant points of the grid. Each voltage sensor PCB has a header that must be connected to a $15V_{DC}$ power supply, and another header for its connection to Arduino.

There are four voltage sensors that will be connected in parallel in four different points. These points are:

- The load subsystem
- The low transformer side (output of the grid)
- The high side of the transformer in the discharging battery circuit.
- The batteries.

To measure the current, a current probe clamp will be coupled to the correspondent wires of the spots of the grid mentioned above. There are four current sensors that will be connected differently depending on the type:

- SCT-013-005: There are two current sensors of this type. The first one will be clipped on the red wire of the loads. The second will be clipped on the red wire of the low side of the second grid transformer.

- ACS172: There are two current sensors of this type. The first one will be connected in series with batteries at the discharging circuit and the second one will be connected in series with the batteries at the charging circuit.

These sensors will be connected to Arduinos. The two ACS172 sensors and one voltage sensor will be connected to the same Arduino in Analog pins 1, 2 and 3. One of the SCT-013-005 sensors will be connected with one voltage sensor to another Arduino board. The other SCT-013-005 sensor will be connected as well with one voltage sensor to an Arduino. The last voltage sensor will be connected to the forth Arduino.

Arduino will read these measurements and by multiplying the voltage by the current we get the power. 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.

In order to display the measurements, four different LCD screens need to be connected. Each LCD screen is already connected to a small yellow perfboard that contains the potentiometer able to change the brightness of the screen. In addition, each LCD screen should be connected to a different Arduino as follow:

LCD screen pin	Arduino digital pin
4	8
6	9
11	4
12	5
13	6
14	7

Table 17. Connections LCD screen and Arduino

When all the connections are done, the user needs to follow the instructions for displaying and acquiring the data explained in the software section.

Battery Installation

There are two modes of operation for 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 this case the Variac transformer. To discharge the batteries, a switch on the DC-AC inverter is enabled to discharge the DC current from the batteries into AC for the load on the grid.

In order to achieve this a switch scheme has been implemented. When it is time for charging, i.e. a red LED is on, the user will toggle on the first switch while the other switch is off. For discharging, when the white LED is on, 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 as it can disrupt any data analysis as well as damage the circuit of the battery installation system.

The batteries will not be charging/discharging at all times, so isolation of the battery installation from the grid is vitally important.

<u>Instructions for Operation</u>

Charging Stage:

1. From a parallel connection from the "transmission line" of the power grid, connect the XT360 connector to that of the full bridge rectifier circuit
    a. Make sure the input voltage of the full bridge rectifier is $10V_{rms}$
    b. The output of the rectifier should be $12V_{DC}$
2. Connect the output of the full bridge rectifier to the input of the DROK DC Car Power Supply Voltage Regulator Buck Converter

a. The buck converter has a potentiometer where the output voltage can be set by using a flat head screwdriver and turning the knob until the LED display shows the voltage for the following battery packs:

i. $8.4V_{DC}$ for the Lithium- Ion pack

ii. $9.3V_{DC}$ for the Nickel Cadmium Pack

3. Connect the output of the buck converter to the charge stage via the switch on the battery switch scheme PCB

Discharging Stage:

1. Connect the battery to the battery switch scheme PCB and enable the discharge stage via the DPDT switch
2. Couple the output side of the switch scheme PCB to the DROK LTC1871 3.5V-30V DC Boost Converter Power Transformer Voltage Regulator.
   a. Using the potentiometer on the converter, use a flathead screwdriver to make the output of the boost converter to 11-$13V_{DC}$, voltage required to turn on the inverter
   b. Connect the output of the boost converter to the power inverter
3. Turn on the switch of the power inverter
   a. If the LED light turns green, the inverter is operational
   b. If the LED turns red there is a fault and the user should double check the connections
4. Couple the output of the inverter which is $110V_{rms}$ to a step-down transformer to get around $10V_{rms}$

Operating Mode: Abnormal Operations

Starting with the "power plant" of the mock power grid, a Variac transformer followed by two transformers were used to represent how voltages are stepped up and down in a real power grid network. There were no problems with the installation of these devices, however, just make a note that each transformer has a 3A circuit breaker. There were a couple of times when we were testing them and circuit breaker turned. When this happens, a black button on top of the transformer has to be pressed down so that it can be used.

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 that the connection between Arduino and the computer is correct, as well as the connection between the PCB and Arduino.

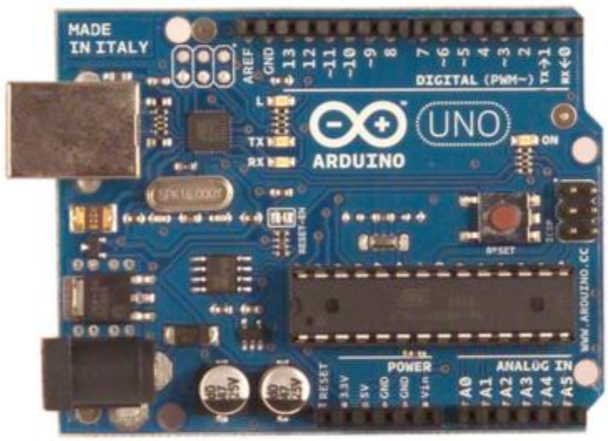
Once the overall grid is running, the LCD screens should display the voltage, current and power. If the screen is ON (light blue), but nothing is displayed, the user should try rotating the potentiometer of the yellow perfboard next to the screen in order to change the brightness of the screen. If this does not work, check the connections carefully.

Safety Issues

The project has an enclosure to secure the user's safety during operation. However, the Variac is outside of the enclosure with its input wires coming into it through a hole. The only precaution to the user is that the Variac should not exceed the reading of $10V_{rms}$ 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. In addition, the Variac has a built in 3A fuse.

Arduino UNO



Product Overview

The Arduino Uno is a microcontroller board based on the ATmega328 (datasheet). It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The Uno differs from all preceding boards in that it does not use the FTDI USB-to-serial driver chip. Instead, it features the Atmega8U2 programmed as a USB-to-serial converter.

"Uno" means one in Italian and is named to mark the upcoming release of Arduino 1.0. The Uno and version 1.0 will be the reference versions of Arduno, moving forward. The Uno is the latest in a series of USB Arduino boards, and the reference model for the Arduino platform; for a comparison with previous versions, see the index of Arduino boards.

Index

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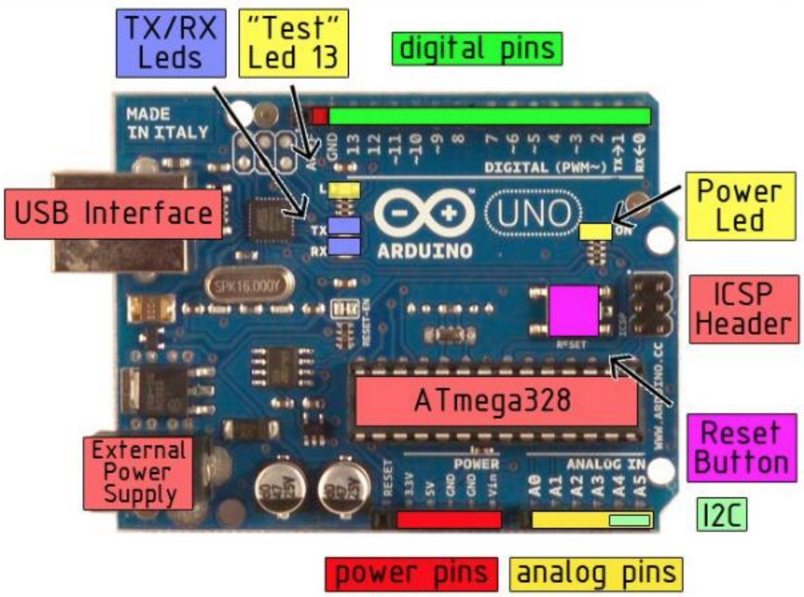
Technical Specification

EAGLE files: arduino-duemilanove-uno-design.zip Schematic: arduino-uno-schematic.pdf

Summary

Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB of which 0.5 KB used by bootloader
SRAM	2 KB
EEPROM	1 KB
Clock Speed	16 MHz

the board



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Power

The Arduino Uno can be powered via the USB connection or with an external power supply. The power source is selected automatically.

External (non-USB) power can come either from an AC-to-DC adapter (wall-wart) or battery. The adapter can be connected by plugging a 2.1mm center-positive plug into the board's power jack. Leads from a battery can be inserted in the Gnd and Vin pin headers of the POWER connector.

The board can operate on an external supply of 6 to 20 volts. If supplied with less than 7V, however, the 5V pin may supply less than five volts and the board may be unstable. If using more than 12V, the voltage regulator may overheat and damage the board. The recommended range is 7 to 12 volts.

The power pins are as follows:

- **VIN.** The input voltage to the Arduino board when it's using an external power source (as opposed to 5 volts from the USB connection or other regulated power source). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.
- **5V.** The regulated power supply used to power the microcontroller and other components on the board. This can come either from VIN via an on-board regulator, or be supplied by USB or another regulated 5V supply.
- **3V3.** A 3.3 volt supply generated by the on-board regulator. Maximum current draw is 50 mA.
- **GND.** Ground pins.

Memory

The Atmega328 has 32 KB of flash memory for storing code (of which 0,5 KB is used for the bootloader); It has also 2 KB of SRAM and 1 KB of EEPROM (which can be read and written with the EEPROM library).

Input and Output

Each of the 14 digital pins on the Uno can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 kOhms. In addition, some pins have specialized functions:

- **Serial: 0 (RX) and 1 (TX).** Used to receive (RX) and transmit (TX) TTL serial data. TThese pins are connected to the corresponding pins of the ATmega8U2 USB-to-TTL Serial chip .
- **External Interrupts: 2 and 3.** These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value. See the attachInterrupt() function for details.
- **PWM: 3, 5, 6, 9, 10, and 11.** Provide 8-bit PWM output with the analogWrite() function.
- **SPI: 10 (SS), 11 (MOSI), 12 (MISO), 13 (SCK).** These pins support SPI communication, which, although provided by the underlying hardware, is not currently included in the Arduino language.

- **LED: 13.** There is a built-in LED connected to digital pin 13. When the pin is HIGH value, the LED is on, when the pin is LOW, it's off.

The Uno has 6 analog inputs, each of which provide 10 bits of resolution (i.e. 1024 different values). By default they measure from ground to 5 volts, though is it possible to change the upper end of their range using the AREF pin and the analogReference() function. Additionally, some pins have specialized functionality:

- **I²C: 4 (SDA) and 5 (SCL).** Support I²C (TWI) communication using the Wire library.

There are a couple of other pins on the board:

- **AREF.** Reference voltage for the analog inputs. Used with analogReference().
- **Reset.** Bring this line LOW to reset the microcontroller. Typically used to add a reset button to shields which block the one on the board.

See also the mapping between Arduino pins and Atmega328 ports.

Communication

The Arduino Uno has a number of facilities for communicating with a computer, another Arduino, or other microcontrollers. The ATmega328 provides UART TTL (5V) serial communication, which is available on digital pins 0 (RX) and 1 (TX). An ATmega8U2 on the board channels this serial communication over USB and appears as a virtual com port to software on the computer. The '8U2 firmware uses the standard USB COM drivers, and no external driver is needed. However, on Windows, an *.inf file is required..

The Arduino software includes a serial monitor which allows simple textual data to be sent to and from the Arduino board. The RX and TX LEDs on the board will flash when data is being transmitted via the USB-to-serial chip and USB connection to the computer (but not for serial communication on pins 0 and 1).

A SoftwareSerial library allows for serial communication on any of the Uno's digital pins.

The ATmega328 also support I2C (TWI) and SPI communication. The Arduino software includes a Wire library to simplify use of the I2C bus; see the documentation for details. To use the SPI communication, please see the ATmega328 datasheet.

Programming

The Arduino Uno can be programmed with the Arduino software (download). Select "Arduino Uno w/ ATmega328" from the **Tools > Board** menu (according to the microcontroller on your board). For details, see the reference and tutorials.

The ATmega328 on the Arduino Uno comes preburned with a bootloader that allows you to upload new code to it without the use of an external hardware programmer. It communicates using the original STK500 protocol (reference, C header files).

You can also bypass the bootloader and program the microcontroller through the ICSP (In-Circuit Serial Programming) header; see these instructions for details.

The ATmega8U2 firmware source code is available . The ATmega8U2 is loaded with a DFU bootloader, which can be activated by connecting the solder jumper on the back of the board (near the map of Italy) and then resetting the 8U2. You can then use Atmel's FLIP software (Windows) or the DFU programmer (Mac OS X and Linux) to load a new firmware. Or you can use the ISP header with an external programmer (overwriting the DFU bootloader).

Automatic (Software) Reset

Rather than requiring a physical press of the reset button before an upload, the Arduino Uno is designed in a way that allows it to be reset by software running on a connected computer. One of the hardware flow control lines (DTR) of the ATmega8U2 is connected to the reset line of the ATmega328 via a 100 nanofarad capacitor. When this line is asserted (taken low), the reset line drops long enough to reset the chip. The Arduino software uses this capability to allow you to upload code by simply pressing the upload button in the Arduino environment. This means that the bootloader can have a shorter timeout, as the lowering of DTR can be well-coordinated with the start of the upload.

This setup has other implications. When the Uno is connected to either a computer running Mac OS X or Linux, it resets each time a connection is made to it from software (via USB). For the following half-second or so, the bootloader is running on the Uno. While it is programmed to ignore malformed data (i.e. anything besides an upload of new code), it will intercept the first few bytes of data sent to the board after a connection is opened. If a sketch running on the board receives one-time configuration or other data when it first starts, make sure that the software with which it communicates waits a second after opening the connection and before sending this data.

The Uno contains a trace that can be cut to disable the auto-reset. The pads on either side of the trace can be soldered together to re-enable it. It's labeled "RESET-EN". You may also be able to disable the auto-reset by connecting a 110 ohm resistor from 5V to the reset line; see this forum thread for details.

USB Overcurrent Protection

The Arduino Uno has a resettable polyfuse that protects your computer's USB ports from shorts and overcurrent. Although most computers provide their own internal protection, the fuse provides an extra layer of protection. If more than 500 mA is applied to the USB port, the fuse will automatically break the connection until the short or overload is removed.

Physical Characteristics

The maximum length and width of the Uno PCB are 2.7 and 2.1 inches respectively, with the USB connector and power jack extending beyond the former dimension. Three screw holes allow the board to be attached to a surface or case. Note that the distance between digital pins 7 and 8 is 160 mil (0.16"), not an even multiple of the 100 mil spacing of the other pins.

How to use Arduino

Arduino can sense the environment by receiving input from a variety of sensors and can affect its surroundings by controlling lights, motors, and other actuators. The microcontroller on the board is programmed using the Arduino programming language (based on Wiring) and the Arduino development environment (based on Processing). Arduino projects can be stand-alone or they can communicate with software on running on a computer (e.g. Flash, Processing, MaxMSP).

Arduino is a cross-platoform program. You'll have to follow different instructions for your personal OS. Check on the Arduino site for the latest instructions. *http://arduino.cc/en/Guide/HomePage*

Linux Install **Windows Install** **Mac Install**

Once you have downloaded/unzipped the arduino IDE, you can Plug the Arduino to your PC via USB cable.

Blink led

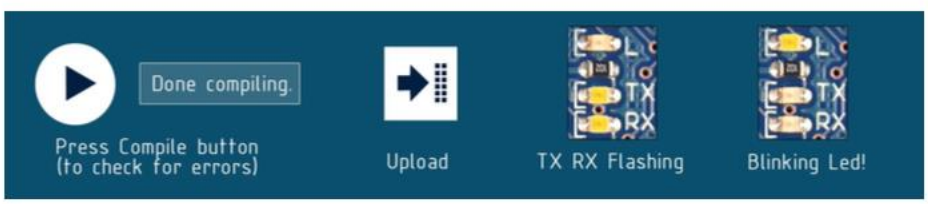
Now you're actually ready to "burn" your first program on the arduino board. To select "blink led", the physical translation of the well known programming "hello world", select

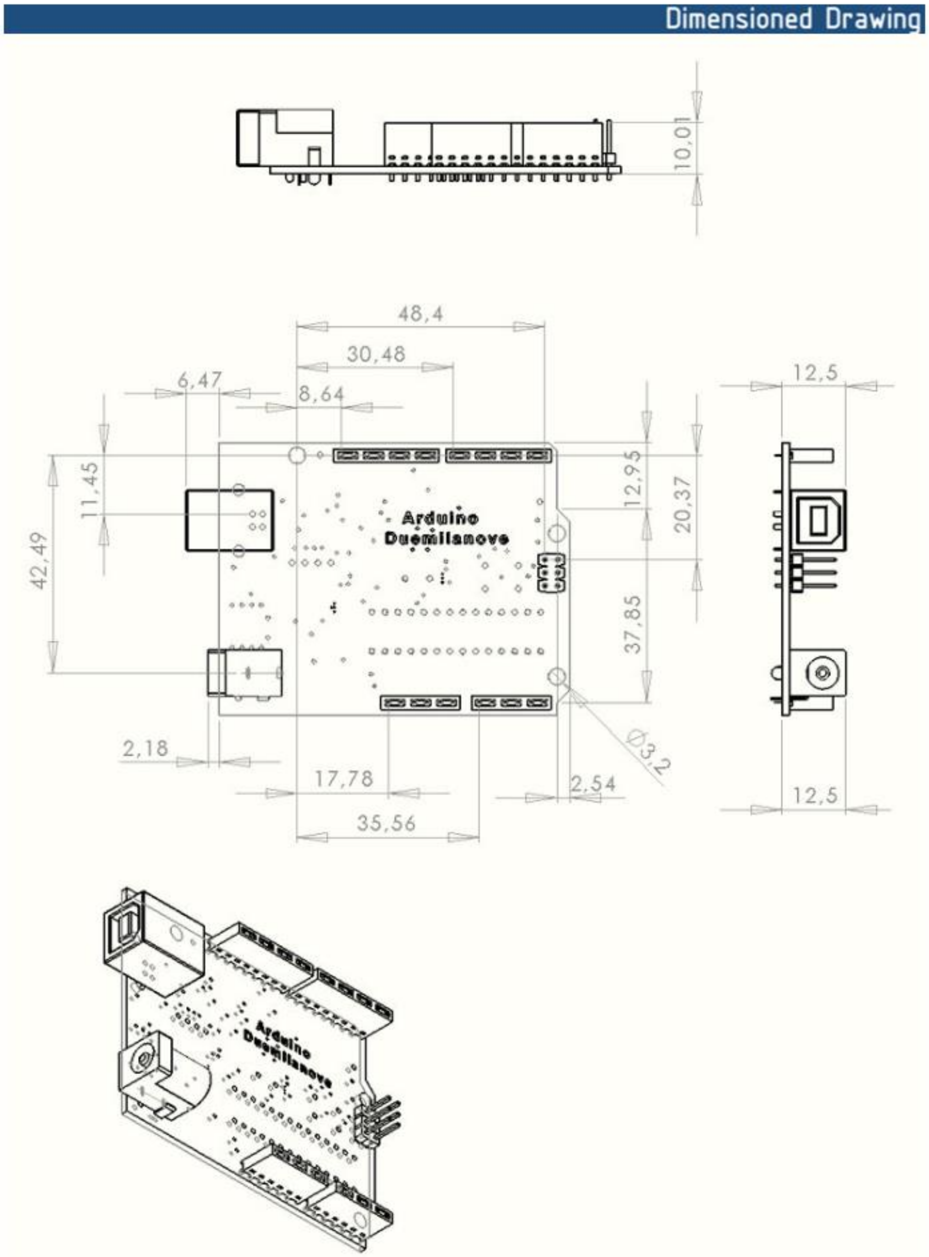
File>Sketchbook>
Arduino-0017>Examples>
Digital>Blink

Once you have your skecth you'll see something very close to the screenshot on the right.

In **Tools>Board** select

Now you have to go to
Tools>SerialPort
and select the right serial port, the one arduino is attached to.





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Terms & Conditions

1. Warranties

1.1 The producer warrants that its products will conform to the Specifications. This warranty lasts for one (1) years from the date of the sale. The producer shall not be liable for any defects that are caused by neglect, misuse or mistreatment by the Customer, including improper installation or testing, or for any products that have been altered or modified in any way by a Customer. Moreover, The producer shall not be liable for any defects that result from Customer's design, specifications or instructions for such products. Testing and other quality control techniques are used to the extent the producer deems necessary.

1.2 If any products fail to conform to the warranty set forth above, the producer's sole liability shall be to replace such products. The producer's liability shall be limited to products that are determined by the producer not to conform to such warranty. If the producer elects to replace such products, the producer shall have a reasonable time to replacements. Replaced products shall be warranted for a new full warranty period.

1.3 EXCEPT AS SET FORTH ABOVE, PRODUCTS ARE PROVIDED "AS IS" AND "WITH ALL FAULTS." THE PRODUCER DISCLAIMS ALL OTHER WARRANTIES, EXPRESS OR IMPLIED, REGARDING PRODUCTS, INCLUDING BUT NOT LIMITED TO, ANY IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE

1.4 Customer agrees that prior to using any systems that include the producer products, Customer will test such systems and the functionality of the products as used in such systems. The producer may provide technical, applications or design advice, quality characterization, reliability data or other services. Customer acknowledges and agrees that providing these services shall not expand or otherwise alter the producer's warranties, as set forth above, and no additional obligations or liabilities shall arise from the producer providing such services.

1.5 The Arduino™ products are not authorized for use in safety-critical applications where a failure of the product would reasonably be expected to cause severe personal injury or death. Safety-Critical Applications include, without limitation, life support devices and systems, equipment or systems for the operation of nuclear facilities and weapons systems. Arduino™ products are neither designed nor intended for use in military or aerospace applications or environments and for automotive applications or environment. Customer acknowledges and agrees that any such use of Arduino™ products which is solely at the Customer's risk, and that Customer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

1.6 Customer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products and any use of Arduino™ products in Customer's applications, notwithstanding any applications-related information or support that may be provided by the producer.

2. Indemnification

The Customer acknowledges and agrees to defend, indemnify and hold harmless the producer from and against any and all third-party losses, damages, liabilities and expenses it incurs to the extent directly caused by: (i) an actual breach by a Customer of the representation and warranties made under this terms and conditions or (ii) the gross negligence or willful misconduct by the Customer.

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Enviromental Policies

The producer of Arduino™ has joined the Impatto Zero® policy of LifeGate.it. For each Arduino board produced is created / looked after half squared Km of Costa Rica's forest's.

ELECTRONICS, INC.
44 FARRAND STREET
BLOOMFIELD, NJ 07003
(973) 748–5089

NTE5645
TRIAC – 10A
Isolated Tab

Description:

The NTE5645 is an 10 Amp TRIAC in a TO220 type package designed to be driven directly with IC and MOS devices and features proprietary, void–free glass passivated chips.

This device is a bi–directional triode thyristor and may be switched from off–state to conduction for either polarity of applied voltage with positive or negative gate trigger current. The NTE5645 is designed for control applications in lighting, heating, cooling and static switching relays.

Absolute Maximum Ratings:

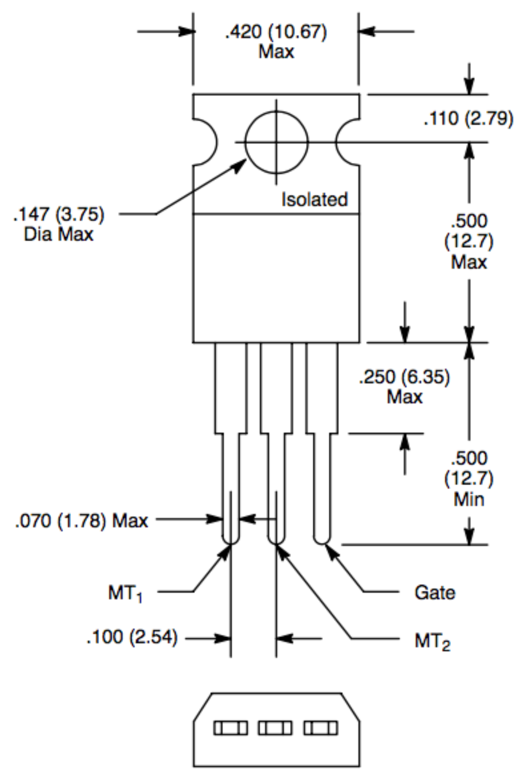
Repetitive Peak Off–State Voltage (Gate Open, T_J = +100°C), V_{DRM} 600V
RMS On–State Current (T_C = +75°C, Conduction Angle of 180°C), $I_{T(RMS)}$ 10A
Peak Surge (Non–Repetitive) On–State Current (One Cycle, 50Hz or 60Hz), I_{TSM} 100A
Peak Gate–Trigger Current (3μs Max), I_{GTM} 4A
Peak Gate–Power Dissipation ($I_{GT} \leq I_{GTM}$ for 3μs Max), P_{GM} 40W
Average Gate–Power Dissipation, $P_{G(AV)}$ 200mW
Operating Temperature Range, T_J . . . . . –40° to +150°C
Storage Temperature Range, T_{stg} . . . . . –40° to +100°C
Typical Thermal Resistance, Junction–to–Case, R_{thJC} . . . . . 2.5°C/W

Electrical Characteristics: (T_C = +25°C, Maximum Ratings unless otherwise specified)

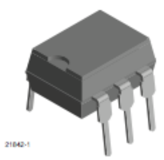
Parameter	Symbol	Test Conditions	Min	Typ	Max	Unit
Peak Off–State Current	I_{DRM}	V_{DRM} = 600V, Gate Open, T_J = +100°C	–	–	2	mA
Max. On–State Voltage	V_{TM}	I_T = 14A	–	–	2.2	V
DC Holding Current	I_H	Gate Open	–	–	50	mA
Critical Rate–of–Rise of Off–State Voltage	Critical dv/dt	V_D = 600V, Gate Open, T_C = +100°C	–	5	–	V/μs
DC Gate Trigger Current	I_{GT}	V_D = 12V, R_L = 30Ω				
T_2 (+) Gate (+), T_2 (–) Gate (–)			–	–	50	mA
T_2 (+) Gate (–), T_2 (–) Gate (+)			–	–	80	mA

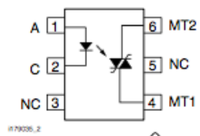
Electrical Characteristics (Cont'd): (T_C = +25°C, Maximum Ratings unless otherwise specified)

Parameter	Symbol	Test Conditions	Min	Typ	Max	Unit
DC Gate Trigger Voltage	V_{GT}	V_D = 12V, R_L = 30Ω	–	–	2.5	V
Gate–Controlled Turn–On Time	t_{gt}	V_D = 600V, I_{GT} = 80mA, t_r = 0.1μs, i_T = 10A (Peak)	–	2.5	–	μs



Optocoupler, Phototriac Output, High dV/dt, Low Input Current





DESCRIPTION

The IL420 and IL4208 consists of a GaAs IRLED optically coupled to a photosensitive non-zero crossing TRIAC network. The TRIAC consists of two inverse parallel connected monolithic SCRs. These three semiconductors are assembled in a six pin dual in-line package.

High input sensitivity is achieved by using an emitter follower phototransistor and a cascaded SCR predriver resulting in an LED trigger current of less than 2 mA (DC).

The use of a proprietary dV/dt clam results in a static dV/dt of greater than 10 kV/μs. This clamp circuit has a MOSFET that is enhanced when high dV/dt spikes occur between MT1 and MT2 of the TRIAC. When conducting, the FET clamps the base of the phototransistors, disabling the first stage SCR predriver.

The 600 V, 800 V blocking voltage permits control of offline voltages up to 240 VAC, with a safety factor of more than two, and is sufficient for as much as 380 V_{AC}.

The IL420, IL4208 isolates low-voltage logic from 120 V_{AC}, 240 V_{AC}, and 380 V_{AC} lines to control resistive, inductive, or capacitive loads including motors, solenoids, high current thyristors or TRIAC and relays.

FEATURES

- High input sensitivity I_{FT} = 2 mA
- 600 V, 800 V blocking voltage
- 300 mA on-state current
- High static dV/dt 10 kV/μs
- Very low leakage < 10 μA
- Isolation test voltage 5300 V_{RMS}
- Small 6-pin DIP package
- Material categorization: For definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT

APPLICATIONS

- Solid state relays
- Industrial controls
- Office equipment
- Consumer appliances

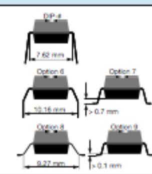
AGENCY APPROVALS

- UL1577, file no. E52744 system code H, double protection
- CSA 93751
- DIN EN 60747-5-5 (VDE 0884), available with option 1
- CQC: GB8898-2001

ORDERING INFORMATION

I	L	4	2	0	#	-	X	0	#	#	T

PART NUMBER — PACKAGE OPTION — TAPE AND REEL



AGENCY CERTIFIED/PACKAGE	BLOCKING VOLTAGE V_{DRM} (V)	
UL, cUL, CQC	**600**	**800**
DIP-6	IL420	IL4208
DIP-6, 400 mil, option 6	IL420-X006	-
SMD-6, option 7	IL420-X007T (1)	IL4208-X007T (1)
SMD-6, option 8	IL420-X008T	-
SMD-6, option 9	IL420-X009T (1)	IL4208-X009T (1)
VDE, UL, cUL, CQC	**600**	**800**
DIP-6	IL420-X001	-
DIP-6, 400 mil, option 6	IL420-X016	-
SMD-6, option 7	IL420-X017T (1)	IL4208-X017T

Note

(1) Also available in tubes, do not put T on the end.

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)					
PARAMETER	**TEST CONDITION**	**PART**	**SYMBOL**	**VALUE**	**UNIT**
INPUT					
Reverse voltage			V_R	6	V
Forward current			I_F	60	mA
Surge current			I_{FSM}	2.5	A
Power dissipation			P_{diss}	100	mW
Derate from 25 °C				1.33	mW/°C
OUTPUT					
Peak off-state voltage		IL420	V_{DRM}	600	V
		IL4208	V_{DRM}	800	V
RMS on-state current			I_{TM}	300	mA
Single cycle surge current			I_{TSM}	3	A
Power dissipation			P_{diss}	500	mW
Derate from 25 °C				6.6	mW/°C
COUPLER					
Isolation test voltage between emitter and detector	t = 1 s		V_{ISO}	5300	V_{RMS}
Isolation resistance	V_{IO} = 500 V, T_{amb} = 25 °C		R_{IO}	$\geq 10^{12}$	Ω
	V_{IO} = 500 V, T_{amb} = 100 °C		R_{IO}	$\geq 10^{11}$	Ω
Storage temperature range			T_{stg}	- 55 to + 150	°C
Ambient temperature range			T_{amb}	- 55 to + 100	°C
Soldering temperature (1)	max. ≤ 10 s dip soldering ≥ 0.5 mm from case bottom		T_{sld}	260	°C

Notes

- Stresses in excess of the absolute maximum ratings can cause permanent damage to the device. Functional operation of the device is not implied at these or any other conditions in excess of those given in the operational sections of this document. Exposure to absolute maximum ratings for extended periods of the time can adversely affect reliability.

(1) Refer to reflow profile for soldering conditions for surface mounted devices (SMD). Refer to wave profile for soldering condditions for through hole devices (DIP).

ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	**TEST CONDITION**	**SYMBOL**	**MIN.**	**TYP.**	**MAX.**	**UNIT**
INPUT						
Forward voltage	I_F = 10 mA	V_F		1.16	1.35	V
Reverse current	V_R = 6 V	I_R		0.1	10	µA
Input capacitance	V_F = 0 V, f = 1 MHz	C_{IN}		40		pF
Thermal resistance, junction to ambient		R_{thja}		750		°C/W
OUTPUT						
Off-state current	$V_D = V_{DRM}$, T_{amb} = 100 °C	I_{DRM}		10	100	µA
On-state voltage	I_T = 300 mA	V_{TM}		1.7	3	V
Surge (non-repetitive), on-state current	f = 50 Hz	I_{TSM}			3	A
Holding current		I_H		65	500	µA
Latching current	V_T = 2.2 V	I_L			500	µA
LED trigger current	V_D = 5 V	I_{FT}		1	2	mA
Trigger current temperature gradient		$\Delta I_{FT}/\Delta T_j$		7	14	µA/°C
Critical rate of rise off-state voltage	$V_D = 0.67\ V_{DRM}$, T_j = 25 °C	dV/dt_{cr}	10 000			V/µs
	$V_D = 0.67\ V_{DRM}$, T_j = 80 °C	dV/dt_{cr}	5000			V/µs
Critical rate of rise of voltage at current commutation	$V_D = 230\ V_{RMS}$, $I_D = 300\ mA_{RMS}$, T_J = 25 °C	dV/dt_{crq}		8		V/µs
	$V_D = 230\ V_{RMS}$, $I_D = 300\ mA_{RMS}$, T_J = 85 °C	dV/dt_{crq}		7		V/µs
Critical rate of rise of on-state current commutation		dI/dt_{crq}		12		A/ms
Thermal resistance, junction to ambient		R_{thja}		150		°C/W

ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
COUPLER						
Critical rate of rise of coupled input/output voltage	I_T = 0 A, $V_{RM} = V_{DM} = V_{DRM}$	dV/dt		5000		V/μs
Capacitance (input to output)	f = 1 MHz, V_{IO} = 0 V	C_{IO}		0.8		pF

Note

- Minimum and maximum values are testing requirements. Typical values are characteristics of the device and are the result of engineering evaluation. Typical values are for information only and are not part of the testing requirements.

SWITCHING CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Turn-on time	$V_{RM} = V_{DM} = V_{DRM}$	t_{on}		35		μs

SAFETY AND INSULATION RATINGS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Climatic classification (according to IEC68 part 1)				55/100/21		
Comparative tracking index		CTI	175		399	
V_{IOTM}			8000			V
V_{IORM}			630			V
P_{SO}					500	mW
I_{SI}					250	mA
T_{SI}					175	°C
Creepage distance	Standard DIP-8		7			mm
Clearance distance	Standard DIP-8		7			mm
Creepage distance	400 mil DIP-8		8			mm
Clearance distance	400 mil DIP-8		8			mm
Insulation thickness	For IL4208 only		0.4			mm

Note

- As per IEC60747-5-2, § 7.4.3.8.1, this optocoupler is suitable for "safe electrical insulation" only within the safety ratings. Compliance with the safety ratings shall be ensured by means of protective circuits.

TYPICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)

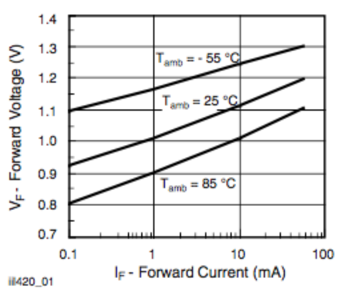


Fig. 1 - Forward Voltage vs. Forward Current

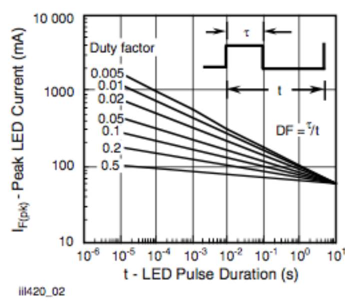


Fig. 2 - Peak LED Current vs. Duty Factor, τ

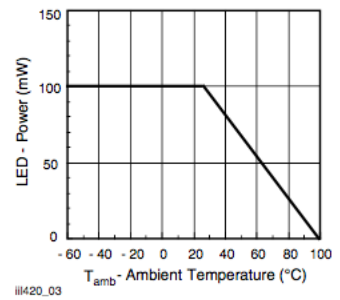


Fig. 3 - Maximum LED Power Dissipation

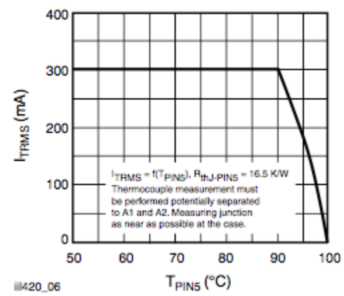


Fig. 6 - Current Reduction

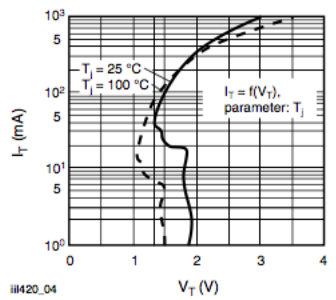


Fig. 4 - Typical Output Characteristics

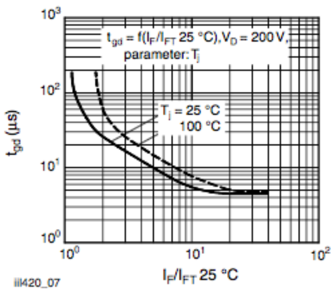


Fig. 7 - Typical Trigger Delay Time

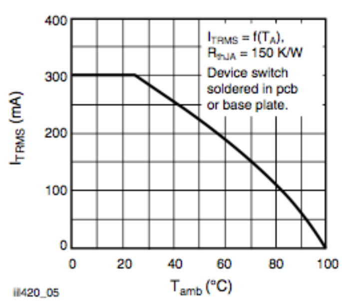


Fig. 5 - Current Reduction

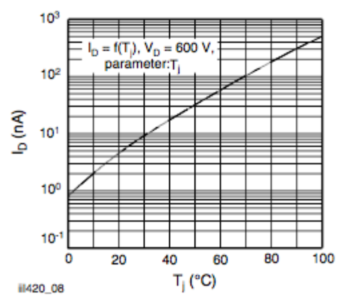


Fig. 8 - Typical Off-State Current

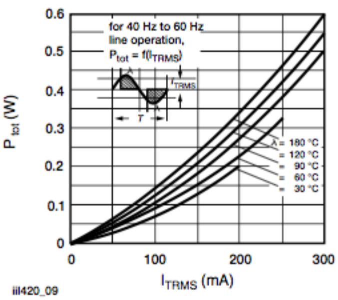


Fig. 9 - Power Dissipation

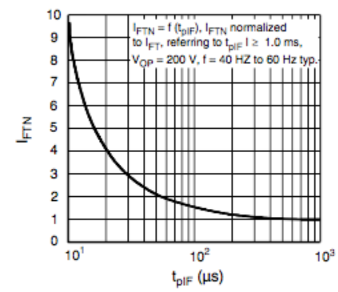
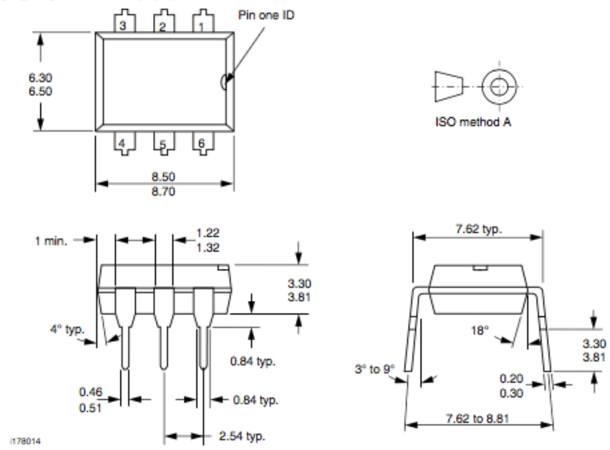
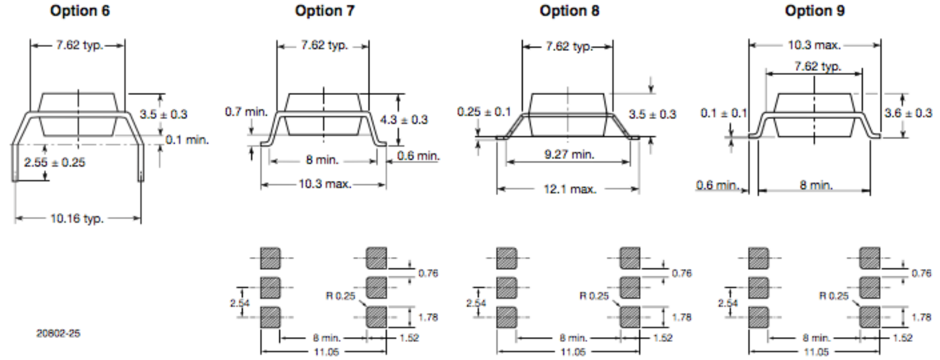


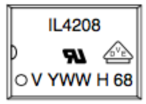
Fig. 10 - Pulse Trigger Current

PACKAGE DIMENSIONS in millimeters





PACKAGE MARKING (example)



Notes

- Only options 1, 7, and 8 are reflected in the package marking.
- The VDE Logo is only marked on option 1 parts.
- Tape and reel suffix (T) is not part of the package marking.

Type SQ Series

Key Features

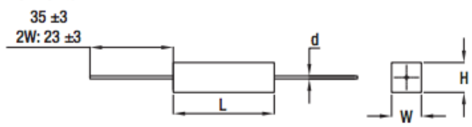
- Choice of Styles
- Bracketed Types Available
- Temp. Op. -55°C to +250°C
- Wide Value Range
- Stable TCR 300ppm/°C
- Custom Designs Welcome
- Inorganic Flame Proof Construction

This flexible range of Power Wirewound Resistors either have wire or power oxide film elements. The SQ series resistors are wound or deposited on a fine non - alkali ceramic core then embodied in a ceramic case and sealed with an inorganic silica filler. This design provides a resistor with high insulation resistance, low surface temperature, excellent T.C.R., and entirely fire proof construction. These resistors are ideally suited to a range of areas where low cost, and efficient thermal performance are important design criteria. Metal film cores adjusted by laser spiral are used where the resistor value is above that suited to wire. Similar performance is obtained although short time overload is slightly derated.

Characteristics - Electrical

	Test Condition	Performance
Resistance Temp. Coefficient:	-55°C ~ 155°C	± 300ppm/°C
*Short Time Overload:	10 times rated power for 5 seconds	± 2%
Rated Load:	Rated power for 30 minutes	± 1%
Voltage Withstand:	1000V AC 1 minute	no change
Insulation Resistance:	500V megger	1000 Meg
Temperature Cycle:	-30°C ~ 85°C for 5 cycles	± 1%
Load Life:	70°C on-off cycle for 1000 hours	± 5%
Moisture-proof Load Life:	40°C 95% RH on-off cycle 1000 hours	± 5%
Incombustability:	16 times rated wattage for 5 minutes	No flame
Max. Overload Voltage:	2 times max. working voltage	
*Metal Film Elements:	Short time overload 5 times rated power, 5 seconds	

Type SQP - Horizontal



Power Rating	Dimensions					Resistance Range		Max. Working Voltage
	W ± 1	H ± 1	L ± 1.5	d ± 0.05	l ± 0.3	Wire	Metal Film	
2W	7	7	18	0.65	23	R10 - 82R	83R - 10K	150V
3W	8	8	22	0.8	35	R10 - 180R	181R - 33K	350V
5W	10	9	22	0.8	35	R10 - 180R	181R - 100K	350V
7W	10	9	35	0.8	35	R10 - 430R	431R - 100K	500V
10W	10	9	48	0.8	35	R10 - 470R	471R - 100K	750V
15W	12.5	11.5	48	0.8	35	R50 - 600R	601R - 150K	1000V
20W - 25W	14	13.5	60	0.8	35	R50 - 1K0	1.1K - 150K	1000V

Rated Continuous Working Voltage (RCWV)
RCWV: $\sqrt{\text{Rated Power x Resistance Value}}$ or Maximum Working Voltage listed above whichever is lower

Dimensions are in millimeters and inches unless otherwise specified. Values in brackets are standard equivalents.

Dimensions are shown for reference purposes only. Specifications subject to change.

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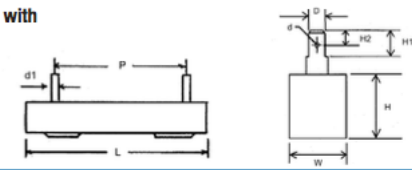
Type SQ Series

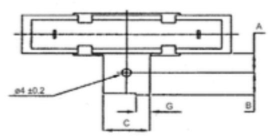
Type SQH - Horizontal with Faston Connectors



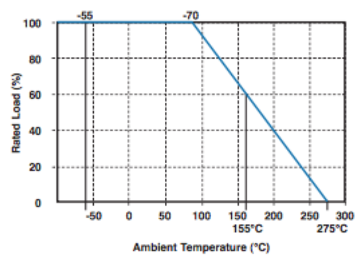
Power Rating	Dimensions								Resistance Range	
	W ± 1	H ± 1	L ± 1.5	P	H1± 1	D±0.5	P1±0.2	P2±0.2	Wire	Metal Film
10W	10	10	48	32 ±1	21	5	2.5	1.7	R50 - 600R	601R - 50K
15W	12.5	11.5	48	32 ±1	21	5	2.5	1.7	1R0 - 600R	601R - 50K
20W	14.5	13.5	60	42 ±1	24	6	3.0	2.5	1R0 - 1K0	1K1 - 50K
30W	19	19	75	55 ±2	31	7.5	–	–	1R0 - 2K0	–
40W	19	19	90	67 ±2	31	7.5	–	–	1R0 - 2K0	–

Type SQB - Horizontal with Faston Connectors and Bracket

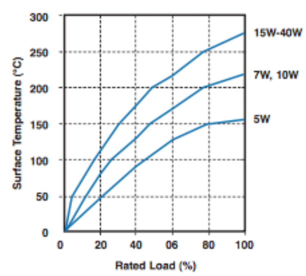
Power Rating	Dimensions			
	A ± 0.5	B ± 0.5	C ± 0.5	G ± 0.5
10W	8.0	5.0	12.0	3.0
15W	8.0	5.5	12.0	3.0
20W	8.0	5.5	12.0	3.0
30W	10.5	8.0	18.0	3.5
40W	10.5	8.0	18.0	3.5



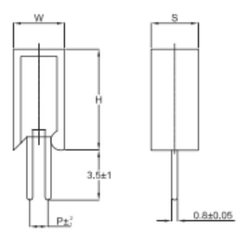
Power Derating Curve



Load Against Temperature



Type SQM - Vertical



Power Rating	Dimensions				Resistance Range	
	W ± 1	H ± 1	S ± 1.5	P ± 2.0	Wire	Metal Film
2W	11	20	7	5	R10 - 82R	83R - 10K
3W	12	25	8	5	R10 - 180R	181R - 33K
5W	13	25	9	5	R10 - 180R	181R - 100K
7W	13	39	9	5	R10 - 430R	431R - 100K
10W	13	51	9	5	R10 - 470R	471R - 100K
10WS	16	35	12	7.5	R10 - 360R	361R - 100K

N.B. Custom design versions in wire at low tolerances, better T.C.R., and higher ohmic values are available to special order. Please enquire.

Dimensions are in millimeters and inches unless otherwise specified. Values in brackets are standard equivalents.

Dimensions are shown for reference purposes only. Specifications subject to change.

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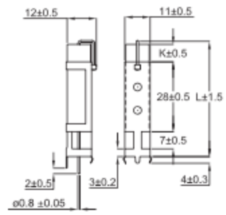
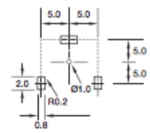
Type SQ Series

Type SPS - Vertical Mounting with Stabilising Bracket

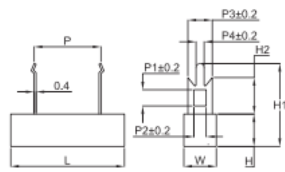




Suggested PCB Layout Plan

Power Rating	Dimension		Resistance Range	
	L ± 1.5	K ± 0.5	Wire	Metal Film
7W	48	8.5	R10 - 430R	431R - 100K
10W	60	20	R10 - 470R	471R - 100K

Type SQZ - Horizontal Pluggable

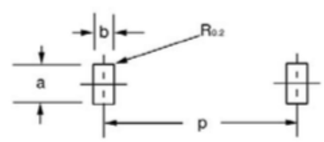


Power Rating	Dimensions										Resistance Range	
	W±1	H±1	L±1.5	P±1.5	P1	P2	P3	P4	H1±1	H2±1	Wire	Metal Film
5W	10	10	28	15	4.2	2	5	1.5	25	10.5	R10 - 130R	131R - 100K
7W	10	10	36	20	4.2	2	5	1.5	25	10.5	R10 - 430R	431R - 100K
10W	10	10	48	32	4.2	2	5	1.5	25	10.5	R20 - 470R	471R - 100K
15W	12.5	12	48	32	4.2	2	5	1.5	26	10.5	1R0 - 600R	601R - 150K
20W-25W*	15	13	60	42	7	6	10	2.7	36	15.0	1R0 - 1K0	1K1 - 150K

*NB: 20W & 25W Devices Terminations are not crimped

Type SQZ - Recommended PCB Hole Dimensions

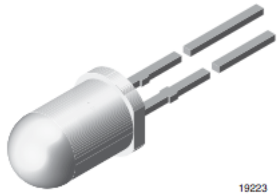
Power Rating	a	b	p
5W	2.0	0.8	15
7W	2.0	0.8	20
10W	2.0	0.8	32
15W	2.0	0.8	32
20W_25W	3.5	1.0	42



How to Order

SQP	W	20	1R0	F
Common Part	**Element**	**Rated Power**	**Resistance Value**	**Resistance Tolerance**
SQP - Axial Type SQZ - Pluggable Type SQM - Vertical Type SPS - Vertical Type SQH - Horizontal Type SQB - Horizontal Type (with bracket)	W - Wire R - Metal Film	2 - 2 Watts 3 - 3 Watts 5 - 5 Watts etc	0.1 ohm (1 milliohm) R10 1 ohm (1000 milliohms) 1R0 1K ohm (1000 ohms) 1K0 1M ohm (1000000 ohms) 1M0	F - ±1% G - ±2% J - ±5% K - ±10%

High Intensity LED, Ø 5 mm Untinted Non-Diffused Package



19223

DESCRIPTION

The TLH.51.. series is a clear, non diffused 5 mm LED for outdoor application.

These clear lamps utilize the highly developed technologies like AlInGaP and GaP.

The lens and the viewing angle is optimized to achieve best performance of light output and visibility.

FEATURES

- Untinted non-diffused lens
- Choice of three colors
- TLH.5100 for cost effective design
- Medium viewing angle
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

Pb Pb-free
e3
RoHS COMPLIANT
HALOGEN FREE
GREEN (5-2008)

APPLICATIONS

- Outdoor LED panels
- Central high mounted stop lights (CHMSL) for motor vehicles
- Instrumentation and front panel indicators
- Light guide design
- Traffic signals

PRODUCT GROUP AND PACKAGE DATA

- Product group: LED
- Package: 5 mm
- Product series: standard
- Angle of half intensity: ± 9°

PARTS TABLE

PART	COLOR	LUMINOUS INTENSITY (mcd)			at I_F (mA)	WAVELENGTH (nm)			at I_F (mA)	FORWARD VOLTAGE (V)			at I_F (mA)	TECHNOLOGY
		MIN.	TYP.	MAX.		MIN.	TYP.	MAX.		MIN.	TYP.	MAX.		
TLHK5100	Red	320	1400	-	20	626	630	639	10	-	2	2.6	20	AllnGaP on GaAs
TLHE5100	Yellow	750	1800	-	20	581	588	594	10	-	2	2.6	20	AllnGaP on GaAs
TLHG5100	Green	240	450	-	20	562	-	575	10	-	2.4	3	20	GaP on GaP

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)
TLHK510., TLHE510., TLHG510.

PARAMETER	TEST CONDITION	SYMBOL	VALUE	UNIT
Reverse voltage		V_R	6	V
DC forward current	$T_{amb} \leq 65$ °C	I_F	30	mA
Surge forward current	$t_p \leq 10$ μs	I_{FSM}	1	A
Power dissipation	$T_{amb} \leq 65$ °C	P_V	100	mW
Junction temperature		T_j	100	°C
Operating temperature range		T_{amb}	-40 to +100	°C
Storage temperature range		T_{stg}	-55 to +100	°C
Soldering temperature	t ≤ 5 s, 2 mm from body	T_{sd}	260	°C
Thermal resistance junction-to-ambient		R_{thJA}	350	K/W

OPTICAL AND ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified) TLHK510., RED						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Luminous intensity [(1)]	I_F = 20 mA	I_V	320	1400	-	mcd
Dominant wavelength	I_F = 10 mA	λ_d	626	630	639	nm
Peak wavelength	I_F = 10 mA	λ_p	-	643	-	nm
Angle of half intensity	I_F = 10 mA	φ	-	± 9	-	deg
Forward voltage	I_F = 20 mA	V_F	-	2	2.6	V
Reverse voltage	I_R = 10 μA	V_R	5	-	-	V
Junction capacitance	V_R = 0 V, f = 1 MHz	C_j	-	15	-	pF

Note

[(1)] In one packing unit $I_{Vmin.}/I_{Vmax.} \leq 0.5$

OPTICAL AND ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified) TLHE510., YELLOW						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Luminous intensity [(1)]	I_F = 20 mA	I_V	750	1800	-	mcd
Dominant wavelength	I_F = 10 mA	λ_d	581	588	594	nm
Peak wavelength	I_F = 10 mA	λ_p	-	590	-	nm
Angle of half intensity	I_F = 10 mA	φ	-	± 9	-	deg
Forward voltage	I_F = 20 mA	V_F	-	2	2.6	V
Reverse voltage	I_R = 10 μA	V_R	5	-	-	V
Junction capacitance	V_R = 0 V, f = 1 MHz	C_j	-	15	-	pF

Note

[(1)] In one packing unit $I_{Vmin.}/I_{Vmax.} \leq 0.5$

OPTICAL AND ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified) TLHG510., GREEN						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Luminous intensity [(1)]	I_F = 20 mA	I_V	240	450	-	mcd
Dominant wavelength	I_F = 10 mA	λ_d	562	-	575	nm
Peak wavelength	I_F = 10 mA	λ_p	-	565	-	nm
Angle of half intensity	I_F = 10 mA	φ	-	± 9	-	deg
Forward voltage	I_F = 20 mA	V_F	-	2.4	3	V
Reverse voltage	I_R = 10 μA	V_R	6	15	-	V
Junction capacitance	V_R = 0 V, f = 1 MHz	C_j	-	50	-	pF

Note

[(1)] In one packing unit $I_{Vmin.}/I_{Vmax.} \leq 0.5$

LUMINOUS INTENSITY CLASSIFICATION		
GROUP	LIGHT INTENSITY (mcd)	
STANDARD	MIN.	MAX.
Z	240	480
AA	320	640
BB	430	860
CC	575	1150
DD	750	1500
EE	1000	2000
FF	1350	2700
GG	1800	3600
HH	2400	4800
II	3200	6400
KK	4300	8600

Note

- Luminous intensity is tested at a current pulse duration of 25 ms. The above type numbers represent the order groups which include only a few brightness groups. Only one group will be shipped on each bag (there will be no mixing of two groups on each bag).
  In order to ensure availability, single brightness groups will not be orderable.
  In a similar manner for colors where wavelength groups are measured and binned, single wavelength groups will be shipped in any one bag.
  In order to ensure availability, single wavelength groups will not be orderable

COLOR CLASSIFICATION				
GROUP	DOM. WAVELENGTH (nm)			
	YELLOW		GREEN	
	MIN.	MAX.	MIN.	MAX.
0				
1	581	584		
2	583	586		
3	585	588	562	565
4	587	590	564	567
5	589	592	566	569
6	591	594	568	571
7			570	573
8			572	575

Note

- Wavelengths are tested at a current pulse duration of 25 ms

TYPICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)

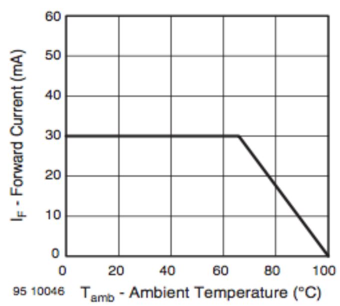


Fig. 1 - Forward Current vs. Ambient Temperature

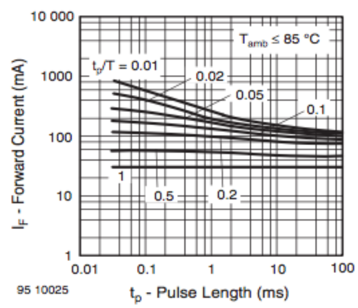


Fig. 2 - Forward Current vs. Pulse Length

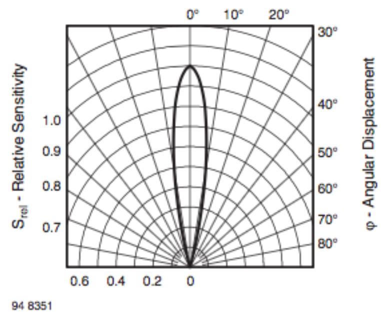


Fig. 3 - Relative Radiant Sensitivity vs. Angular Displacement

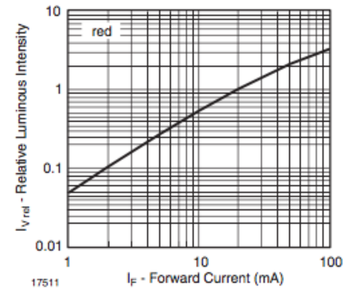


Fig. 6 - Relative Luminous Intensity vs. Forward Current

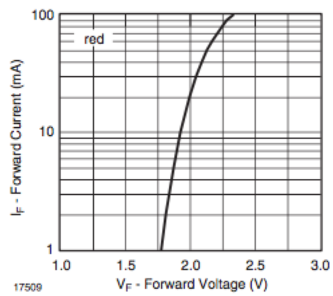


Fig. 4 - Forward Current vs. Forward Voltage

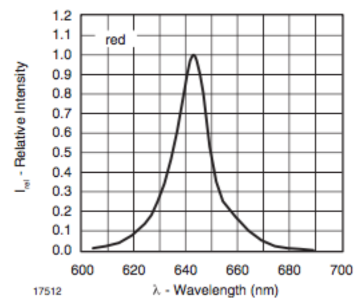


Fig. 7 - Relative Intensity vs. Wavelength

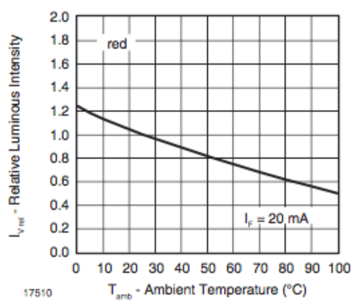


Fig. 5 - Relative Luminous Intensity vs. Ambient Temperature

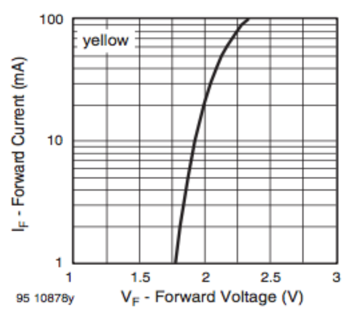


Fig. 8 - Forward Current vs. Forward Voltage

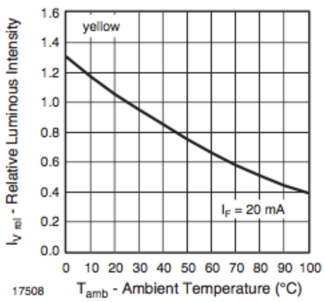


Fig. 9 - Relative Luminous Intensity vs. Ambient Temperature

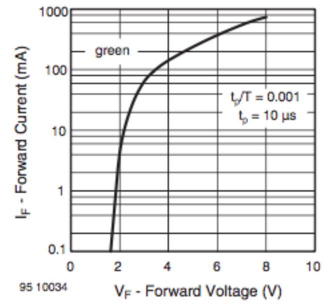


Fig. 12 - Forward Current vs. Forward Voltage

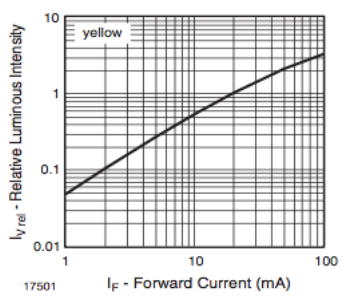


Fig. 10 - Relative Luminous Intensity vs. Forward Current

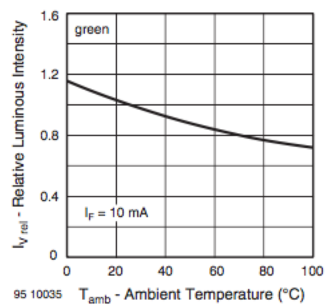


Fig. 13 - Relative Luminous Intensity vs. Ambient Temperature

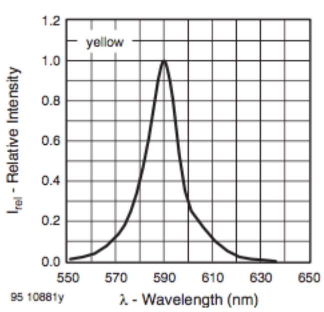


Fig. 11 - Relative Intensity vs. Wavelength

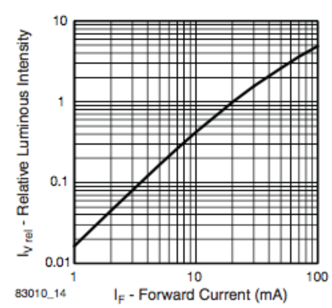


Fig. 14 - Relative Luminous Intensity vs. Forward Current

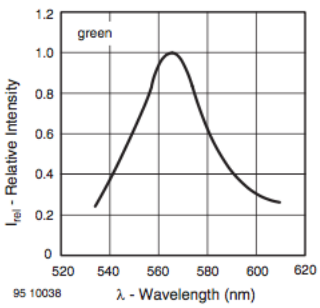
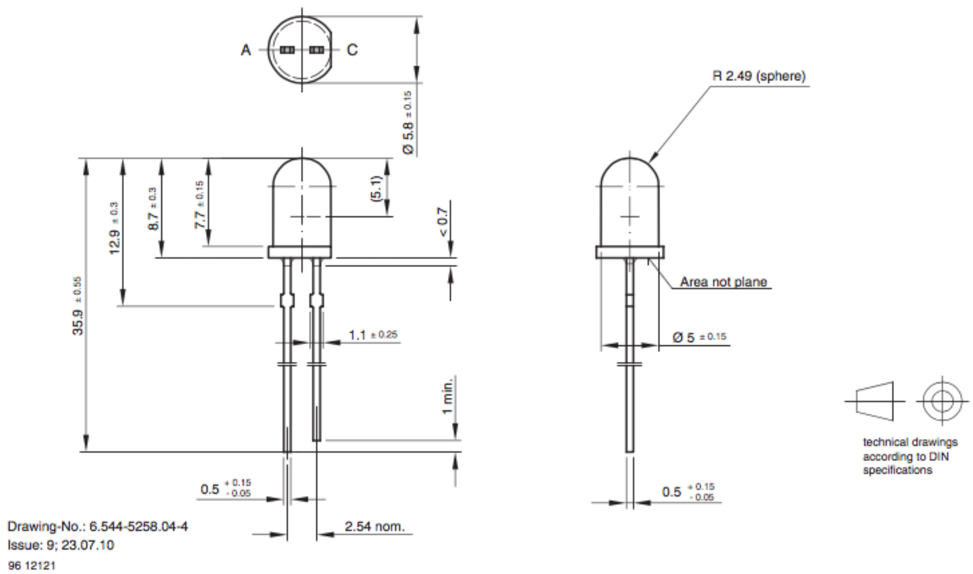


Fig. 15 - Relative Intensity vs. Wavelength

PACKAGE DIMENSIONS in millimeters



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CHAPTER IV. LETTER OF ACCEPTANCE

BELD
BRAINTREE ELECTRIC LIGHT DEPARTMENT

150 Potter Road
Braintree, MA 02184
781.348.BELD (2353)

BELD
BROADBAND

April 29, 2018

Dear BELD Battery Team,

I have reviewed your senior design progress on the energy storage project. My assessment takes into account the team's ability to meet customer requirements, ability to work as a team, quality of deliverables, and ability to manage a project from start to finish.

The BELD Battery Team has addressed a satisfactory number of customer requirements. The team has achieved significant progress in the generation, transmission, distribution, and data acquisition aspects of their grid simulation. Future students may have the opportunity to build upon this edition of the project. On behalf of BELD, I would like to issue a formal acceptance of the senior design project.

The group will present at the APPA E&O Conference the week of April 30th. On Friday May 4th, the team will participate in ECE Day to complete their capstone project. Findings from their research will be shared with the customer and BU faculty.

Sincerely,

Tim Leung
Electrical Engineer
Office: 781-348-2382
Cell: 339-237-8408