ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

ESPECIALIDAD ELÉCTRICA

ENERGY RECOVERY SYSTEM FOR PIPELINES POWER CONVERSION SUBSYSTEM

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Energy Recovery System for Pipelines

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ENERGY RECOVERY SYSTEM FOR PIPELINES POWER CONVERSION SUBSYSTEM

Directors: Thomas Galvin (Instructor) and Katherine O´Kane (Teacher Assistant) from University of Illinois at Urbana-Champaign.
Author: Adrian Portillo Quesada

This project was design and developed by a group of two ICAI students during their exchange curse in University of Illinois at Urbana-Champaign.

All the information regarding the other half of the project can be found on the final paper of my teammate, Ana Carrasco y Fonseca.

SUMMARY

Introduction

Nowadays, energy efficiency is one of the most challenging goals for many engineering designs and projects. Due to the continuous growth in population, goods and services needed by the society, the energy requirements are increasing as well. In fact, the scarcity of cheap energy resources produced by the transition between fossil fuels to renewable and clean sources of energy, will force us to develop new systems with minimum energy requirements and improve the existing ones by reducing their energy consumption.

Applying the principles and goals of the energy efficiency, the hydraulic circuits were considered as a possible field of development. One of the first observations made was that in many hydraulic circuits and systems the fluid has to be slowed down before sharp turns. This process implies a loss of energy and a wear on the materials of the pipeline.

Objectives

This project wants to address this challenge by providing a reliable, flexible and economical system to harness the excessive kinetic energy of the fluids while flowing through pipelines.

To do so, small turbines attached to an alternator or an electrical motor will be installed inside the pipelines. They will be installed prior to critical sections when the fluid has excessive kinetic energy. That kinetic energy will be converted into electricity.

The final objective would be to build a prototype containing both the electrical and mechanical components of the system. However, due to the time and budget constraints, the focus of the project has been to design

exclusively the electrical and electronic components of the system, leaving all the mechanical calculations and design for future courses or other students.

More precisely, the objective of this first step of the project is to design the power conversion subsystem. This subsystem is responsible of transforming and converting the electricity generated in the alternator being able to store it reliably and safely on a battery.

This subsystem includes a three-phase full-wave rectifier to convert the three-phase AC output of the alternator into a single-phase DC with an AC ripple voltage. A low-pass passive filter to reduce and eliminate the AC ripple of the rectifier. A DC/DC buck converter to step down the DC voltage obtained in the filter. And finally, a battery charge circuit to be able to charge the battery following its charging characteristics.

Methodology

Firstly, all the research needed to fully understand the requirements of the system that was being designed. This includes information about all the different modules required for the power conversion, as well as information about the different types of batteries and their charging characteristics. As this is a power project, research was made regarding safety measures recommended for this systems.

Secondly, once all the modules required were know and understood, the overall requirements and objectives for the project were settled in accordance with the teacher assistant of the group and the instructor of the course.

With the final requirements and objectives settled, all the calculations of the magnitudes, variables and ratings of the components were performed. This was the first step of the designing process and it provided information to start choosing the components to build and test the modules.

Thirdly, in addition to the calculations performed, several simulations were performed with Matlab to understand better the functioning of the modules, their interconnections and their response under different inputs and variations. This simulations provided more values for the components required for the design.

Once all the components were obtained from the University or from external suppliers, all the modules were built in protoboards and tested.

Finally, all the possible modules were welded on the final PCB, which was designed in parallel with the rest of the design process. All the subsystems were connected together and tested. All the modules fulfil their requirements, nevertheless a total integration was not fully achieved.

As a final requirement for the curse, the system was demonstrated to the instructor of the curse for evaluation.

Results

In summary, all the modules fulfil the requirements and verifications that were established for them during the design process and most of them worked together providing the expected outputs.

The rectifier converts the three-phase 12V AC output of the alternator into a single-phase 25V DC plus an AC ripple of 4Vpp.

The filter attenuates the AC ripple of the rectifier from 4Vpp to 0.1Vpp.

The DC/DC buck converter steps down the voltage from 25V to 15V as required for the battery chip. An iterative control was integrated to control the converter. This implementation was done by my teammate.

Finally, the battery charge circuit is capable to charge safely the 12V sealed lead acid battery following its charging characteristics.

Additionally, the first part of the power conversion module was able to provide the expected 25V DC at the output of the filter while the second part of that module effectively and safely charged the chosen battery. Even though both parts of the power conversion module could not be tested together, the control of the buck converter demonstrated that it could handle the output of the other half of the module. This means that the designed system can work as a whole achieving full integration.

Conclusions

Overall, most of the requirements and initial expectations were achieved.

Not only a functional and reliable design has been made and improved over different processes, but also the design has been physically built, tested and verified.

The power conversion subsystem worked together with the subsystem designed and developed by my teammate demonstrating the viability of the project.

SISTEMA DE RECUPERACIÓN ENERGÉTICO
SUBSISTEMA DE POTENCIA

Directores: Thomas Galvin (Coordinador) and Katherine O´Kane (Supervisora) de la University of Illinois at Urbana-Champaign.
Autor: Adrián Portillo Quesada

Este Proyecto fue llevado a cabo por dos estudiantes de ICAI durante su año de intercambio en la University of Illinois at Urbana-Champaign.

Toda la información referente a la otra mitad del proyecto grupal puede encontrarse en el proyecto final de mi compañera, Ana Carrasco y Fonseca.

RESUMEN

Introducción

La eficiencia energética es uno de los desafíos y objetivos más importantes para muchos proyectos de ingeniería.

Debido al continuado aumento de población y bienes y servicios demandados por la sociedad, las necesidades y demandas energéticas también se incrementan significativamente. De hecho, la posible escasez de fuentes y recursos energéticos baratos durante la transición de los recursos fósiles a fuentes renovables puede forzarnos a desarrollar nuevos sistemas eléctricos con menores consumos y mejorar los existentes reduciendo sus consumo energético.

Si se aplican los principios de la eficiencia energética, por ejemplo, a los sistemas hidráulicos puede descubrirse una posible oportunidad de mejora. Por ejemplo, en los sistemas hidráulicos cuando el fluido ha de realizar un giro cerrado éste debe frenarse. Este proceso implica una pérdida de energía cinética en el fluido y desgaste en el material de la tubería.

Objetivos

Este proyecto quiere solucionar este problema presentando un sistema fiable, versátil y económico para aprovechar el exceso de energía cinética de los fluidos cuando fluyen por tuberías.

Para llevar esto a cabo, se instalarán dentro de las tuberías pequeñas turbinas conectadas a un alternador. La idea es colocarlas en los puntos previos a la pérdida de carga. La energía cinética extraída será convertida en electricidad y se almacenará en una batería.

El objetivo final sería poder construir un prototipo con todos los elementos eléctricos y mecánicos. Sin embargo, debido a las limitaciones temporales y al presupuesto del curso, el objetivo de este proyecto se ha limitado al diseño del sistema eléctrico y de los componentes electrónicos, aplazando todos los cálculos mecánicos y diseño de esos componentes para cursos futuros u otros estudiantes.

El objetivo para esta primera etapa de desarrollo del proyecto ha sido el diseño del subsistema de potencia. Este subsistema es el encargado de convertir y transformar la energía eléctrica generada en el alternador para poder almacenarla de manera segura en una batería.

Este subsistema incluye un rectificador trifásico de onda completa para convertir la salida alterna trifásica del alternador en un voltaje monofásico de corriente continua con un rizado de corriente alterna. Un filtro pasivo de paso bajo para reducir y eliminar el rizado de corriente alterna. Un conversor Buck de corriente continua para reducir el voltaje de corriente continua desde el valor de salida del filtro. Y por último, un circuito de carga de batería para poder cargar de manera segura la batería escogida siguiendo las características de carga recomendadas.

Metodología

Primero se realizó toda la investigación y estudio necesarios para comprender el sistema que se estaba diseñando. Esto incluye información acerca de los circuitos necesarios para el subsistema de potencia, información acerca de los diferentes tipos de baterías y sus características y procesos de carga.

Como se trata de un proyecto de potencia, también se realizó investigación sobre las medidas de seguridad recomendadas para este tipo de sistemas.

Seguidamente, una vez que todos los módulos eran conocidos, se acordaron los objetivos y condiciones generales del proyecto con el coordinador del curso y la supervisora del grupo.

Con todos los objetivos y requerimientos decididos, se realizaron los cálculos de valores de las variables principales y de los componentes necesarios. Este fue el primer paso del proceso de diseño y ofreció información para comenzar a escoger los componentes para los módulos del sistema.

Posteriormente, aprovechando los cálculos teóricos realizados, se realizaron múltiples simulaciones con Matlab para conocer mejor el funcionamiento de los módulos, sus interconexiones y su respuesta ante diferentes entradas y posibles variaciones. Estas simulaciones ofrecieron más valores y medidas para la elección de los componentes necesarios.

Una vez que se obtuvieron todos los componentes necesarios, tanto de la propia universidad como a través de distribuidores externos, se montaron todos los módulos en protoboards para probarlos.

Finalmente los módulos posibles se soldaron e integraron en el circuito impreso final, el cual se diseñó de manera paralela con el resto de módulos y subsistemas del proyecto. Todos los módulos se conectaron juntos y se probaron.

Todos los módulos cumplieron con los requisitos y objetivos establecidos para cada uno en las primeras etapas de diseño. Sin embargo no se pudo conseguir una integración plena entre todos los módulos del subsistema.

El último requisito del curso era realizar una demostración completa del sistema al coordinador del curso para su evaluación.

Resultados

En resumen, todos los módulos del subsistema cumplieron con los requisitos y objetivos impuestos al principio del curso y casi todos ellos funcionaban correctamente conectados a los demás.

El rectificador convierte la salida trifásica de 12V AC del alternador en un voltaje monofásico de 25V DC con un rizado de 4Vpp.

El filtro atenúa el rizado del rectificador de 4Vpp a 0.1Vpp.

El conversor Buck de continua reduce el voltaje desde 25V a los 15V establecidos para alimentar el circuito de carga de la batería. Se ha implementado un control iterativo en el convertidor para optimizar su funcionamiento. Esta tarea fue realizada por mi compañera de proyecto.

Finalmente, el circuito de carga de la batería es capaz de cumplir su objetivo utilizando una batería de 12V de ácido de plomo sellado escogida siguiendo su característica de carga recomendada.

De manera adicional, se debe destacar que la primera parte del subsistema de potencia proporcionaba los 25V DC requeridos a la salida del filtro mientras que la otra mitad del subsistema es capaz de cargar la batería de manera segura. Aunque las dos mitades del subsistema no pudieron ser probadas de manera conjunta debido a un problema con sus tierras, el control del conversor DC/DC demostró que puede mantener la salida del convertidor constante ante una entrada que simula la salida del filtro. Por lo tanto, una vez solucionado el problema que impide su conexión, se puede asegurar que ambos módulos pueden trabajar conectados alcanzando la integración de todos los componentes del proyecto.

Conclusiones

En definitiva, todos los requisitos y objetivos iniciales se han cumplido tanto para el subsistema tratado en este documento como en el proyecto en grupo. No solo se ha conseguido un diseño fiable que se ha mejorado a través de varios procesos y etapas, sino que también se ha plasmado de manera física. El sistema construido ha sido probado y verificado.

El subsistema de potencia funciona trabajando integrado con el resto de subsistemas desarrollados por mi compañera demostrando la viabilidad del proyecto grupal.

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1. INTRODUCTION

1.1. Statement of Purpose

Nowadays, energy efficiency is one of the most challenging goals for many engineering designs and projects. Due to the continuous growth in population, goods and services needed by the society, the energy requirements are increasing as well. In fact, the scarcity of energy resources produced by the transition between fossil fuels to renewable and clean sources of energy, will force us to develop new systems with minimum energy requirements and improve the existing ones by reducing their energy consumption.

In many hydraulic circuits and systems the fluid has to be slowed down before sharp turns and section changes. This process implies a loss of energy and a wear on the materials of the pipeline. This project wants to address this challenge by providing a reliable, flexible and economical system to harness the excessive kinetic energy of the fluids while flowing through pipelines.

To do so, small turbines attached to an alternator or an electrical motor will be installed inside the pipelines. The power and size of the alternator will depend on the speed of the fluid and the diameter of the pipeline. They will be installed prior to critical sections when the fluid has excessive kinetic energy. That kinetic energy will be converted into electricity. As this electric energy generation can be very intermittent, the possibility of storing it in a battery will be included.

The final objective would be to build a prototype containing both the electrical and mechanical components of the system. Nevertheless, due to time constraints and the available budget and available resources, the focus of the project has been to design exclusively the electrical and electronic components of the system, leaving all the mechanical calculations and design for future courses or other students. This electrical system includes all the modules and components required to fulfil the power conversion, the safety and security measures and the control for several components. In addition to that, a wireless communication system has been designed. The function of this system is to transmit different measurements and variables to a remote display center.

To finalize, the power conversion circuit design, development and testing will be explained in detail in this project. The connection and interactions with the rest of the components of the system will be addressed too, although with less detail because they involve the developments and achievements carried out by my teammate. It will be possible to find the required level of detail and explanations of those components in her final project document.

Therefore, this project is going to cover and analyze all the components regarding the power conversion circuit and its connections with the rest of the system.

1.2. Goals and Benefits

Those are the main final objectives for the project:

- Reduce the energy losses in hydraulic systems.
- Reduce the wear on the materials of the critical sections of the pipeline, principally when the fluid makes sharp turns.
- Harness the excessive kinetic energy of the fluid prior to critical sections and convert it into electric energy.
- Store the energy harnesses and converted in a battery.
- Measure and manage data such as fluid speed and temperature and display it on a remote center.

1.3. Functions and Features

- Compact and low losses system.
- Convert the variable AC three-phase voltage output of the alternator into a constant and DC voltage.
- Measure the voltage at different points to ensure the correct and safe functioning of the system.
- All the components are integrated in one printed board circuit (PCB).
- Charge the battery following the recommended charging characteristics of the sealed acid batteries.
- Stop automatically the battery charging process when the battery is fully charged.

Additionally, the following functions and features will be addressed by my teammate:

- Adjust automatically the duty cycle of the buck converter in order to obtain a constant 15V output to charge the battery.
- Transmit wirelessly the existing temperature, pressure and velocity of the fluid, as well as the charge of the battery and the power stored into the battery.
- Display the data acquired and transmitted in a LCD screen in the remote center.

2. DESIGN

2.1. Fluid Mechanical Principles

One important part of the project, such as the designing of the water turbine, the upstream conduct design and the waterproof low-hydraulic resistant case will require a more mechanical in depth study which should be carried out on following courses or years.

The project is mainly ruled by the forces and principles of fluid mechanics. Therefore, in this section of the project, the principles and design considerations taken into account for our design will be shown and explained.

The main objective is to reduce energy losses when the fluid makes sharp turns by extracting some kinetic energy from the fluid previously.

Figure 1 represents the ideal location for the system. The points shown on it represent the different stages that the fluid has to go through experimenting different changes on its pressure, speed and ultimately its kinetic energy.

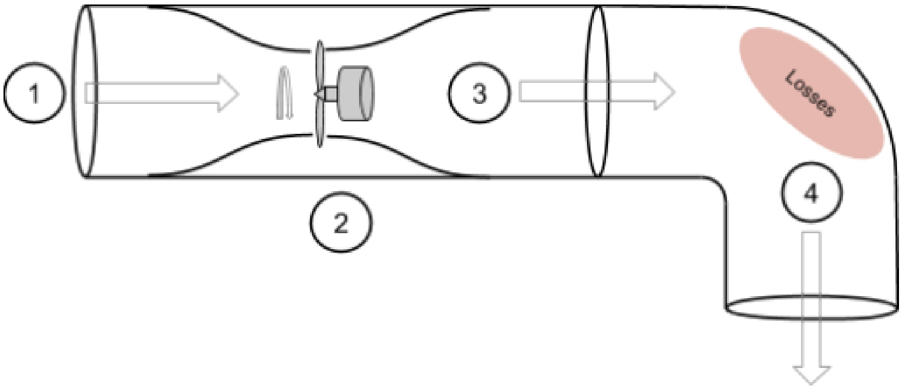


Figure 1 Schematic of the System

Firstly, applying the general conservation of mass flux equation between points 1 and 2 for and incompressible fluid:

$$m_1 = m_2 \Rightarrow v_1 S_1 \rho = v_2 S_2 \rho$$

$$S_1 > S_2 \Rightarrow v_2 > v_1$$

Reducing the section prior to the water turbine we increase the speed of the fluid and therefore, we increase the possible energy output of the turbine. The kinetic energy extracted will be:

$$E_k = \frac{1}{2}\rho v^2$$

And the power generated from this process is a function of the cube of the speed:

$$P = \frac{1}{2}\rho S_2 v_2^3$$

One a determined amount of kinetic energy is extracted, which would depend on the angle of attack of the blades of the turbine, the section of the pipeline has to be changed again to conserve the mass flux without having to compress the water:

$$m_2 = m_3 \Rightarrow v_2 S_2 \rho = v_3 S_3 \rho$$

$$v_2 > v_3 \Rightarrow S_3 > S_2$$

Between points 3 and 4, the energy of the fluid is based on the Bernoulli's equation

$$\frac{v_3^2 \rho}{2} + p_3 + \rho g z_3 = \frac{v_4^2 \rho}{2} + p_4 + \rho g z_4 + \sum \lambda_{3-4}$$

v = velocity of the fluid

p = pressure of the fluid

ρ = density of the fluid

g = acceleration of the gravity

$\sum \lambda_{3-4}$ = losses through points 3 and 4

S_3 = cross sectional area of the pipeline

E_k = kinetic energy

The loss of load produced in the sharp turn can be described by the following equation:

$$\lambda_{3-4} = k\frac{v_3^2}{2g} \rightarrow k(90^o turn) = 1$$

By reducing the speed of the water by 2 in the turbine we are reducing the losses in the turn by 4. Moreover, the power generated by the turbine is a function of the cube of the speed. Hence, the energy recovery will be much more successful in high speed water distribution systems.

The power generated from this process is a function of the cube of the speed and the square of the radius of the turbine.

$$P = \frac{1}{2}\rho\pi \mathrm{r}_2^2 v_2^3$$

The maximum power that can be harnessed from a fluid flow is determined by the Betz's limit. According to Betz's law, the maximum efficiency of the rotor blades of a turbine is 16/27 or a 59%.

This means that the maximum power that can be harnessed from a fluid is around 60% of its total kinetic energy.

The maximum harvested energy is determined by the power of the alternator because, based on that power, the following students will be able to design the appropriate turbine rotor blades to extract that energy from the fluid flow.

Future work on this project will have to take into account all the constraints stated before: the maximum power of the alternator, the maximum rotor efficiency (totally related with the turbine blades design), the speed of the fluid (it will include the design of a gearbox if the cross sectional area of the pipeline cannot be modified), the diameter of the blades of the water turbine and the diameter of the cross sectional area of the pipeline where the system will be installed.

2.2. Block Diagram

Figure 2 shows the four subsystems in which the design is divided.

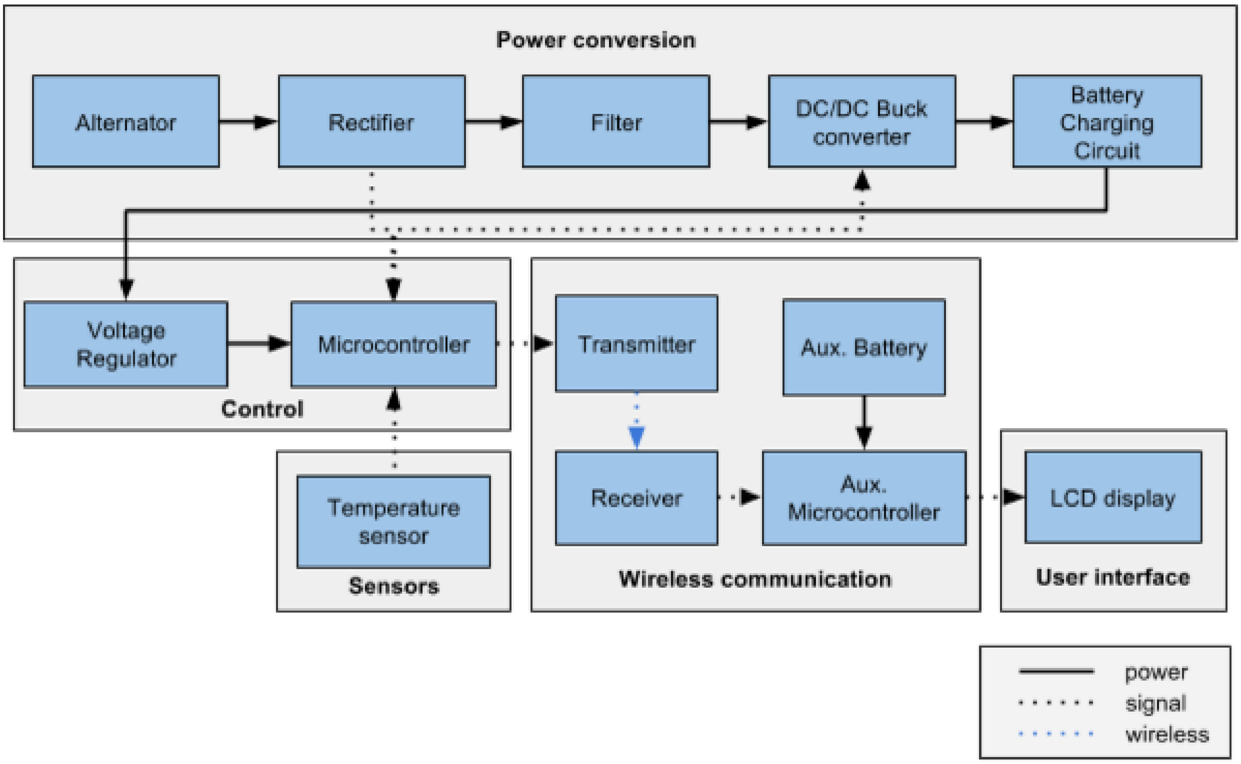


Figure 2 Block Diagram

2.3. Block Description

In the following section all the different subsystems of the design and all its components will be explained and described. As stated before, the components of the power conversion subsystem will be explained with more detail including their schematics. The components related with the work of my teammate are included and shown in order to provide the big picture of the whole project. The ones regarding mechanical components will only be introduced with guidelines for future work.

2.3.1. Power Conversion

The power conversion subsystem is designed to convert the kinetic energy into electric energy and transform it to store this energy effectively and safely in the battery. This subsystem will manage the electric power and all the progressive steps of the electricity conversion and it will be controlled by the microprocessor. Each description of the components includes the expected input and output and a general description of their functioning. To clarify, all the values will be explained in the calculations and simulations sections as all of them are justified. This subsystem includes the following components:

Alternator

Output: 0-12V AC

The alternator is responsible for converting the rotational kinetic energy of the turbine into electric energy. The rotor of the alternator is attached to the shaft of the turbine to rotate together. By magnetic induction, the rotational movement of the rotor generates an electric voltage on the stator of the alternator.

The chosen alternator is an AC brushless low rpm alternator. It has a rated power of 100W, which means that it is small and light and its rated speed is 600 rpm, suitable to work with fluids like water inside water distribution pipelines. Therefore, at the rated speed the alternator provides 12V AC to the rectifier.

As stated before, the following work and research on this project will address all the mechanical and physical design considerations and requirements.

Due to budget restrictions, the system was tested being powered from a variable voltage 60 Hz three-phase AC bench. It fulfils all the requirements and it is a perfect substitute of the alternator chosen.

Rectifier

Input: 12 +/-1V AC

Output: 26V DC + AC Ripple (4Vpp)

The rectifier is responsible for converting the three-phase variable-frequency alternating current from the alternator into a single-phase continuous current. The system will be a three-phase full-wave rectifier formed by 6 Schottky diodes to minimize the voltage drop and increase the efficiency.

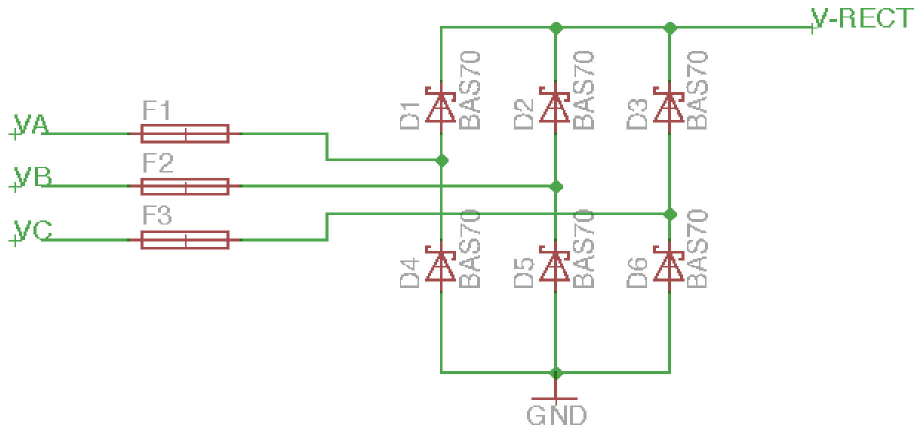


Figure 3 Rectifier Schematic

Low-Pass Passive Filter

Input: 26V DC + AC Ripple (4Vpp)

Output: 27 +/-0.1V DC

As the current delivered by the rectifier has a high-voltage and high-frequency ripple, a low-pass filter is needed to improve the quality of the current and facilitate the control of the duty cycle of the converter. The chosen configuration is a second order filter composed exclusively of passive elements. The corner frequency is 10Hz. This value is chosen because the frequency of the first, and most significant, harmonic of the output voltage of the rectifier is 360 Hz. The corner frequency is set more than one decade before in order to sufficiently attenuate the input voltage ripple. More detail and explanations will be provided in the calculations section.

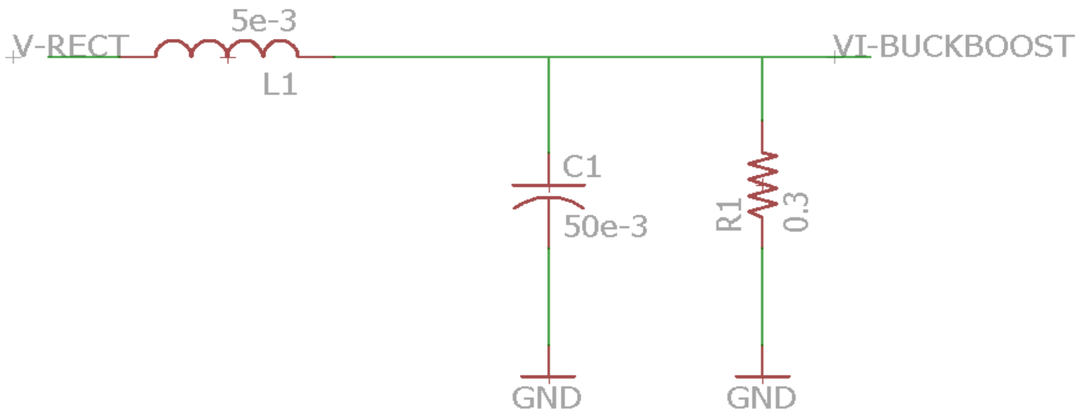


Figure 4 Second Order Low-Pass Passive Filter Schematic

DC/DC Buck Converter

Input: 27 +/-0.1V DC

Output: 15 +/-0.1V DC

The Buck converter is responsible for providing a constant 15V to the battery charge circuit to effectively charge the battery. The chosen configuration is a Buck converter because the maximum output voltage of the filter for the rated input is 25V and a constant 15V input is required to power the battery charge system. Therefore, and taking into account possible input variations and minor losses in the system, the output voltage of the filter had to be stepped down and the most efficient way to do so is using a Buck Converter. DC/DC converters are the most efficient and cheaper configuration to change DC voltages.

In addition to that, the control possibilities for a Buck Converter are wider than for other DC/DC converter configurations and one of the objectives of the project is to include a robust control system to maintain constant the output voltage of the converter.

An IRS 2183 mosfet driver is used to generate the gate signal to control the mosfet. The input of the driver is provided by the microcontroller as a high frequency PWM signal.

During the development process several control techniques were discussed, but due to the time constrains, the buck converter was only tested using an iterative control. This control was enough to test and demonstrate the functionality of the module under real conditions and attached to other modules.

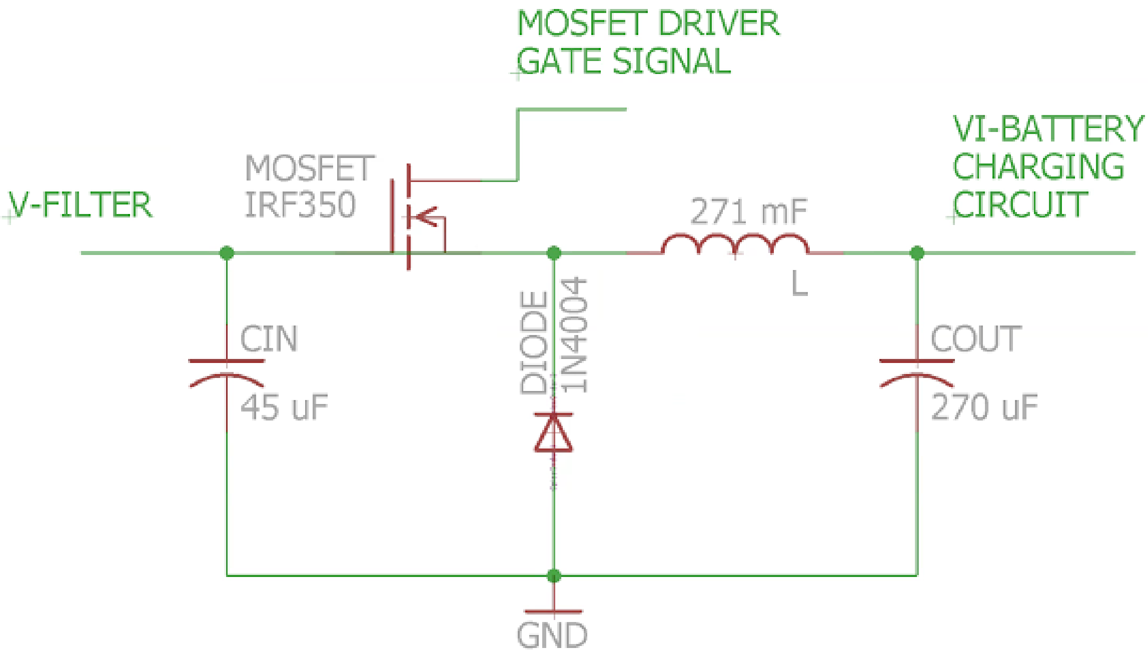


Figure 5 Buck Converter Schematic

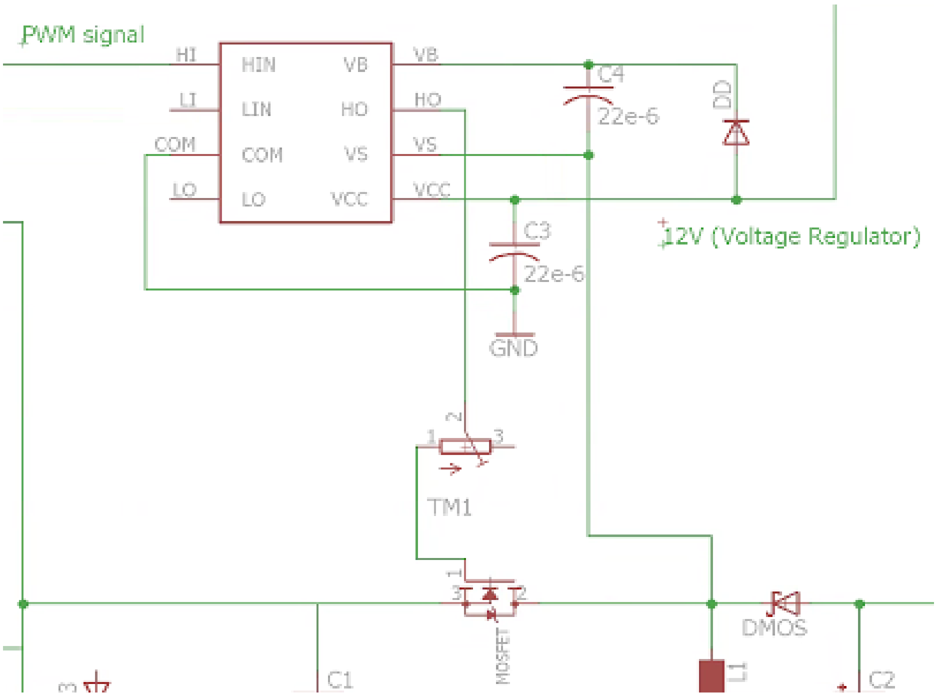


Figure 6 Mosfet Driver Schematic

Battery Charge Circuit

Input: 15 +/-0.1V DC

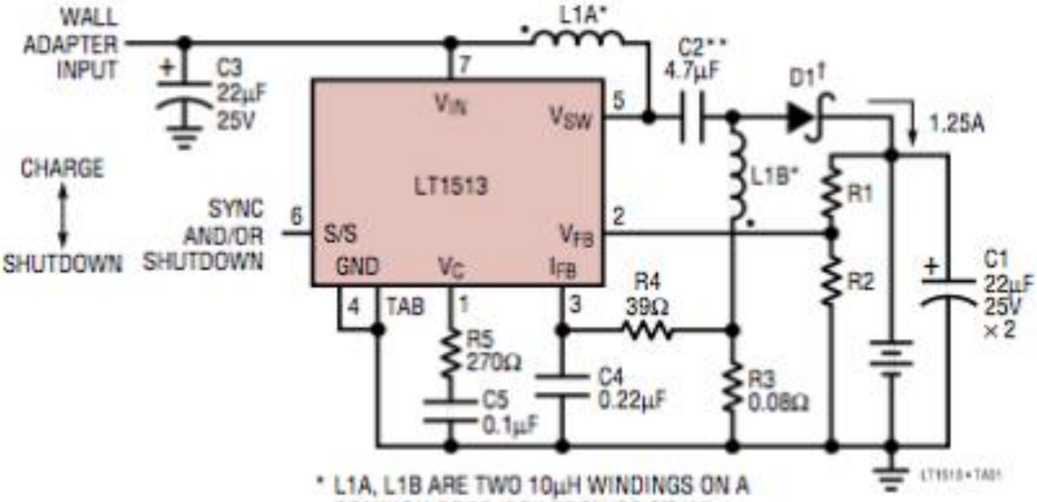
Output: variable DC current

The battery chosen is a 12V sealed lead acid battery because this type of battery provides high reliability, high ratio capacity/price and its charging characteristics and charging process are easier than other and require less restrictive safety measures. It will store the energy harnessed by the turbine and properly converted by the power conversion subsystem.

The charge circuit is based on a SEPIC LT1513 battery charger chip and all the components required for its implementation. To ensure safety while the battery is being charged, the recommended configuration has been implemented. The values of the components in this configuration are chosen so that the requirements of a 12V sealed acid battery are achieved.

The battery charger chip is already configured to follow the ideal charging characteristic curve of the battery attached to it. Moreover, it is capable to charge the battery when it is powered with voltages below, equal or higher than the battery rated voltage. Therefore, this component improves the robustness of the system because it can charge the battery even if the output voltage of the converter is not totally constant or temporary lower than the rated one.

Additionally, the implementation of this chip in the system increases the robustness and safety of the design because, even if the control of the converter is not very accurate, quick or robust, the battery charge circuit will adjust the voltage and the current provided to the battery automatically despite the variations in the input.



* L1A, L1B ARE TWO 10µH WINDINGS ON A COMMON CORE: COILTRONICS CTX10-4

** CERAMIC MARCON THCR40EIE475Z OR TOKIN 1E475ZY5U-C304

† MBRD340 OR MBRS340T3. MBRD340 HAS 5µA TYPICAL LEAKAGE, MBRS340T3 50µA TYPICAL

Figure 7 LT1513 General Schematic

The charging characteristics for a sealed lead acid battery are exposed in the following Figure and explained in detail.

Lead acid batteries have to be charged in three stages, which are constant-current charge (1), topping charge (2) and float charge (3).

The constant-current charge applies the bulk of the charge and takes up half of the required charge time. It charges the battery to about 70 percent.

The topping charge continues applying a lower charge current and provides saturation. The topping charge is essential for the well-being of the battery. If continually deprived, the battery will eventually lose the ability to accept a full charge and the performance will decrease due to sulfation.

Finally, the float charge compensates for the loss caused by self-discharge and it maintains the battery at full charge.

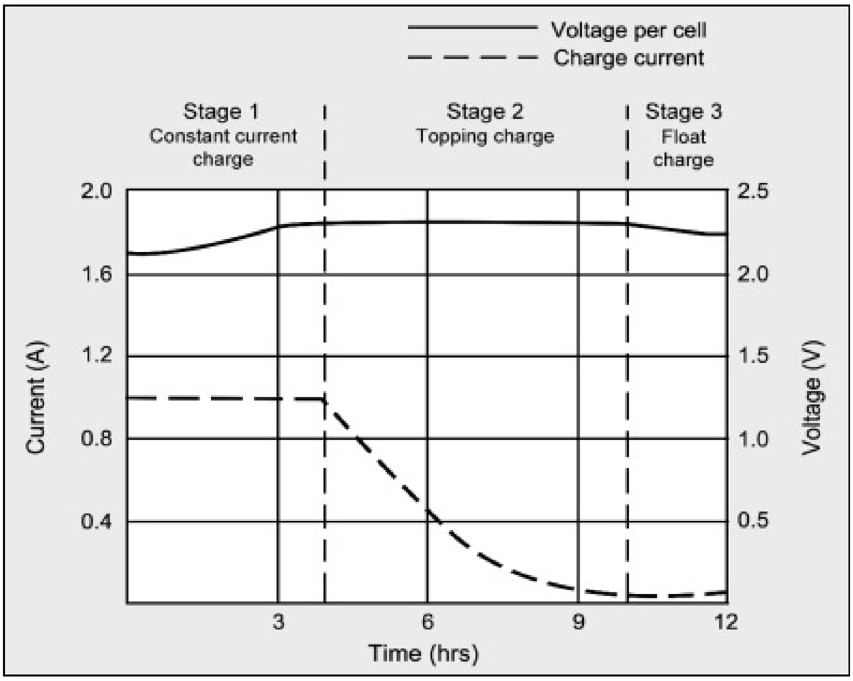


Figure 8 Lead Acid Battery Charge Characteristics

2.3.2. Control

One of the requirements the system has to fulfil, is to give a constant 15 V input to the battery charge circuit. However, given a certain duty cycle for the boost converter, its output voltage will depend on the input voltage, which depends on the fluid's velocity. Therefore, a control is needed to adjust the duty cycle, so despite the velocity of the fluid, the battery is charged within the safety voltage range and following its charging characteristics. In addition to that, the control module performs several measurements along the power conversion circuit to ensure that none of the variables surpasses the maximum values for the components chosen and, if necessary, shut down the system.

Voltage Regulators

Input: 15 +/-0.1V DC

Output 1: 10V DC

Output 2: 12V DC

Two voltage regulators are required for the system. The first one provides a constant 10V voltage to power the main microcontroller, which is and Arduino Uno. The second voltage regulator is responsible of powering the mosfet driver with a constant 12V voltage. Both voltage regulators are powered from the output voltage of the buck converter.

A voltage regulator configuration has been chosen because they can power these components efficiently and reliably despite possible fluctuations on its input voltage. As the Arduino and the mosfet driver have low power consumption compared with the power transmitted through the system, the voltage drop and the energy losses provoked by the voltage regulators in the system can be modeled as insignificant, as well as the current drawn from the circuit. Moreover, a voltage regulator does not need any kind of external or additional control, which reduces the complexity of the code of the microcontroller.

Microcontroller

To provide and ensure a constant 15V output voltage of the converter the microcontroller has to control and adjust the duty cycle of the DC/DC buck converter. One of the requirements the system had to fulfill, was to give a constant 15 V input to the battery. However, given a certain duty cycle for the buck converter, its output voltage depends on the input voltage, which depends on the fluid's velocity. Therefore, a control was needed to adjust the duty cycle so that the battery could be charged within the safety voltage range, regardless of the fluid's velocity.

All the control functions are performed by the microcontroller. An Arduino Uno was chosen as the microcontroller because a fast response is needed in order to efficiently change the control variable, and PWM outputs are required. These latter ones create the mosfet driver's input signal, which controls the switching of the mosfet.

Arduino Uno has enough PWM output ports and its clock speed is high enough to perform all the task and processes needed in our system. Moreover, this microcontroller is well known, easy to program and configure and its cost is lower than the rest of possible options.

2.3.3. Wireless Communication

The data that has to be displayed on the LCD is sent wirelessly from the microcontroller trough a transmitter circuit. We will use a transmitter and a receiver based on 434MHz RF technology for this purpose to simplify the transmission protocol and ensure that no further infrastructure is needed. The receiver will be connected to an auxiliary microcontroller to decode the data sent.

Auxiliary Microcontroller

Another objective of the project is to display some variables and measurements from our system in a remote center. To do so, the data is sent wirelessly from a transmitter to a receiver and displayed on an LCD screen. Therefore, an auxiliary microcontroller is required to manage the received data. Since this task is simpler and less demanding than the one performed by the main microcontroller, Arduino Uno fulfilled the requirements for this purpose too.

Transmitter

The transmitter is connected to the main microcontroller and its function is to send the power generated, fluid's speed and fluid's temperature to the receiver. The transmitter was chosen based on the desired transmission frequency, which is 434MHz. Once all the variables are calculated based on the measurements performed by the microcontroller they are codified and sent wirelessly.

Receiver

The receiver is responsible for receiving the data sent from the transmitter. Since the transmitter sends all the variables codified in one string of data, the microcontroller on the receiver's side has to decode it, separate it into three different variables. This information is sent directly to the LCD display.

Auxiliary Battery

To power the auxiliary microcontroller of the remote center an auxiliary source of power is required. A small power bank based on a Li-ion 10V battery provides reliably enough power at the required 10V for the Arduino Uno. The battery has an output voltage of 10V and a capacity of 1500mah. The consumption of LCD display, the receiver and the auxiliary microprocessor and the remote are relatively low, hence this rechargeable power bank will be enough to power all those elements.

2.3.4. User Interface

The user interaction with the system consists of showing different measures displayed on a screen. There is no input needed from the user in this project, as all the control functions will be performed automatically by the microcontroller.

LCD (liquid crystal display)

A simple 16x2 LCD display served the purpose as it was able to receive data from the microcontroller and it displays all the variables alternatively and automatically. This means that, automatically, only one measure was showed in the LCD screen to facilitate its lecture.

2.3.5. Sensor

For the design the traditional mechanical measurement methods are substituted by electronic sensor, in order to obtain a more accurate and simple measure.

Temperature Sensor

The temperature sensor provides feedback of the temperature conditions of the fluid. In order to avoid unnecessary complications, an lm335 temperature sensor was isolated and made completely waterproof. This sensor functions like the typical voltage drop sensors used in many electrical circuits and applications. The microcontroller measures the voltage across the sensor and calculates the temperature of the water following the voltage/temperature characteristics of the sensor and the circuit required.

2.3.6. Safety Measures

These possible failures could be produced by the following components or events due to the conditions and requirements of the project:

- The generator could rotate at a higher speed than the rated one. It would produce a temporary increase in the current and voltage through the components.
- A shortcut circuit could happen in any point of the PCB due to the failure of a component.
- A failure in the control systems could lead into an increase of the input voltage of the battery which can be very hazardous.
- If the battery is charged with a high current it can decrease drastically its lifetime or even provoke a leakage of acid fluids.
- If water came into the system it would cause terrible damage.

For those reasons, several security measures have been included in the design of the project.

Firstly, as the system is required to charge a sealed lead acid battery and expected to handle high currents, therefore, additional security measures have to be implemented to protect the circuit and isolate the critical components against possible failures.

Secondly, the design includes fuses between the most important sections of the power conversion system.

- Three fuses are installed, one in each phase between the alternator and the rectifier to avoid possible over-currents provoked by a temporary over-speed of the water turbine or due to a short circuit in the alternator. The expected current is 5A, so the rated current for these fuses are 6A and the components have been chosen to handle up to 6A.
- Another fuse is included between the DC/DC converter output and the battery charger circuit input. The rated current for this fuse is 8A, since the expected output current for the DC/DC converter is 6.5A and the battery cannot be charged with a current above 8A to avoid reducing its lifetime.

In addition to that, safety protocols in the microcontroller are implemented to immediately shut down the system avoiding or reducing possible damages to the components when a failure is detected.

Measurements at the following points of the power conversion circuit are included:

- Output voltage of the rectifier. The objective is to control that the voltage does not experiment dangerous variations or unexpected increases over the security ranges.
- Output voltage of the rectifier. The output voltage has to remain at 15V to ensure that the battery is being charged safety.

2.4. Calculations

In this section the calculations done and required for the election components, the design and the most important magnitudes for our system are presented, explained and justified.

2.4.1. Calculations of the Components of the AC/DC Rectifier

The alternator chosen has a rated power of 100W and a maximum output voltage of 12V

$$V_{Gen} = 12V \qquad P = 100W$$

Applying the following equation, which is the voltage output for a full-wave three-phase rectifier from the input voltage, we can obtain the voltage output of it.

$$V_{in} = 0{,}955 * V_{p,L-L} = 0{,}955 * \sqrt{2} * V_{Gen} * \sqrt{3} = 27.92V$$

The rectifier steps up the voltage to a value of 27.92V

The voltage rating for the diodes is exactly the same as the maximum output voltage of the rectifier, therefore, the diodes are going to face a maximum voltage of 28V.

The voltage ripple is determined by the harmonic component of the output waveform. In this case, the amplitude of each harmonic can be calculated from the following equation.

$$V_n = \frac{6 * V_{m,L-L}}{\pi(n^2 - 1)} \qquad n = 6{,}12{,}18{,}\ldots$$

In Figure 8 shows the amplitude of the different harmonics in the output voltage and their frequencies as a function of the frequency of the alternator. The amplitude has been calculated from the rated output voltage of the alternator as well, in this case 12V.

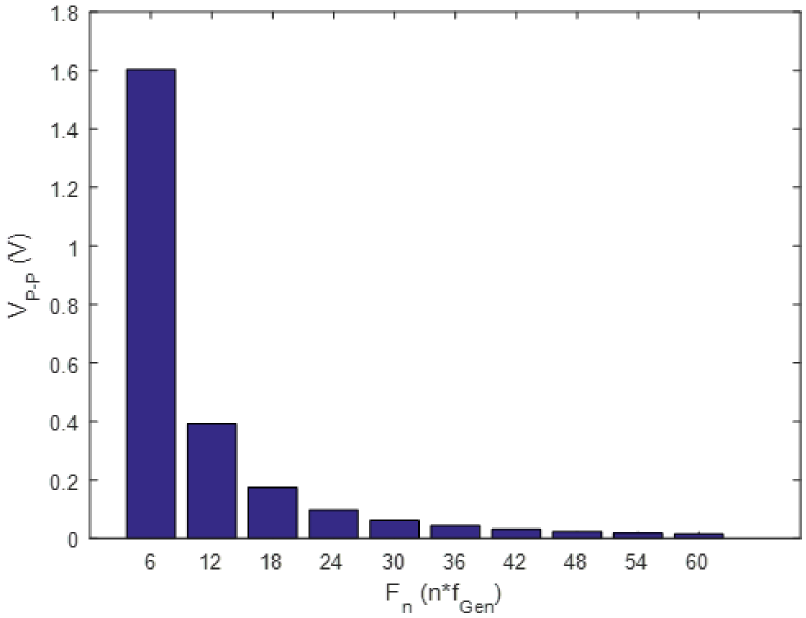


Figure 9 Harmonic Content of the Rectifier

As it can be inferred from previous figure and equation, the harmonics tend to attenuate very significantly from the second harmonic. Moreover, the only important and disruptive harmonic is the first one with amplitude of 1.6V.

Finally, the maximum current across the diodes can be calculated with this equation:

$$I_D = \frac{P}{\sqrt{3} * V_{Gen}} = \frac{100}{\sqrt{3} * 12} = 4.81\ A$$

The minimum current that the diodes have to handle is 4.81A.

2.4.2. Calculations of the Components of the Low-Pass Passive Filter

The objective of this module is to attenuate as much as possible the output voltage ripple of the rectifier to facilitate the step down conversion of the DC/DC converter and avoid unnecessary distortions on the battery charge process. Therefore, a Low-Pass second order passive filter is required to attenuate the high frequency harmonic content in the output voltage.

A passive filter is being used instead of an active one because the power transmitted through the circuit and the current cannot be handled by an Operational Amplifier.

The transfer function for the filter and its corner frequency are:

$$\frac{V_{out}}{V_{in}} = \frac{1}{LCs^2 + \frac{L}{R}s + 1} \qquad \omega_0 = \sqrt{\frac{1}{LC}}$$

From the previous equations it is possible to obtain the frequency respond of the second order filter:

$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{\sqrt{(1-\omega^2 LC)^2 + (\omega\frac{L}{R})^2}}$$

$$Arg\left(\frac{V_{out}}{V_{in}}\right) = 1 - arctg(\frac{\omega\frac{L}{R}}{1-\omega^2 LC})$$

This design has to minimize the active power losses and maximize the attenuation for the harmonic content of the voltage ripple.

Calculus of the corner frequency of the filter:

The rated speed of the alternator is 600 rpm, therefore the frequency of the first harmonic of the rectifier is:

$$\omega_{Gen} = 600\, rpm \Rightarrow f_{Gen} = 10\, Hz$$

$$\omega_6 = 2\pi * 6 * f_{Gen} = 376.991\, rad/s$$

The corner frequency for the low-pass filter should be settled more than one decade before the desired frequency to attenuate. Hence, the corner frequency has to be:

$$f_6 = 60\, Hz \Rightarrow f_0 = 10 Hz = 62.8319\, rad/s$$

This value is sufficient to meet the requirements for the input voltage for the DC/DC converter. In the following section, several simulations and graphs show the adequacy of this values and how the attenuate the different harmonics of the voltage ripple.

From the corner frequency equation, it is possible to obtain the following expression relating the values of the capacitor and the inductor:

$$\frac{1}{C} = 3947.84 * L$$

The following values were decided attending strictly to the availably of the components in the lab were the project was being developed. The bigger inductor available and suitable for the design and the value of the capacitors required are:

$$L = 35\ mH$$

$$C = 7.5\ mF \Rightarrow C_{Tot} = \begin{cases} 2 \times 1mF \\ 2 \times 1{,}8mF = 7.8mF \\ 1 \times 2{,}2mF \end{cases}$$

These values are relatively high for the power system designed.

Firstly, the value for the capacitor and its rated voltage imply a large discharging time and high energy storage. These could produce failures if the system has to be shuttled down fast.

Secondly, the value of the inductor and its rated current imply that the size and weight of the inductor are very high which provokes that the system has to be bigger and heavier than expected or recommended initially. The weight for the inductor is around 2 Kg, twice the weight of all the electrical components and the PCB. And it has the same size as all the PCB which prevents it from installing it on the same board as the rest of the components.

This module was not implemented in the final PCB due to its size and weight.

The corner frequency of the filter with these final values is:

$$\omega_0 = 63.245\, rpm \Rightarrow f_0 = 10.065\, Hz$$

Figure 12 presents the Bode diagram for the final design of the filter:

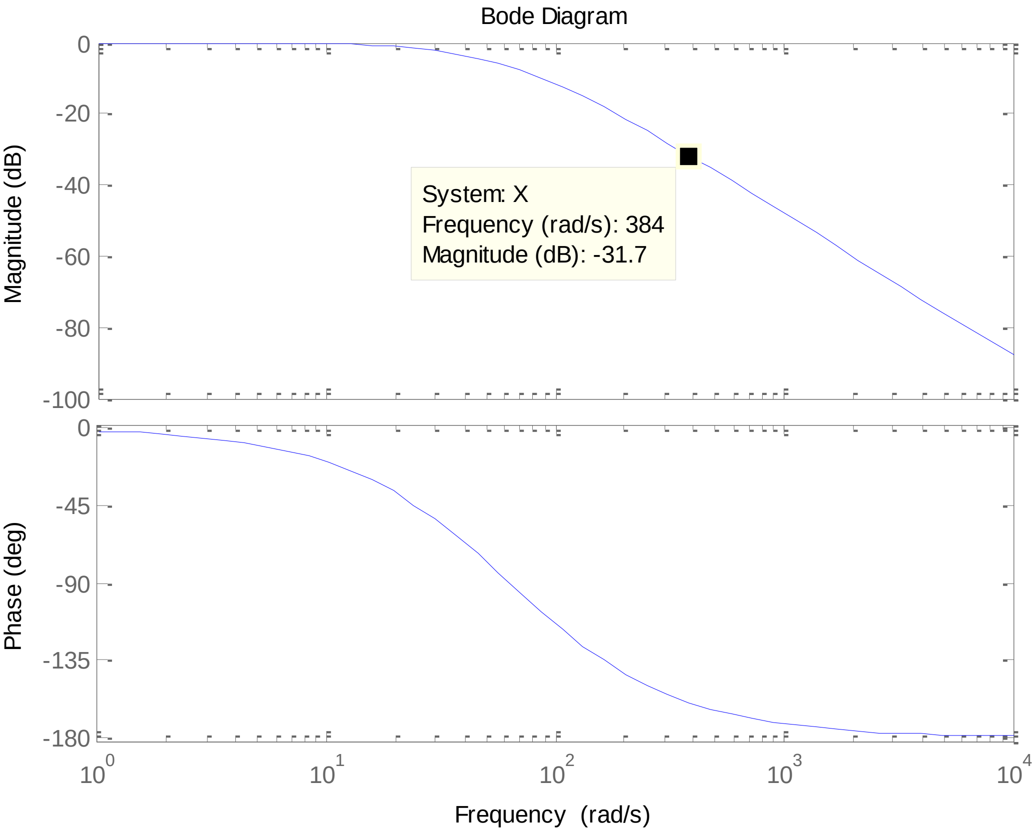


Figure 10 Bode Diagram of the Low-Pass Filter

The value of the attenuation for the first harmonic of the output voltage at the rated speed of 600 rpm of the alternator is included in the previous figure.

As the attenuation is -31dB at the frequency of the first harmonic, the peak-to-peak value of the first harmonic of the output of the filter is 0.1V

To reduce the resonance response of the system it is possible to add a small resistor in parallel with the output shunt of capacitors. That resistor could be any value between 0.1 and 0.5 Ohms.

2.4.3. Calculations of the Components of the DC/DC Buck Converter

From the calculations of the filter and the rectifier we have an input voltage of:

$$V_{in} = 25 \pm 0.05V$$

The requirements for the Buck converter, which are determined by the rest of the components of the power conversion circuit, are the following:

$$V_{out} = 15V \; ; \; P_{out} \approx P_{in} = 100W \; ; \; f_{sw} = 62kHz \; ; \; \Delta V_{out} = 0.1\,V$$

The critical values to fulfill the requirements for each component are obtained from the general equations for a buck converter:

$$V_{out} = V_{in} * D \Rightarrow \frac{V_{out}}{V_{in}} = D = 0.6$$

$$R_{out} = \frac{{V_{out}}^2}{P_{out}} = 2.25\,\Omega$$

The minimum value for the inductor to ensure that the converter will be working strongly in continuous conduction mode is:

$$L_{min} = \frac{(1-D)R_{out}}{2f_{sw}} = 7.258\mu H$$

Hence, the real value recommended for the design has to be bigger than that value. The bigger the value the lower the current ripple through the inductor and, therefore, the smaller the output voltage ripple will be. The inductor chosen has a value of:

$$L = 271\;\mu H$$

The current ripple obtained with an inductor of that value is:

$$\Delta i_L = \frac{(1-D)V_{out}}{L * f_{sw}} = 0.35A$$

Calculus of the minimum output capacitor to ensure the voltage ripple required:

$$C_{out}^{min} = \frac{(1-D)}{8{f_{sw}}^2 * L * \frac{\Delta V_{out}}{V_{out}}} = 7.226\mu F$$

The final value of the output capacitor obtained during the testing phase is:

$$C_{out} = 270\ \mu F$$

The output voltage produced by the output capacitor chosen is:

$$\Delta V_{out} = \frac{V_{out} * (1-D)}{8 * {f_{sw}}^2 * L * C} = 2.66\ mV$$

The output voltage ripple is clearly below the requirements. Hence the value chosen is correct.

2.4.4. Calculations of the Battery Charger Circuit

From the datasheet of the SEPIC LT1513 chip we obtain the following equations to adjust the feedback and control system for the chip. Two resistors have to be selected depending on the battery type, which determines the battery charging characteristics that the chip has to follow and ensure, and the battery voltage to follow them correctly.

The value recommended for R2 for a sealed lead acid battery is 12.4KΩ.

Applying the equation for R1 and taking into account the value recommended for R2 and the battery voltage which is 12V:

$$R_1 = \frac{R_2 * (V_{bat} - 1.245)}{1.245 + R_2 * (0.3 * 10^{-6})} = 115k\Omega$$

Finally, the maximum charging current can be calculated from Figure 11. For a 12V sealed lead acid battery and an input voltage of 15V, settled as output of the buck converter, the maximum charging current is going to be 1.175A approximately.

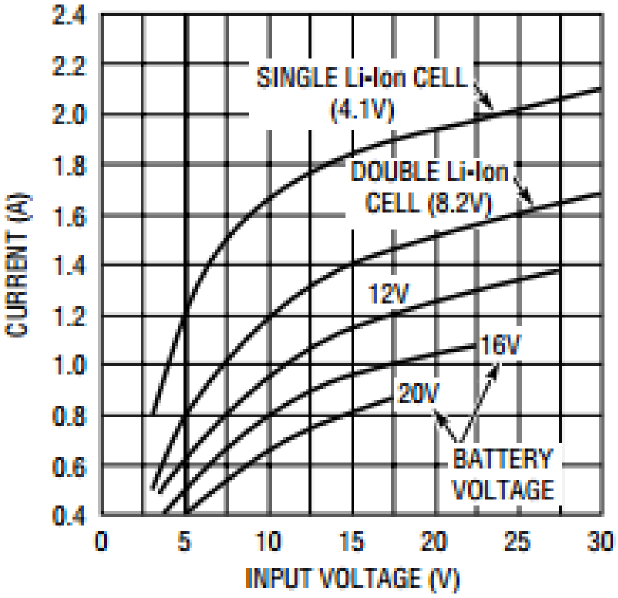


Figure 11 Maximum Charging Current LT1513

2.5. Simulations

In order to know in advance the overall behavior and functioning of the power conversion subsystem, multiple simulations were performed in Matlab. The results of the simulations helped and oriented the election of many of the components, especially the values of their current or voltage ratings. These values are critical in power projects like this one because the high currents and voltages across the components of the system are, in many cases, dangerous for the people.

The program used for the simulations was Matlab and its extension Simulik, using for most of the cases the Simscape library.

Again, as the previous section, the simulations performed and their results are going to be shown successively in the following pages.

2.5.1. Simulations of the AC/DC Rectifier

Figure 12 shows the model that has been used for the simulations of rectifier that is going to be installed between the output of the alternator and the input of the low-pass filter to convert the three-phase AC voltage into a single-phase DC voltage with an AC ripple.

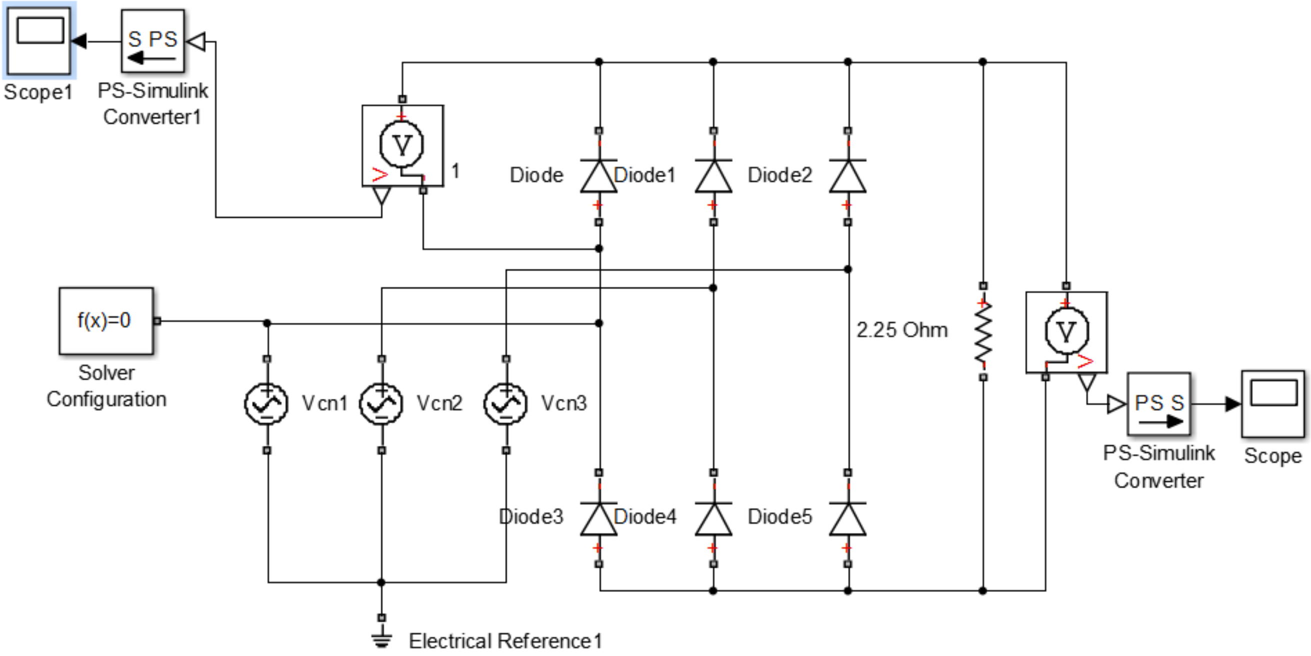


Figure 12 Simulation Model for the Rectifier

The three AC voltage sources simulates the three phase alternator. They are settled to 600 rpm and 12V with the required angular shift between them.

The load is a 2.25 Ohm resistor as calculated in the calculation section for the DC/DC buck converter.

Finally, the voltage drop in the diodes is settled to 0,1V because that is the typical voltage drop for a Schottky diode in comparison with a normal diode which tend to be around 0.7V. A more detailed comparison is included in the following figures.

Figure 13 shows that the output voltage ripple is approximately 3.4V and the maximum voltage across the diodes is 27.5V.

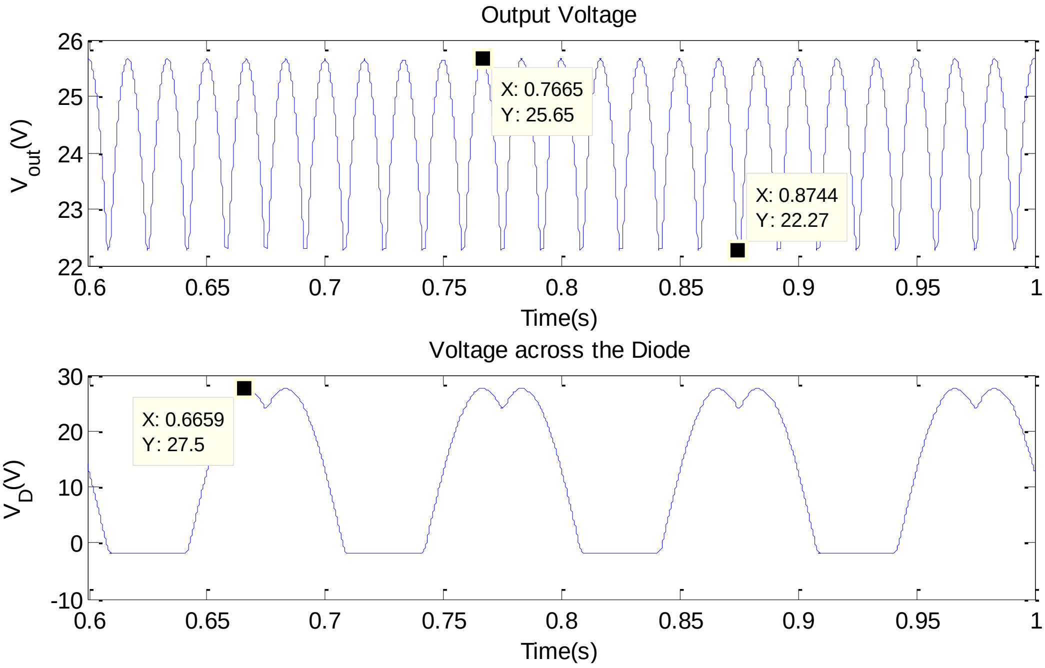


Figure 13 Output Voltage of the Rectifier and Voltage across the Diodes

Figure 14 shows a comparison of the voltage across the diode for the rated speed of the alternator and for half of that speed. The maximum voltage is exactly the same with independence of the rotational speed of the alternator. Therefore, the maximum voltage across the diode is only related with the output voltage of the alternator.

Figures 15 and 16 show the comparison between a Schottky diode and a normal diode. For the simulations, their only difference is their voltage drop when they are conducting. As stated before, 0.7V for a normal diode and 0.1V for a Schottky diode. The difference in the output voltage is around 1V while the voltage difference for the voltage across the diode is 0.5V more similar to the actual voltage drop difference between the two models under study.

Attending to the efficiency difference, main argument in favor of using the Schottky diodes instead of the normal ones, the simulations show an efficiency increase of 9.27% when using Schottky diodes.

$$mean\left(\frac{P_{out}^{Sttky}(t)}{P_{out}^{Normal}(t)}\right) = 1.0927 = \Delta\eta = 9.27\%$$

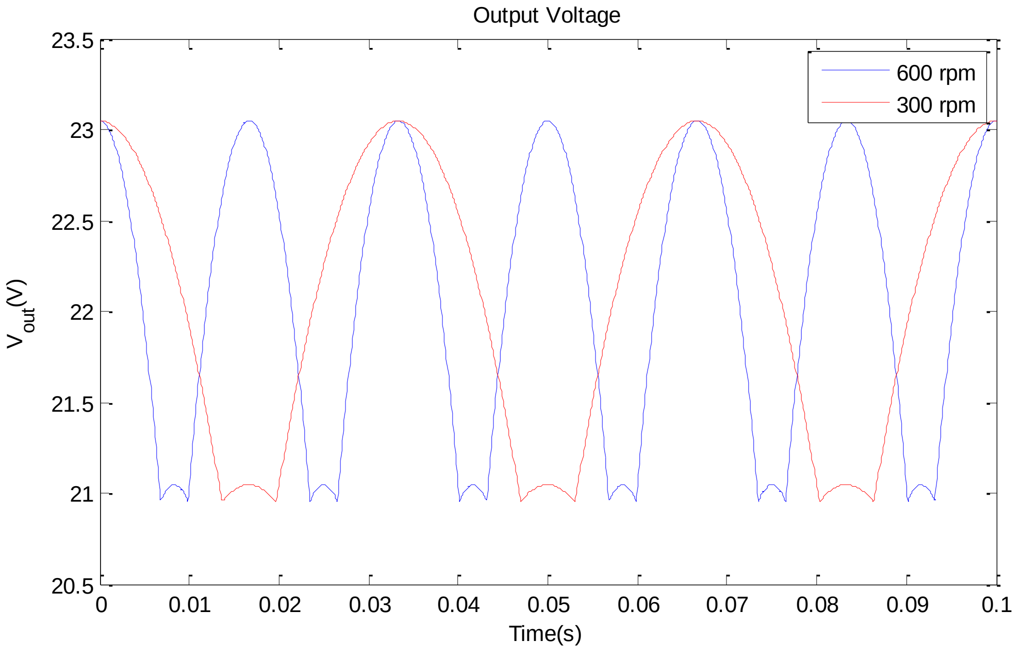


Figure 14 Voltage across the Diode for Different Speeds of the Alternator

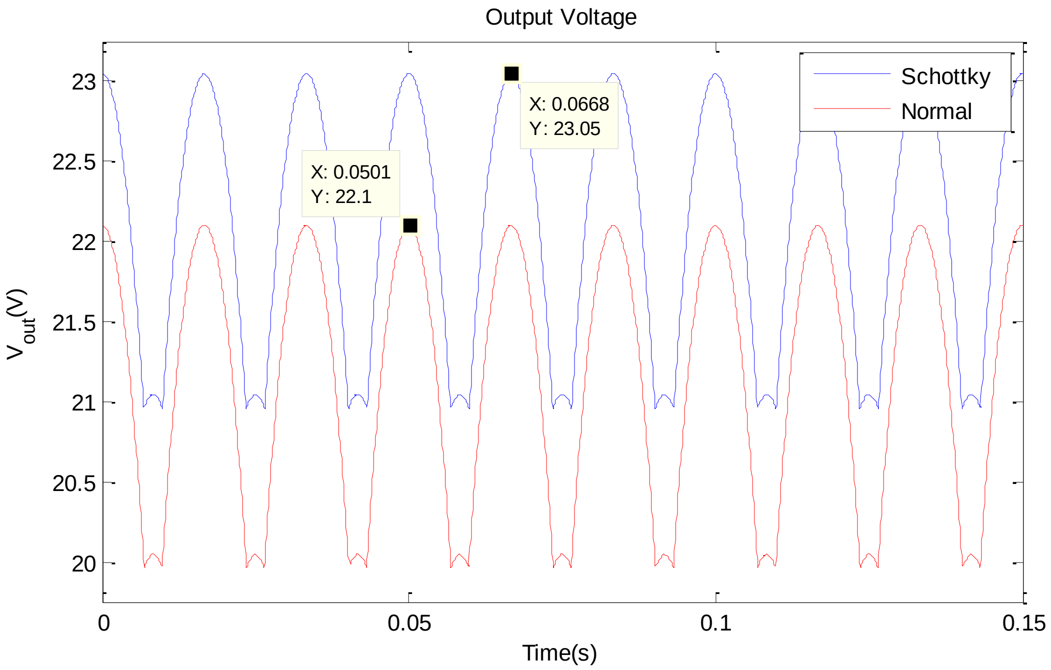


Figure 15 Output Voltage of the Filter for Normal Diode vs. Schottky

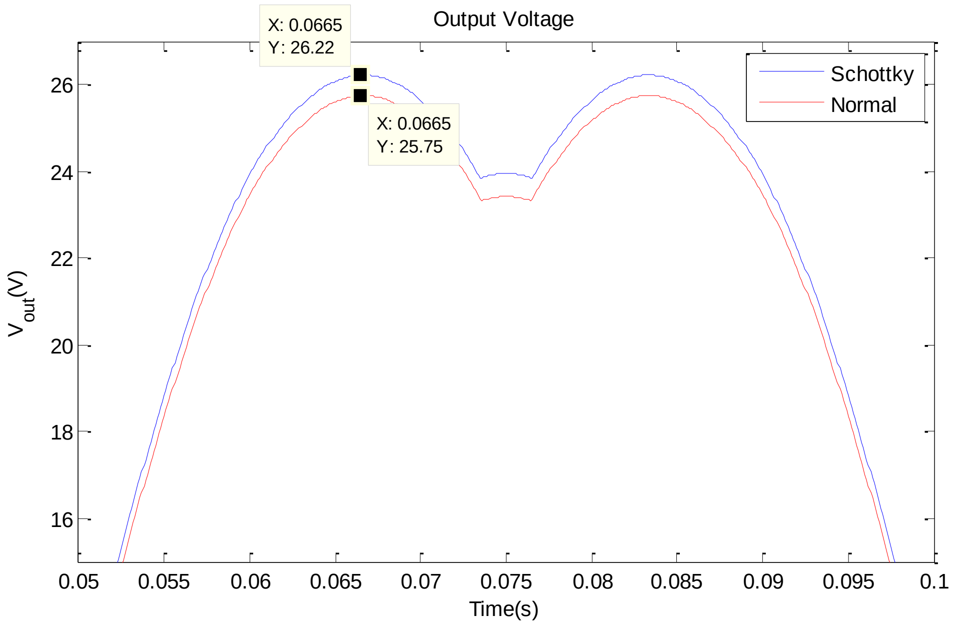


Figure 16 Voltage Drop across a Normal Diode vs. Schottky

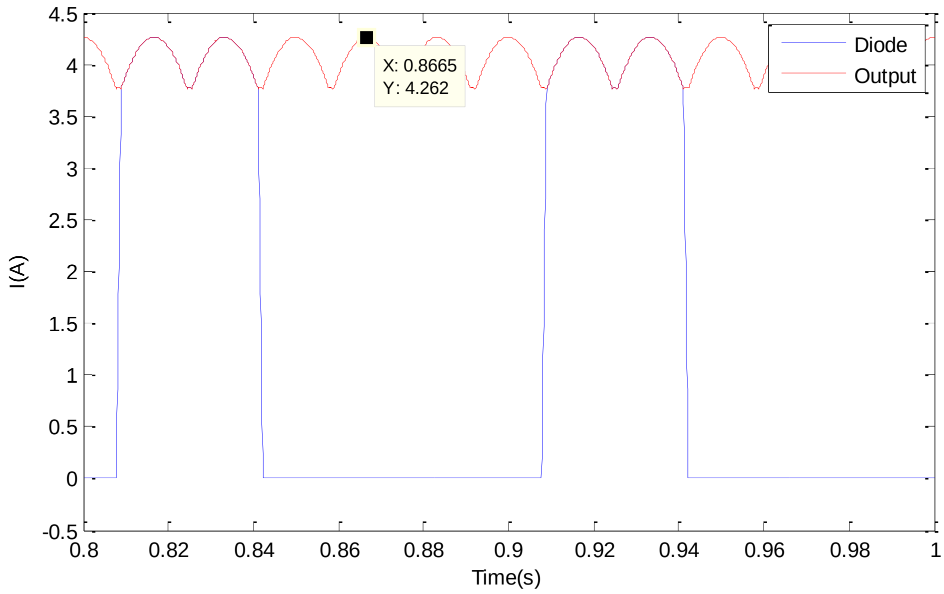


Figure 17 Current across the Diode vs. Output Current

Finally, Figure 17 presents a comparison between the current across one of the diodes and the output current. The maximum current across any of the diodes is exactly the same as the maximum output current, which is 4.26A.

2.5.2. Simulations of the Second Order Low-Pass Passive Filter

Figure 18 shows the model that has been used for the simulations of the low-pass filter that is going to be installed between the output of the rectifier and the input of the DC/DC converter to reduce the ripple of the voltage and the current.

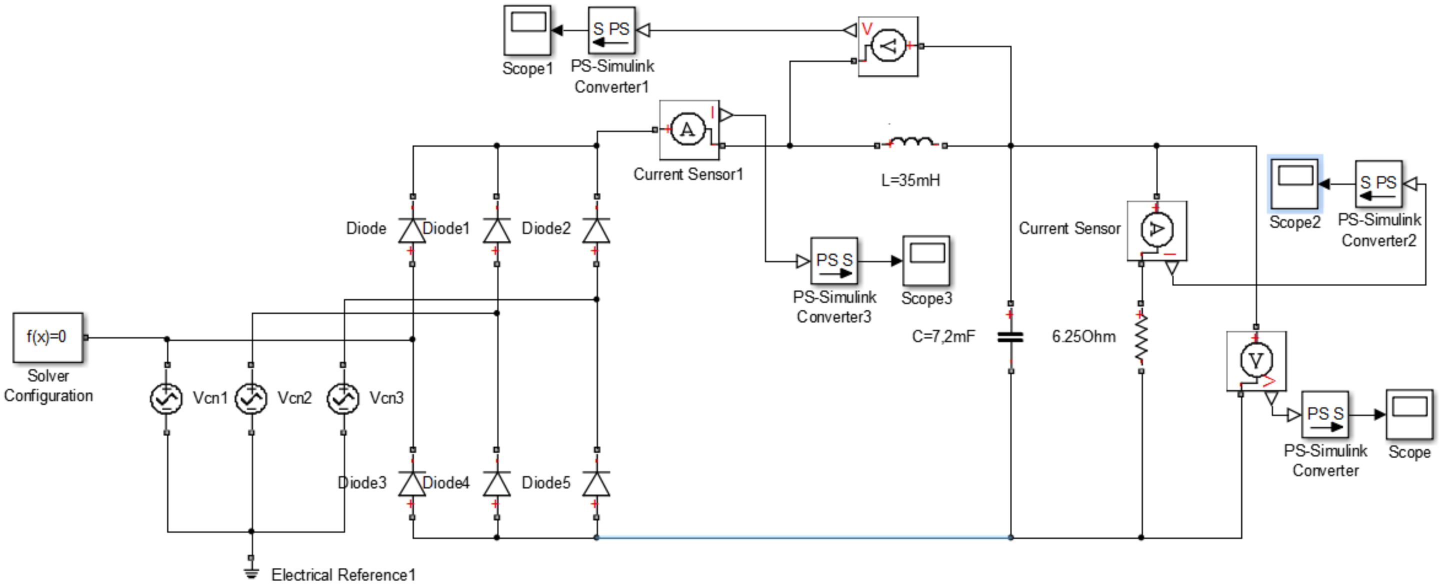


Figure 18 Simulation Model for the Filter

This model is based on the rectifier model. It uses the same components with the same values and using, as discussed previously, Schottky diodes with small voltage drop and fast switch recovery. The inductor and the capacitor introduced for the filter have the same values as the ones obtained in the calculations section. To finalize, the load chosen is approximately the resistor value that consumes 100W. This was done to try to simulate the rated conditions of the system and to obtain the maximum current that is going to handle the inductor in steady state. This will provide an accurate value for its current rating.

Figure 19 presents the output voltage ripple and the output current ripple with their maximum and minimum values remarked. The voltage ripple has a peak-to-peak value of 0.1V and a mean value of 24.35V. The rated current has a mean value of 3.9A approximately and a small ripple of 0.01A

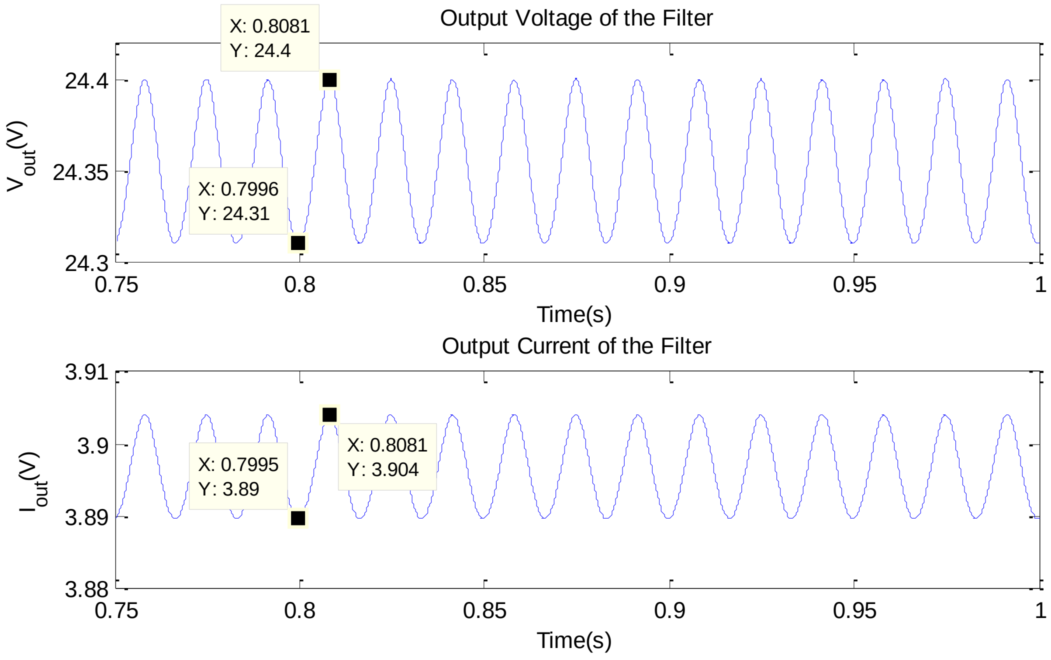


Figure 19 Output Voltage and Current of the Filter

Figure 20 shows a comparison between the output voltage of the filter and the output voltage of the rectifier. As calculated before and as expected the filter improves significantly the output voltage ripple, facilitating the control algorithm of the DC/DC converter on the next step of the power conversion subsystem.

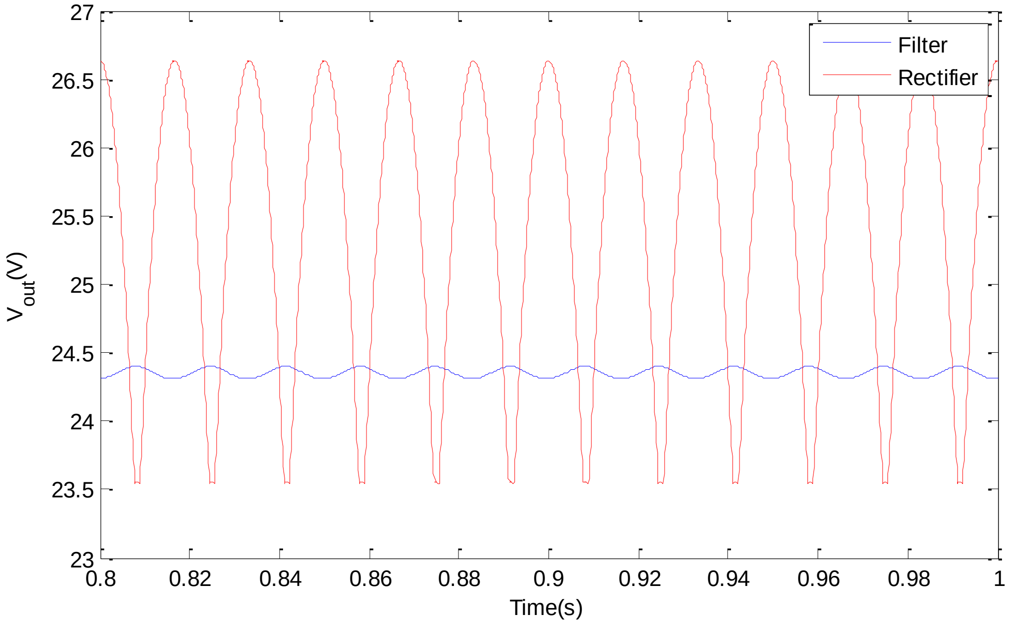


Figure 20 Comparison Output of the Rectifier and the Filter

Finally, Figure 21 shows the results of the final simulation. It was performed to calculate the current rating for the inductor of the filter. It shows that the inductor is going to handle a maximum current of 3.9A with a ripple of 0.25A.

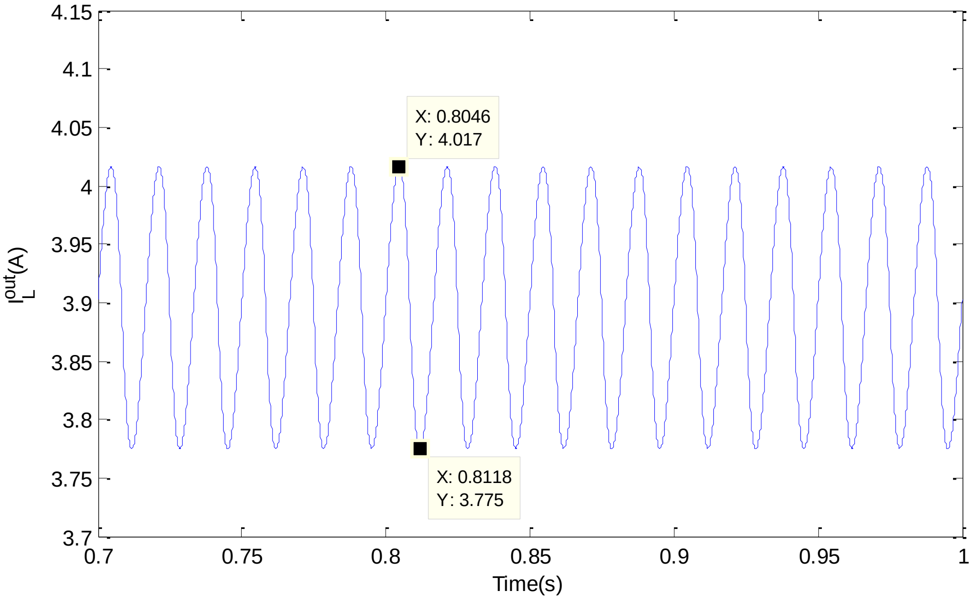


Figure 21 Steady State Current across the Inductor

2.5.3. Simulations of the DC/DC Buck Converter

The following Figure shows the model created for the simulations of the DC/DC buck converter without control. This model was used to obtain the average values and ripple through all the components and to prove the validity of some components. In addition to that, this model was used by my teammate to perform and simulate different control techniques and algorithms

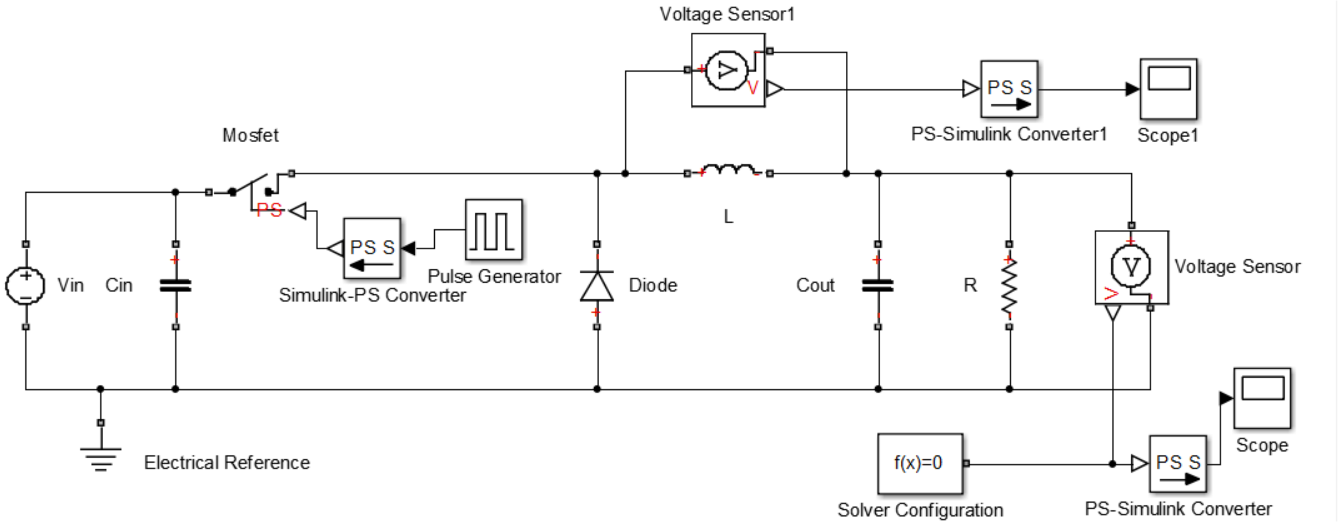


Figure 22 Simulation Model for Buck Converter

The library Simscape, contained in the Simulink extension, has a vast extension of real elements. This elements includes a wide range of parameter to configure following the datasheet of each component to check the behavior of each of them.

The value for the inductor is 210uH, the output capacitor is 270uF, the resistor is 2.25Ω, and the diode has a voltage drop of 0.15V and a conductive resistance of 0.15Ω. All the values came from the calculation section except for the values of the diode which came from the datasheet of a typical Schottky diode.

Firstly, Figure 23 shows the output voltage of the converter for an input voltage of 25V and a duty cycle of 60%, as calculated before. It clearly shows that the mean value of the output voltage is lower than the desired, which is 15V, however, the voltage ripple is almost insignificant and much lower than the required. Hence, the values for the inductor and the output capacitor are correct and the duty cycle should be increased slightly to match 15V as the output voltage.

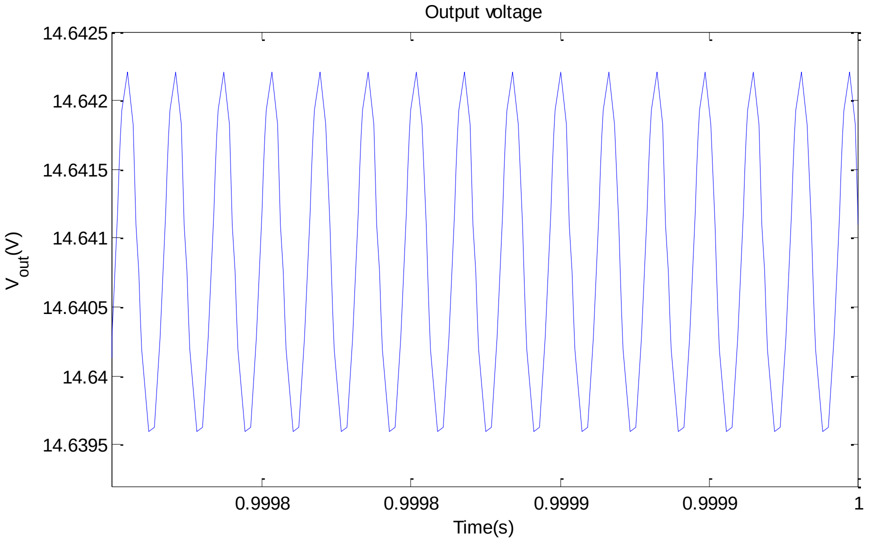


Figure 23 Output Voltage of the Converter

Secondly, Figure 24 presents the voltage across the 210uH inductor and the current that it has to handle on steady state conditions. As expected the mean value of the voltage is 0, and the peak-to-peak value is within the theoretical range of values expected. Moreover, the maximum current is 6.69A. This value is higher than the maximum current that other components of the system are going to handle. Therefore, the inductor of the converter has to have a higher current rating than the rest of inductors.

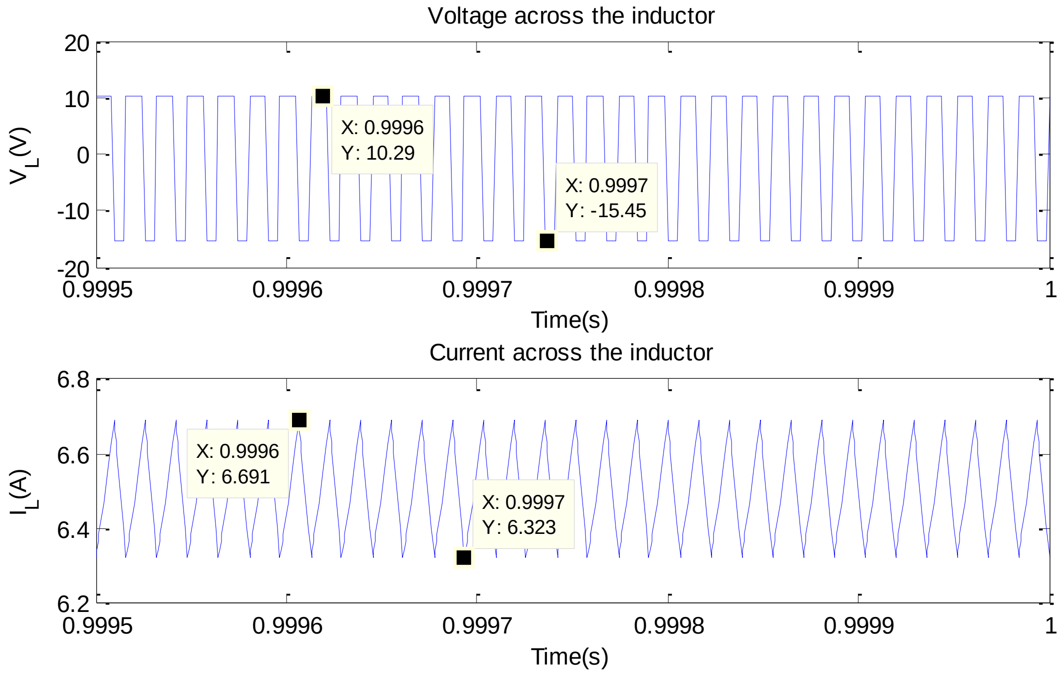


Figure 24 Voltage and Current across the Inductor of the Converter

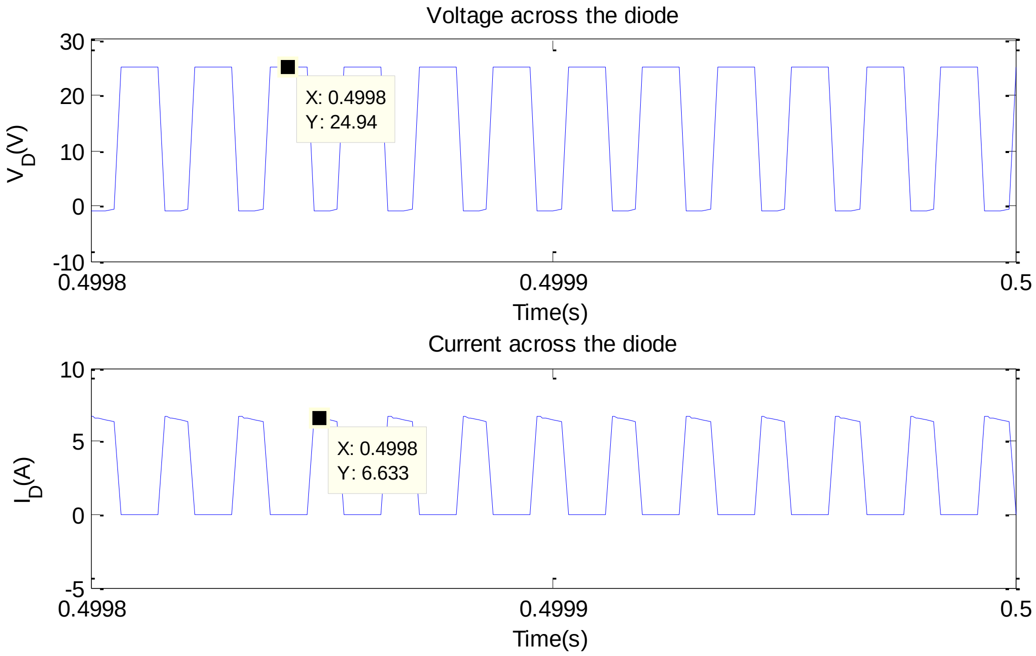


Figure 25 Voltage and Current across the Diode of the Converter

Thirdly, Figure 25 shows the results for the current and the voltage across the diode of the converter. The maximum reverse voltage that the diode is going to face is approximately 25V. In addition to that, the maximum current through it when it is conducting is 6.63A. This values are good references to choose the appropriate diode for the design.

Finally, Figure 26 presents the comparison between using high efficient components such as Schottky diodes, high switching mosfets and installing a shunt of capacitors in parallel to reduce the series resistance of the output capacitance. In this simulation the values of the components under study are the following. All the units are in volts, ohms and siemens.

	Normal	**High Efficiency**
Diode	V_{on}=0.7 & R_{on}=0.5	V_{on}=0.15 & R_{on}=0.1
Mosfet	R_{close}=0.04 G_{open}=3e-8	R_{close}=0.01 G_{open}=1e-8
Output capacitor	R_{ISR}=10e-8	R_{ISR}=1e-8

For the same duty cycle of 60%, the results obtained show an output voltage increase of 1.24V for the system composed by high efficiency elements. In addition to that, the increase in the efficiency is up to a 19% for the more expensive but better high efficiency components.

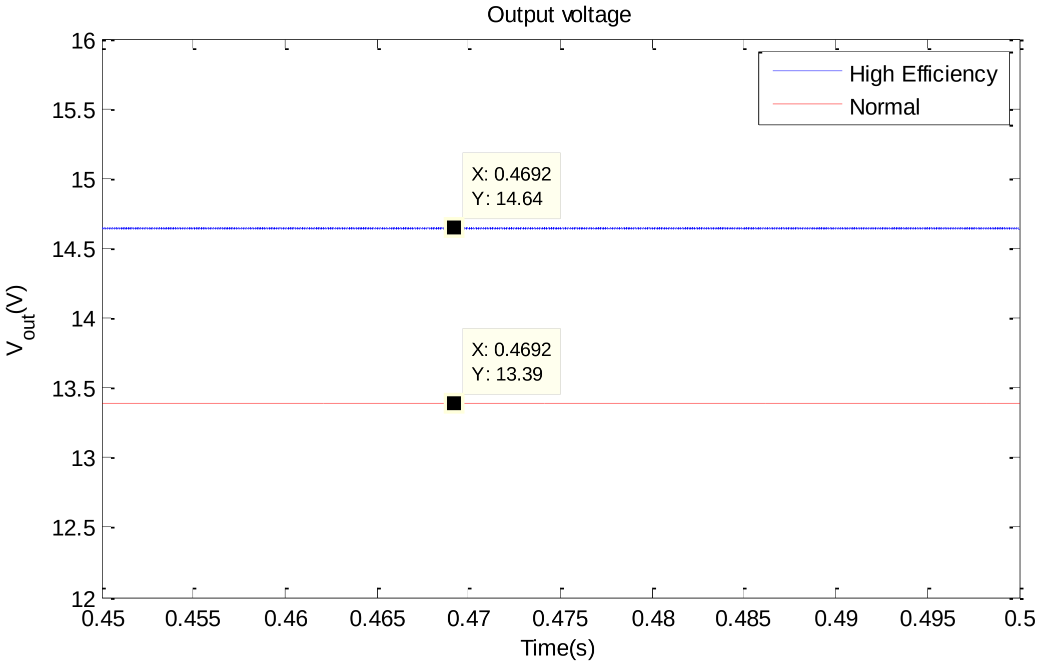


Figure 26 Output Voltage High Efficiency Elements vs. Normal

$$mean\left(\frac{P_{out}^{Effcy}(t)}{P_{out}^{Normal}(t)}\right) = 1.1957 = \Delta\eta = 19.57\%$$

All the previous simulations and their results present valid and useful guidelines to choose the appropriate and best components for the design. Moreover, they showed the minimum values for the current and voltage rating for that components.

2.6. Components

In this section, all the components that has been chosen and has been used in the design are going to be presented and justified based on their characteristics. Only the components that have been simulated are going to be exposed. The rest of components will be disclosed in the PCB and cost sections as they were not subject of study at this point.

2.6.1. Components of the AC/DC Rectifier

Component	Calculation	Simulation	Part Number
6 x Schottky Diode	I = 4.81A V = 28V	I=4.26A V=26.2V	sb80w10t

As this diodes have a high current and voltage rating, they were ordered from an external supplier. 12 Schottky diodes were ordered, 6 for testing in the protoboard and 6 to be welded in the PCB.

2.6.2. Components of the Low-Pass Filter

Component	Calculation	Simulation	Part Number
35mH Inductor	I = 4.81A	I=4.02A	-
7.8mF Capacitor	V=28V	V=24V	-

These two components were taken from the electric machines power lab as they were very expensive to order from an external supplier. These two components were attached independently to the rest of the system allowing their removability and later usage for other applications or projects.

2.6.3. Components of the DC/DC Converter

Component	Calculation	Simulation	Part Number
Mosfet	I = 4.81A	I=4.02A	stp160n3LL
Diode	V=25V	I=6.63A V=24.94V	c3d08060a
210uF Output Capacitor	V=15V	V=15V	Eeu-tp1v271L
271uH Inductor	I=6.67A	I=6.69A	Dfkf-28-0006

As stated before, all these components are power components due to their high current and voltage ranges, hence, there were not available directly for the students. All of them were ordered from an external supplier. Most of them were ordered duplicated to be able to test them in a protoboard and later solder them into the final PCB.

2.7. Printed Circuit Board (PCB) Design

Another important requirement stated by the instructors of the curse was to implement the system, or at least, one of the subsystems into a printed circuit board or PCB. For that reason, several iteration of the PCB for the system were made. In this section it is going to be showed and explained only the latest revision. This revision was the one used to test and show to the instructors and teacher assistants the functioning and viability of our design and, indeed, our project.

This design was based on the idea of being able to test independently all the different subsystems and modules. It includes all the necessary solder pods and drills to attach externally the connections between the different modules. All the modules are separated to facilitate the welding of the components and their testing.

In addition to that, the traces for power and for signal are totally independent maintaining enough space between them to avoid error or problems. The width of the traces for power transmission were calculated to handle the values of current obtained in the simulations.

The following figures show the PCB design and all the different modules and distributions will be explained and detailed.

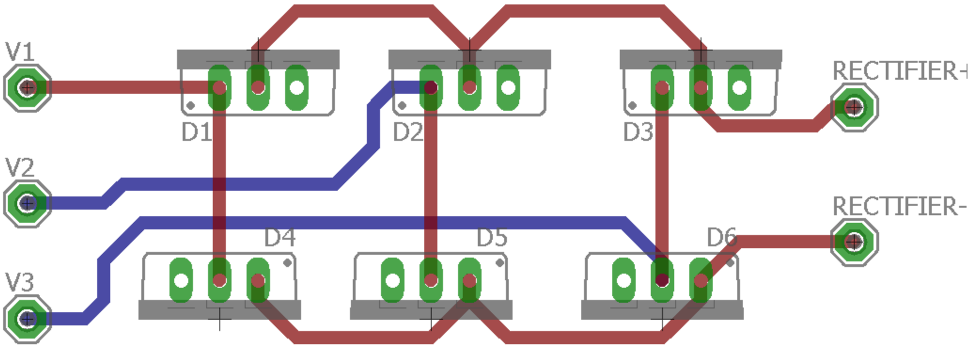


Figure 27 Rectifier PCB Module

The Rectifier module includes 6 Schottky diodes attached through hole and standing in line forming two rows. This was done to facilitate the installment of heat sinks on them to increase the heat dispassion. This module includes the three-phase connection to the alternator and a single-phase connection to the filter.

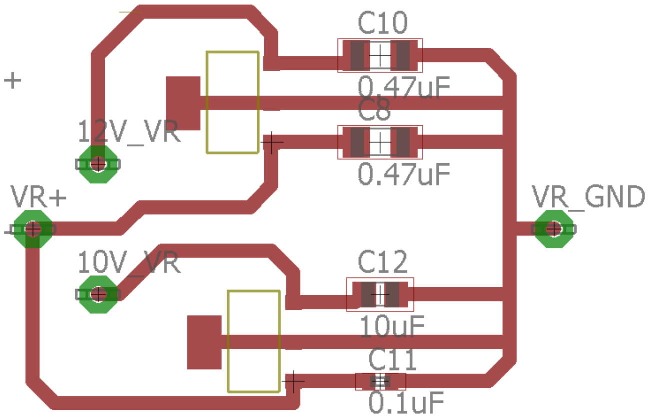


Figure 28 Voltage Regulators PCB Module

This module includes two voltage regulators and the ceramic capacitors required for them. Due to the small size of all the components, the traces were designed to maintain enough distance between them and the components to avoid mistakes and errors during the soldering task. Again, this module includes a common ground connection, a common voltage input coming from the converter, and the outputs of each voltage regulator totally independent.

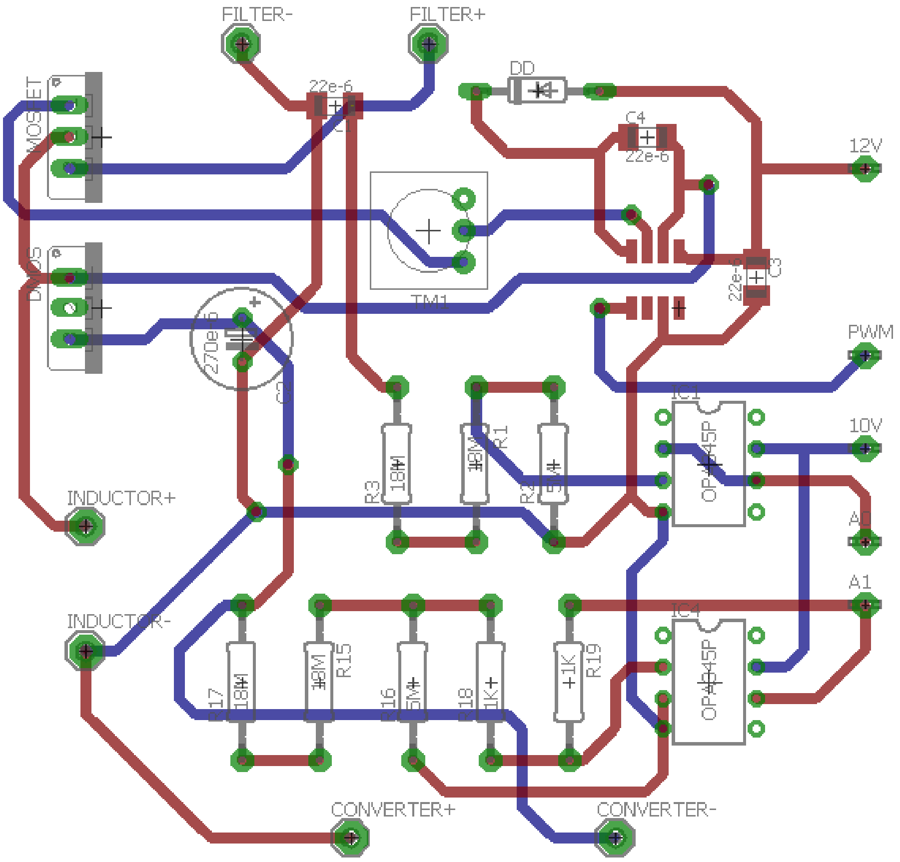


Figure 29 Buck Converter PCB Module

The buck converter module, shown in Figure 29, is one of the most complex ones and includes several submodules.

The first one is the converter itself including all the components that have been calculated and simulated in the previous sections. With exception, as stated before, of the inductor due to its size and weight. The module includes two solder drill on the left size to connect externally the inductor.

The second submodule is the mosfet driver and all the auxiliary elements needed for it. This includes several ceramic capacitors, a small diode, and a potentiometer.

Finally, to be able to perform the required measurements for the control algorithm and for safety protocols, this module includes two measurement circuits. They are composed by an operational amplifier and a voltage divider. The election of the OpAmps and the values for the voltage divider were performed by my teammate as part of the control subsystem.

This module includes as well all the required connections to the filter, battery charge circuit and the microcontroller. All of them trough solder drill to be able to attach and easily solder wires on them.

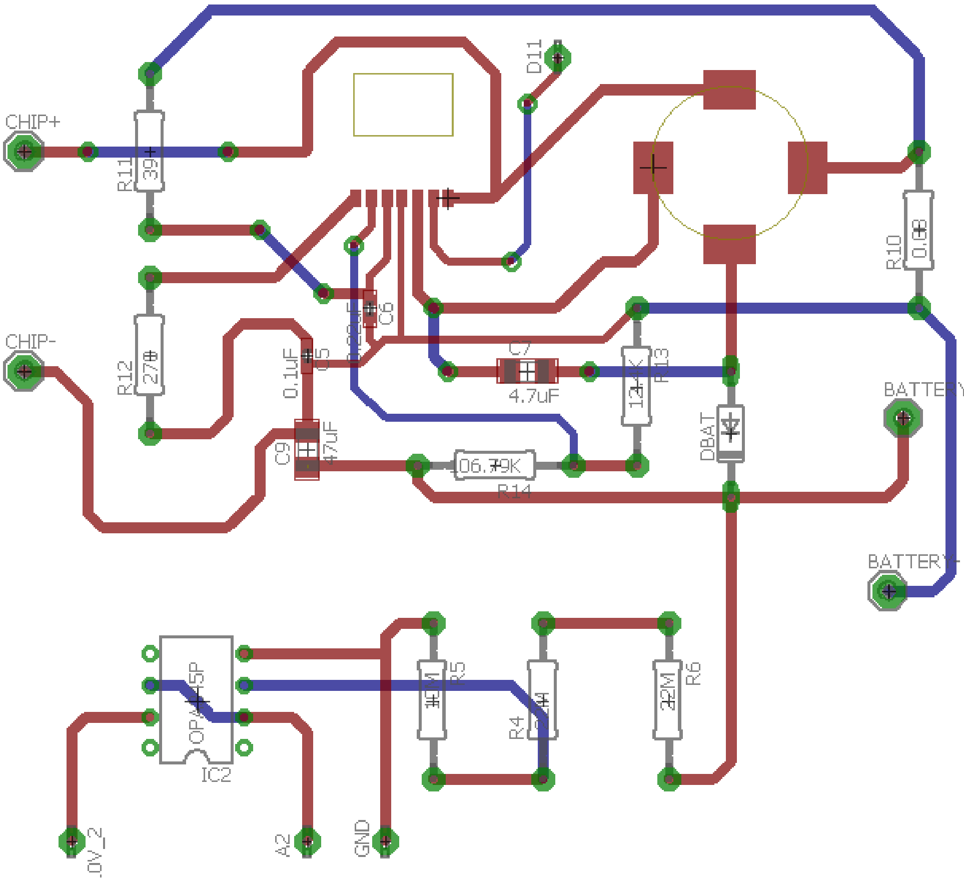


Figure 30 Battery Charge Circuit PCB Module

Figure 30 presents the battery charge circuit module with all the components required. As this circuit is already design, the datasheet of the LT1513 chip includes the value and commercial reference for most of the auxiliary components. This facilitates the design of the circuit and the PCB module.

The LT1513 chip requires several ceramic capacitors, two coupled inductors with common core, one small diode and some resistors with different values. All of them were chosen following the recommendations of the datasheet for our application.

In addition to that, another measurement circuit was included in this module to measure and control the battery voltage and, therefore, the battery charge level at any moment. This measurement circuit includes, as the previous one, one OpAmp and several resistors in a voltage divider.

The design proposed includes, as well all the connections needed to power the module from the converter and to charge the battery. There is also a direct connection between the chip and the microcontroller to be able to shut down the chip if necessary.

To finalize, Figure 31 shows the final PCB layout made for testing the system.

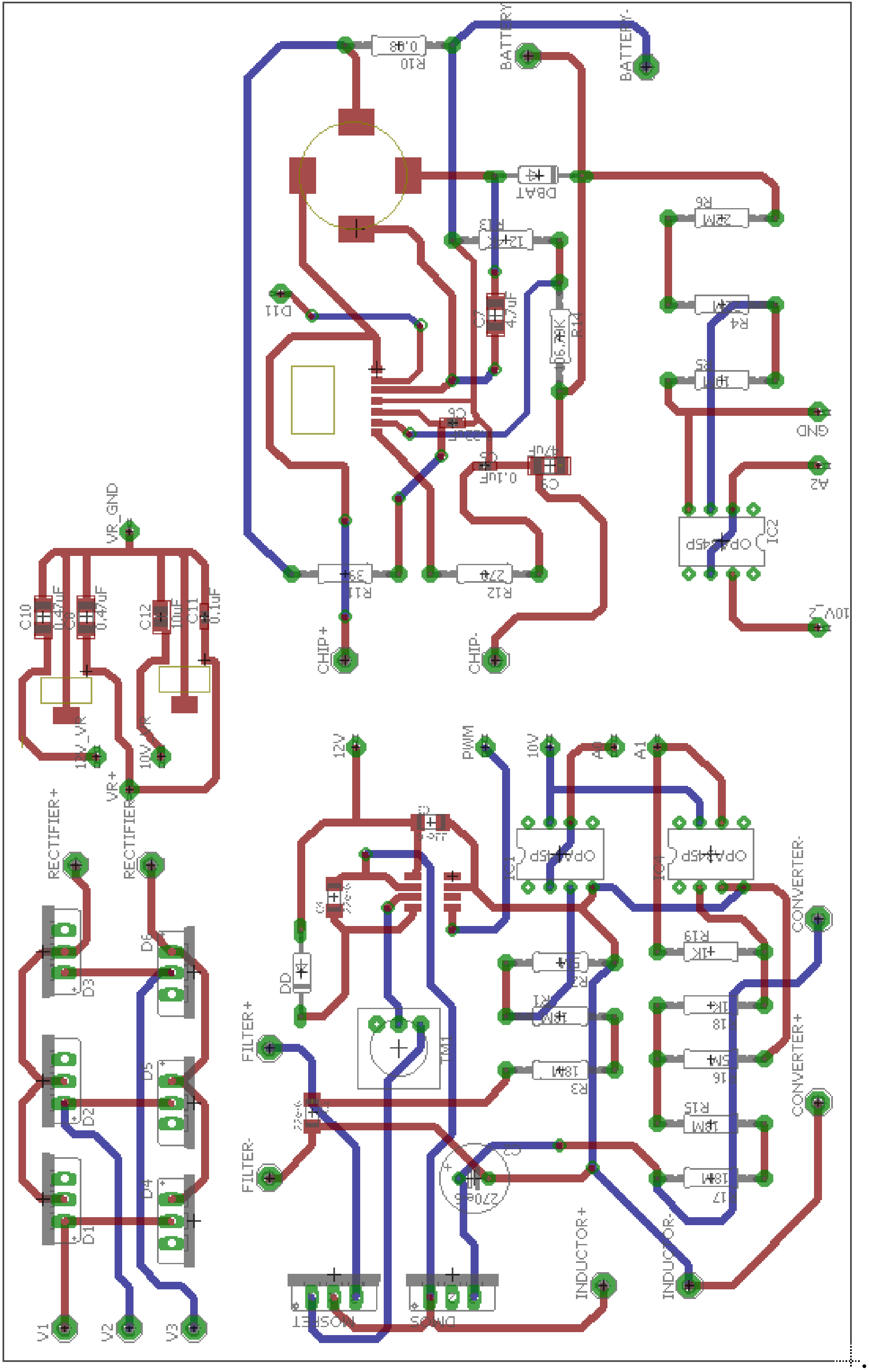


Figure 31 PCB Layout

2.8. Testing Prototype

In this section, the testing prototype used for the demonstration and verification processes is going to be shown and explain.

All the testing and verification process took place in the electric machines lab to be able to use all the power equipment and the three-phase bench.

Figure 32 shows the rectifier built in the PCB. It includes the 6 diodes and the connections between the three-phase bench and the input of the filter.

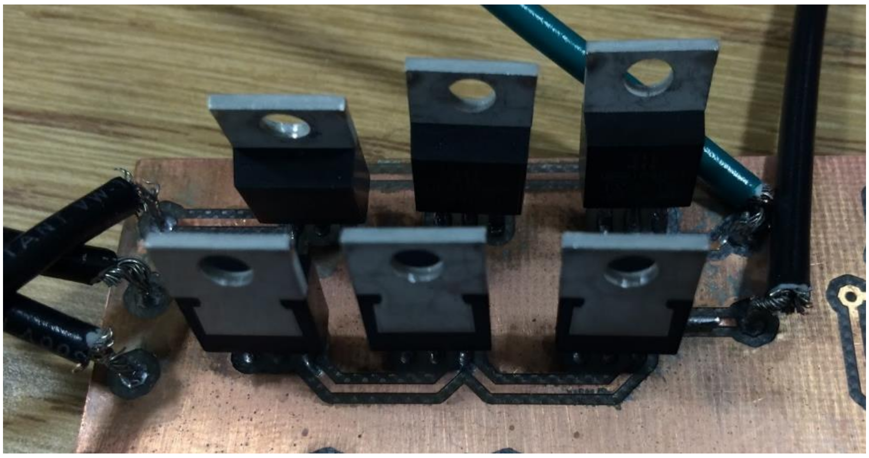


Figure 32 Rectifier

The following Figure shows the low-pass passive filter with all its components. It includes the inductor and the 5 capacitors in parallel to obtain the value of the capacitor required for the filter.

Figure 33 Filter

During the design process, the converter was intended to be a Buck-Boost converter, however, due to a problem with the mosfet driver, the converter was redesign. For that reason it was not possible to weld the components of the converter on the PCB. The buck converter was built on a protoborad for testing and for the demonstration. This representation includes one of the voltage measurement sensors. That was used to perform the iterative control implemented to the converter.

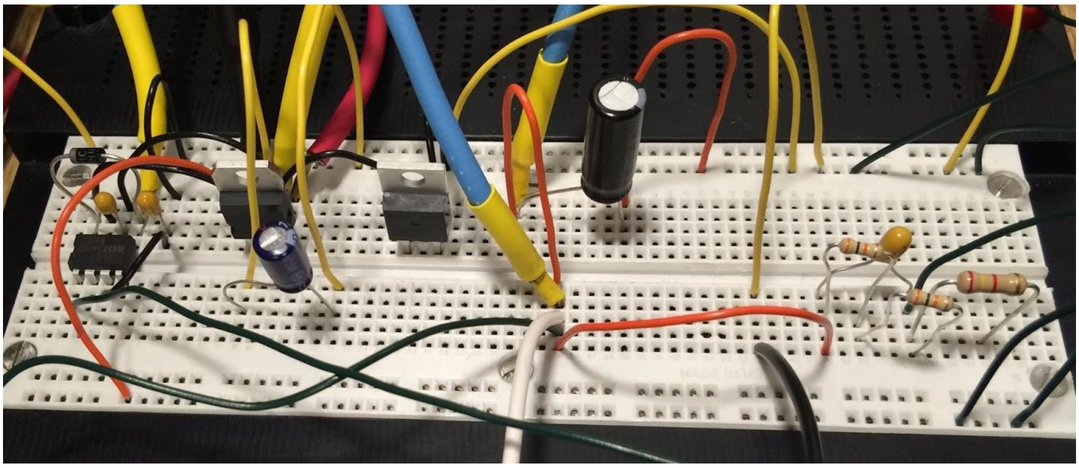


Figure 34 Buck Converter

The final module, the battery charge circuit is shown first, independently in Figure 35 and attached to the battery on Figure 36. This module was fully integrated on the PCB.

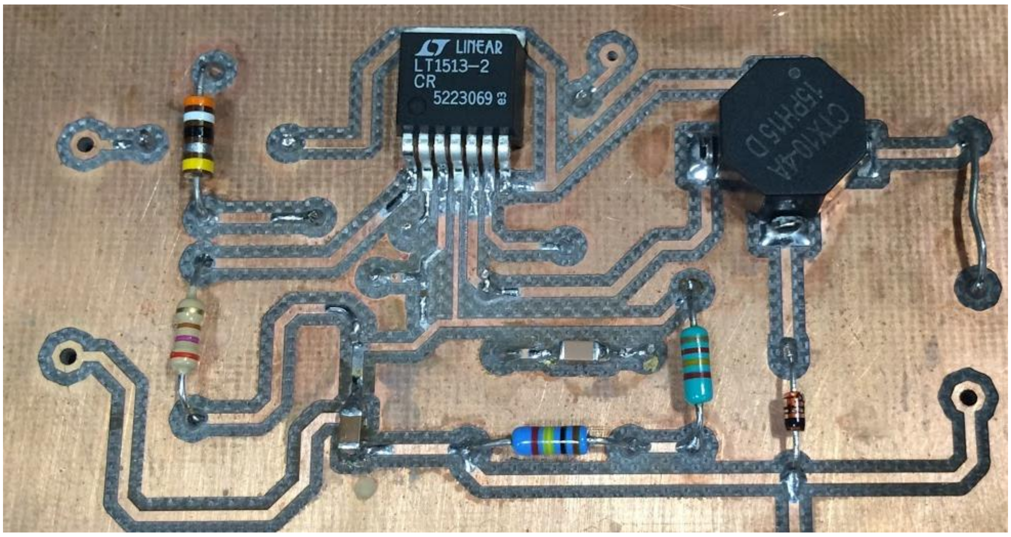


Figure 35 Battery Charge Circuit

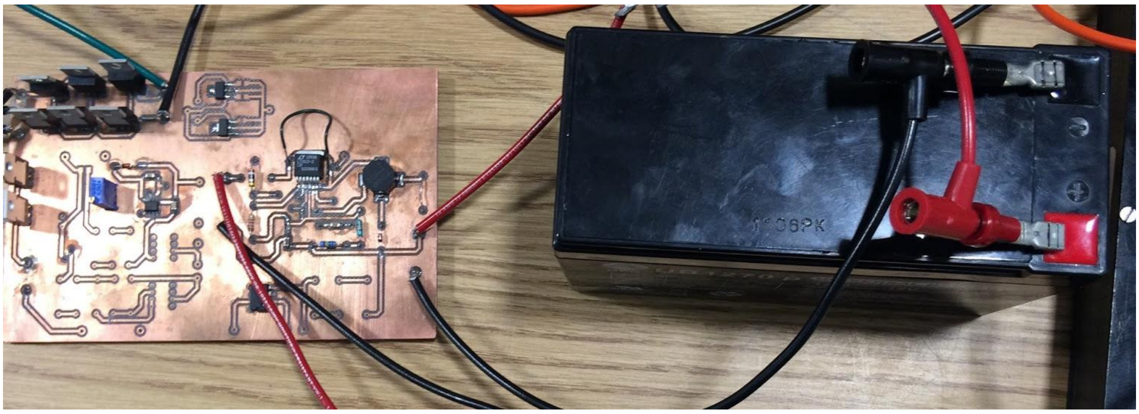


Figure 36 Battery Charge Circuit Attached to the Battery

In addition, Figure 37 presents the rest of the components of the project. This includes both microcontrollers, the transmitter and receiver, the waterproof temperature sensor and the LCD display as user interface. Those modules were built and welded on breadboard due to the time and budget constraints. More information regarding this modules is included and fully explained in the final project of my teammate.

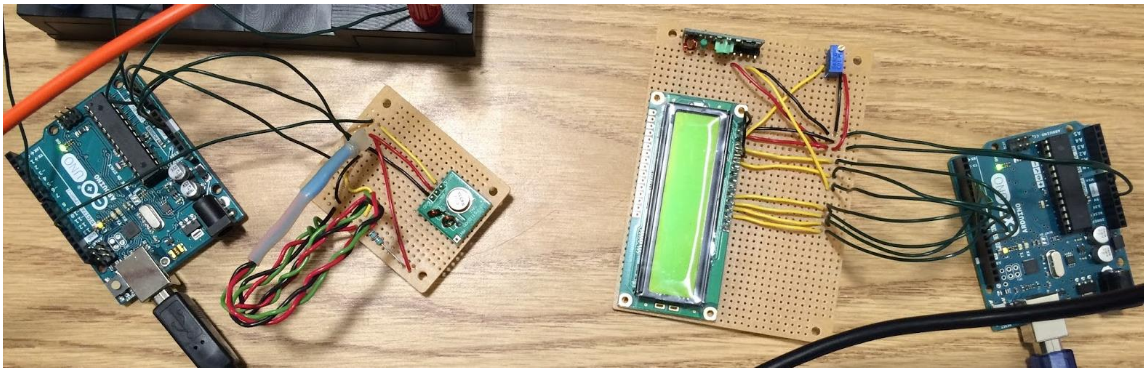


Figure 37 Control, Wireless Transmission and User Interface Modules

To finalize, an overview of the setup built for the demonstration is shown in Figure 38.

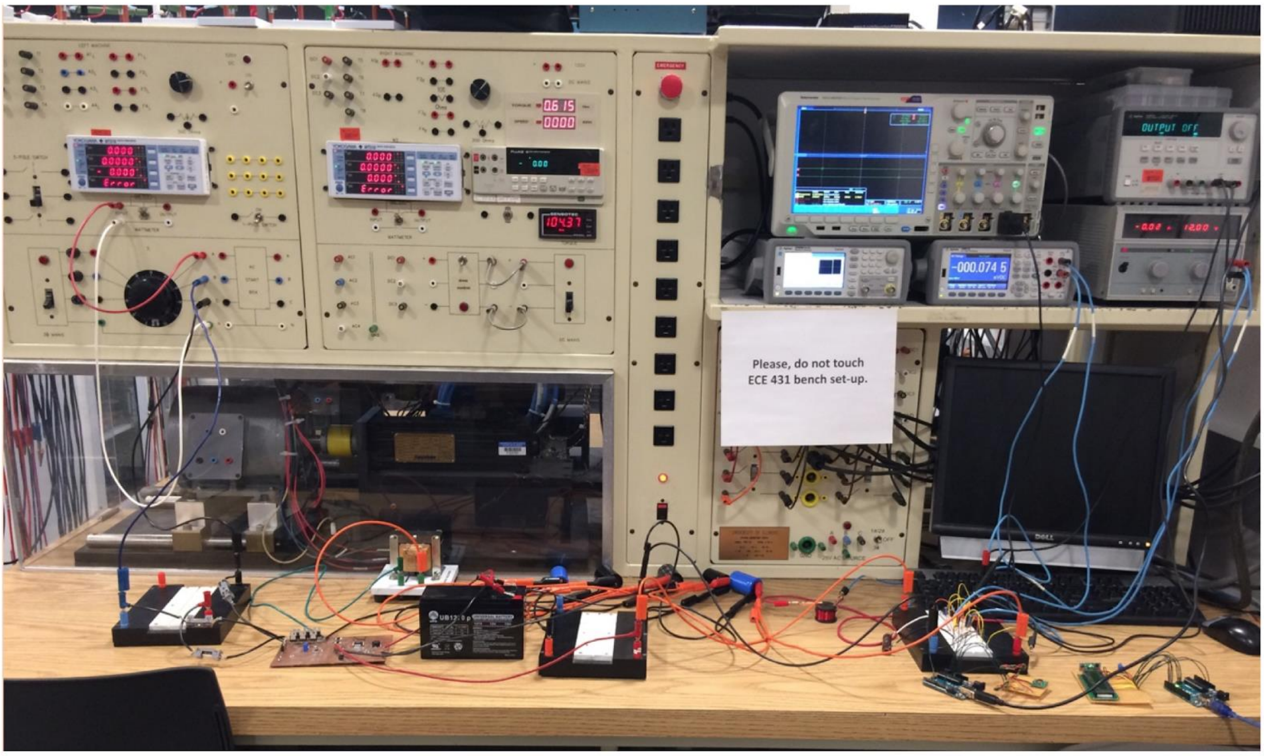


Figure 38 Demonstration Setup

3. VERIFICATIONS AND RESULTS

To verify the correct functioning of each module and the integration between all of them, each module was individually tested by simulating the expected input signal and checking the output. The next step was to add each module to the previous one, starting from the first one.

During the first tests with the PCB, it was discovered that the traces of the PCB could not handle the rated currents. For that reason, all the tests were performed at lower currents and consuming less power as designed.

Overall, all the verifications were made by comparing the voltages obtained and the one stated in the R&V table. As all the components of the power conversion subsystem were designed with voltage objectives, the verification of the system was not prevented by the current and power dissipations limits.

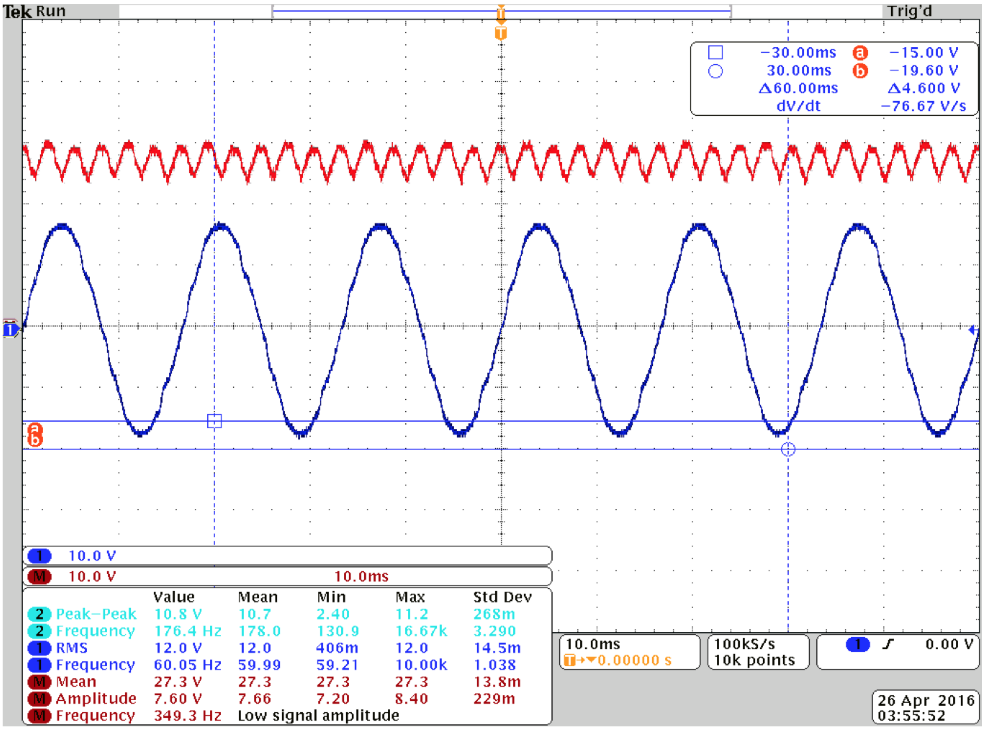
Alternator

The system was powered from a three-phase 60 Hz bench to simulate the rated output of the alternator. The benches available at the electric machines lab included a variac to manually set the output voltage. The output voltage was set at the rated value of our alternator which was 12V.

Rectifier

The rectifier was tested by connecting it to the three-phase bench and attaching a resistive load of 30Ω and 20W to it. The input voltages of the rectifier were set at 12V AC. Figure 39 shows the comparison between the input voltage of one phase of the alternator in blue and the output voltage obtained from the rectifier in red. The output voltage was very similar as the expected and the one obtained in the calculations. The differences are that the mean value is higher than expected and the ripple is more than twice the one obtained in the simulations. Nevertheless, the values are within an acceptable margin and the waveforms are exactly the same as the expected theoretically.

Variable	**Calculation**	**Simulation**	**Measurement**
V_{IN}	12Vrms	12Vrms	12Vrms
V_{OUT}	27.92Vp	25.65Vp	27.3Vmean
$V_{OUTp\text{-}p}$	-	3V	7.6V
f_{OUT}	360Hz	360Hz	349.7Hz



	Value	Mean	Min	Max	Std Dev
2 Peak−Peak	10.8 V	10.7	2.40	11.2	268m
2 Frequency	176.4 Hz	178.0	130.9	16.67k	3.290
1 RMS	12.0 V	12.0	406m	12.0	14.5m
1 Frequency	60.05 Hz	59.99	59.21	10.00k	1.038
M Mean	27.3 V	27.3	27.3	27.3	13.8m
M Amplitude	7.60 V	7.66	7.20	8.40	229m
M Frequency	349.3 Hz	Low signal amplitude			

Figure 39 Input vs. Output Voltage of the Rectifier

The efficiency obtained in this module was:

$$\eta_{Rectifier} = 95.76\%$$

Low-Pass Passive Filter

To test the filter it was attached to the rectifier and, again, the system was powered from the three-phase bench at 12V. The same 30Ω and 20W load was connected to the output of the system.

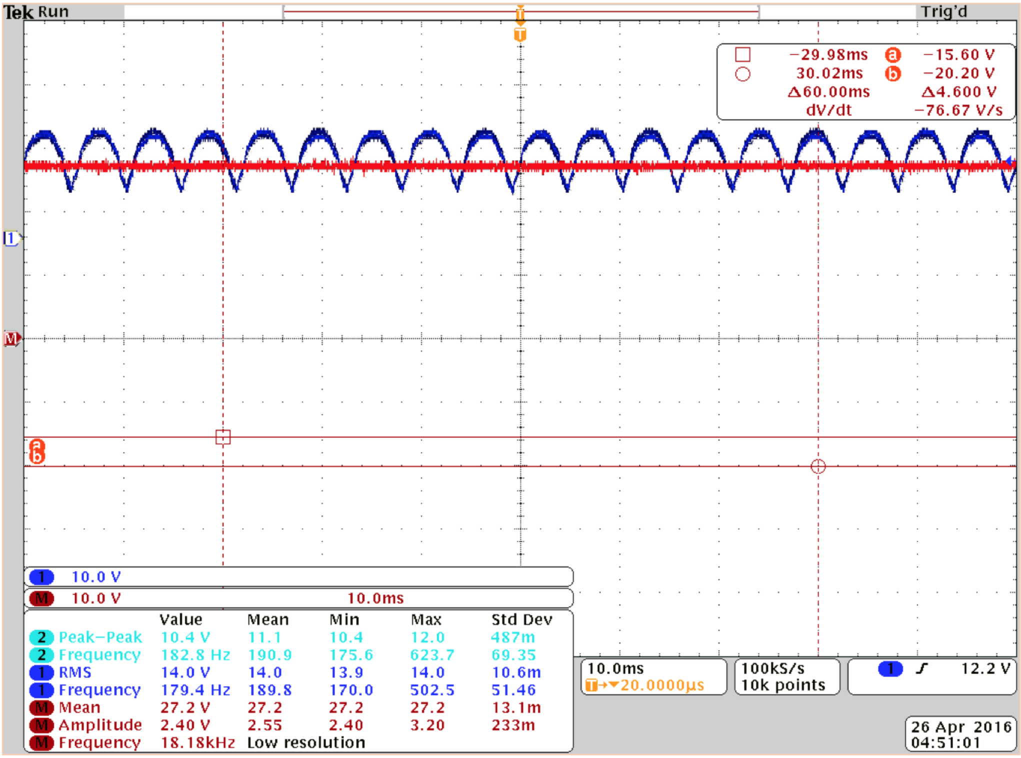
Figure 40 shows the output signal of the rectifier in blue and the output signal of the filter in red.

As the alternator was substituted by a three phase bench for the testing, there was unexpected noise from the grid at the output of the filter. This noise had an amplitude of approximately 2V and a very high frequency. The mean value of the output is slightly higher than the expected, however this value is in consonance with the results obtained in the test of the rectifier.

That high frequency noise affect significantly the DC/DC converter. Hence, a control algorithm is needed to ensure the correct functioning of the converter because, if the input of the converter has a lot of variations, the output will not be constant and the battery charge circuit will have to compensate those variations on its own.

Both modules were able to work together without any problem.

Variable	**Calculation**	**Simulation**	**Measurement**
$V_{INp\text{-}p}$	-	2.15V	7.6V
$V_{OUTp\text{-}p}$	0.1V	0.1V	2.4V
V_{IN}	27.92Vp	25.65Vp	27.3V
V_{OUT}	-	24.4Vp	27.2V
f_{OUT}	360Hz	360Hz	20Khz



	Value	Mean	Min	Max	Std Dev
2 Peak−Peak	10.4 V	11.1	10.4	12.0	487m
2 Frequency	182.8 Hz	190.9	175.6	623.7	69.35
1 RMS	14.0 V	14.0	13.9	14.0	10.6m
1 Frequency	179.4 Hz	189.8	170.0	502.5	51.46
M Mean	27.2 V	27.2	27.2	27.2	13.1m
M Amplitude	2.40 V	2.55	2.40	3.20	233m
M Frequency	18.18kHz	Low resolution			

Figure 40 Input and Output Voltage of the Filter

The efficiency obtained in this module was:

$$\eta_{Filter} = 98.80\%$$

DC/DC Buck Converter

The converter could not be attached to the previous components of the power conversion module. Due to an unexpected ground connection problem between the neutral point of the three-phase bench and the power supplies needed to power components of the converter, such as the mosfet driver, the converter could not be tested powered from the filter.

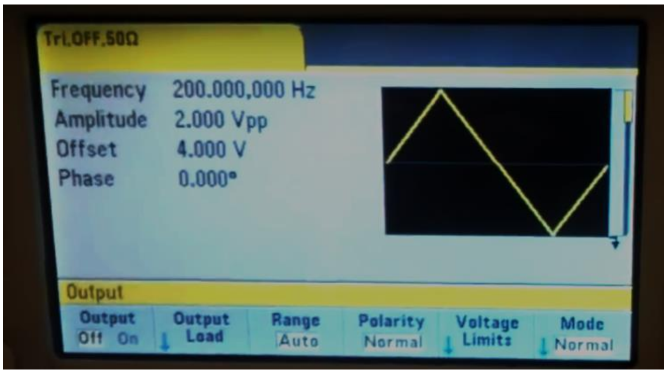
The buck converter was tested by powering it from a DC power supply. For those tests, the input voltage was set at 25V and the required constant 15V at the output were obtained. The load used was a 30Ω and 20W load.

Figure 41 Power Supply Providing 25V

In addition to that, the iterative control was tested to check its robustness. Again, the constant output could be maintained at 15V while the input voltage was manually modified using the DC power supply. The control provided a quick and reliable response for all the variations in the input without overshoot or a damping response.

Figure 42 Output Voltage of the Converter

Finally, the control was tested with an input voltage that simulated the output voltage obtained from the filter. This means that a signal with a voltage ripple of 2V and a frequency of 200Hz was applied to simulate the operation of the buck converter working together with the rest of the previous modules. Figure 43 shows the simulated input and Figure 44 the constant output obtained for a duty cycle of 35%. The expected value was 1.4V


Tri,OFF,50Ω

Frequency 200.000,000 Hz

Amplitude 2.000 Vpp

Offset 4.000 V

Phase 0.000°

Figure 43 Simulated High Frequency Noise for the Converter

Figure 44 Output of the Converter for a High Noise Input

The efficiency obtained in this module was:

$$\eta_{Converter} = 88.12\%$$

Battery Charge Circuit

To test the last component of the power conversion module, the battery charging circuit was connected together with the buck converter. Then a 40Ah 12V sealed lead acid battery was attached to the output of the battery charging circuit.

The buck converter was powered with 25V, maintaining the constant 15V with the control at the input of the battery charging circuit.

Then the charging current provided by the system was measured and tracked to check if the battery was being charged following its charging characteristics. The tests demonstrated that the battery charging circuit works as expected because, for an almost charged battery, the system provided a very small current maintaining the voltage of the battery constant at around its full charge capacity.

Figure 45 shows the measures obtained during the test. The 12.28V measured indicates that the battery was almost charged and the charging current was around 0.15mA which indicates as well the same fact. Therefore, the battery charge chip was providing a very small current to maintain the battery charge level at maximum. This demonstrates that this module works perfectly attached to the buck converter.

Figure 45 Voltage of the Battery and Charging Current

As stated before, all the modules could not be connected together. Nevertheless, the robustness of the control of the buck converter was tested successfully for the input that the filter would provide to the converter if they could work together. For that reason, it could be stated that all the components have the potential to work together when the ground problem is solved.

Finally, as a remainder, Figure 46 shows a block diagram of all the modules designed, developed and tested with the values of voltage and frequency obtained at each stage of the testing and verification process.

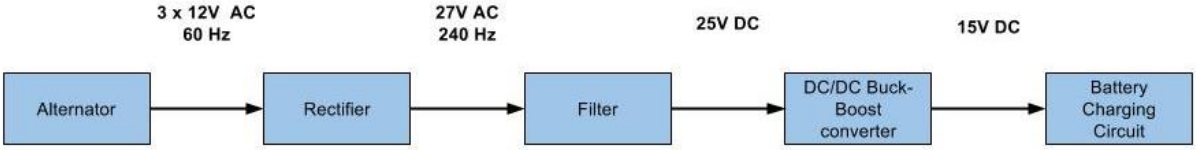


Figure 46 Block Diagram of the Power Conversion Subsystem

In the final paper of my teammate it is possible to find all the information regarding the verification and the results of the rest of modules and subsystems. In that document there are complete analysis and explanations of the control applied in the system, the wireless transmission module, all the codes implemented in the microcontrollers and schematics with all the connections between those modules and the power conversion subsystem.

4. ECONOMIC ANAYLISIS

In the following tables and figures it is possible to find the complete disclose of the cost of the project at this stage. This analysis includes the labor cost of the people involved in this project, the cost of all the components and the material used on the system and a complete economic analysis of the viability of the project as an investment to reduce the energy cost of a hydraulic system.

4.1. Labor Cost

Table 1 presents the labor cost of the project including all the member of the team that have been involved in the development and testing process along the curse.

Name	Hourly Rate	Total Hours Invested	Total Labor*
Ana Carrasco y Fonseca	$35.00	180	$15,750
Adrian Portillo Quesada	$35.00	180	$15,750
Total		360	$31,500

Table 1 Labor Cost

*The total labor is multiplied by a factor of 2.5 to emulate the real total cost to an engineering company hiring somebody for this project.

4.2. Parts Cost

Table 3 presents the total cost of the system that has been built and tested. All the prices that appear in that table are unitary prices per component. The total cost of the project at the current state of development is $293.45.

4.3. Grand Cost

Section	Total
Labor	$31,500
Parts	$293.45
Grand Total	**$31,793.45**

Table 2 Grand Cost

Item	**Part Number**	**Unit Cost**	**Quantity**	**Cost**
Battery	EXP12200	$40.00	1	$40.00
Diodes	SB80W10T	$0.298	6	$1.86
Diode for the converter	MBR1045MFS	$0.43	1	$0.43
Inductor	DFKF-28-0006	$11.73	1	$11.73
Filter inductor	DFKH-31-0008	$34.26	1	$34.26
Filter capacitor	CGS503U030V5L	$7.19	5	$35.95
Voltage regulator	LM2937-12/NOPB	$2.54	1	$2.54
Voltage regulator	LM2937-10/NOPB	$2.12	1	$2.12
Input capacitor converter	GMK316F106ZL-T	$0.28	1	$0.28
Output capacitor converter	KCM55WR7YA336MH01K	$4.03	1	$4.03
Fuse	LITTELFUSE 0239007.MXP	$0.99	6	$5.94
Operational amplifier	LM358	$0.95	3	$2.85
Waterproof temperature sensor	LM335	$9.95	1	$9.95
LCD display	WH1602 16x2 Character LCD Display	$13.95	1	$13.95
Arduino UNO	Arduino Uno-R3	$31.90	2	$63.80
433 MHz Transmitter & Receiver	RB-Ite-108	$3.08	1	$3.08
PCB	ECE Electronics Services	$30.00	1	$30.00
Power bank	Xiaomi 1500mah	$5.99	1	$5.99
Mosfet Driver	IRS2183	$3.59	1	$3.59
Mosfet	STP160N3LL	$0.95	1	$0.95
Battery Charging Chip	LT1513	$9.95	1	$9.95
Inductor Battery Chip	CTX10-4A-R	$9.95	1	$9.95
Diode Battery Chip	1N4148	$0.25	1	$0.25
Total				$293.45

Table 3 Part Cost

4.4. Cost Analysis

Firstly, it is important to analyze the labor cost. As this project was developed and evaluated in the United States the standard formula for the calculation of that cost. The price of $35.00/hour was stablished as the average entry electrical engineer salary in that country. Moreover, the total labor cost had to be multiplied by a factor of around 2.5 to simulate the real cost of hiring and engineer for a company. This factor takes into account other expenses such as maintenance cost, hiring costs, taxes and, if necessary, a health insurance. Therefore, in case this project is developed in other country the labor cost could be reduce. Firstly because in many other countries the salaries are lower and, secondly, because the hiring costs and taxes are lower.

Secondly, as the first build of the project is just a prototype for testing, the cost of the components and materials is high. Once obtained a final and completely functional prototype for testing it would be possible to start manufacturing the project in mass scale.

The unitary cost of electrical components drops significantly when purchasing them in big numbers. It would be possible to order directly the components and material from the manufacturer instead of buying them from a commercial or distributor.

The manufacture of the PCB can be outsourced to an external and more specialized company. For this project, the PCB was provided with no additional cost by the ECE shop of the university. The quality of the board was good but, for a final product, it was not enough. For that reason and to reduce the unitary cost of the board it would be strongly recommended to produce the final PCB in large numbers from an external company.

It is worth to mention that, for the testing build of the project, the inductor and capacitors for the filter were provided by the university and handled back after the demonstration. The price for the equivalent inductor and capacitor have been included in the parts cost table. Instead of buying an inductor from an external supplier, it is possible to build one from the ground. There are several companies that manufacture cores for inductors and transformers. The price of these cores lower than buying the inductor as a whole. Hence, it is possible to reduce the cost of all the inductors by buying the core and then designing the windings for the inductor. This will reduce the price of the project. Nevertheless, there is not a similar solution for the capacitors.

Overall, there are several different possible strategies to reduce the cost of the electrical part of the project to make more economical and ultimately more attractive and successful.

5. CONCLUSIONS

5.1. Accomplishments

In summary, all the modules fulfill the requirements and verifications that were established for them during the design process and most of them worked together providing the expected outputs. The first part of the power conversion module was able to provide the expected 25V DC at the output of the filter while the second part of that module effectively and safely charged the chosen battery. Even though both parts of the power conversion module could not be tested together, the control of the buck converter demonstrated that it could handle the output of the other half of the module. This means that the designed system can work as a whole achieving full integration.

At the same time, the wireless communication module was able to transmit the required measurements and variables to the remote display. The microcontroller was able to perform all the measurements, calculate the variables needed and apply the control of the buck converter simultaneously and without introducing errors or delays into the system.

In addition to that, as this was a power project and suitable to handle high powers and high currents, several passive and active safety measures were included to ensure the reliability and safety of the system.

Overall, most of the requirements and initial expectations were achieved.

Not only a functional and reliable design has been made and improved over different processes, but also the design has been physically built, tested and verified.

If future work enables full integration between the remaining modules, the project will be totally finished and the designed electrical system will be ready for the following design steps of the final project.

5.2. Future Work

Possible plans for the future to continue or improve this part of the project can be:

- Solve the ground problem that produces short-circuit between the output of the filter and the input of the converter. If this is solve the power conversion system would work all together.
- Improve the PCB layout and its current rating. The PCB design chosen was a modular design to be able to test independently all the modules. Moreover, the current rating of the designed PCB was not enough to handle the maximum required currents.
- Design and include in the project a multilevel inverter to be able to connect the system to the grid. This will improve the quality and usefulness of the project.

Additionally, more possible objectives and plans to test the viability of the project can be:

- Improve the control of the buck converter. The idea is to implement a PI control to reduce the time response and increase the quality and reliability of the system. It is worth to mention that my teammate worked very hard on this part of the project and she was able to include this part on her final paper.
- Install the components inside the final turbine and generator casing. To continue this project, the electrical system has to be placed inside the waterproof generator casing and it has to be connected to the turbine.
- Test the system with the alternator and the turbine working together. This is the next step that should be addressed to continue the project in the future.
- Test the viability of the project under real conditions. This will include building a final prototype integrating the electrical system described in this paper, the alternator, the turbine and the waterproof casing. Then, it would be necessary to test the prototype inside a hydraulic circuit to analyze the viability, efficiency and utility of the project.

Hopefully this project can be continued by other students or by any of us at a later time.

5.3. Ethics

The purpose of this project is the development of an energy recovery system for pipelines and water distribution systems. As this has been a group project, the responsibility of it is assumed and shared among all the members of the group.

We assure that this project is capable of achieve all the objectives listed in the benefits and features. It will have to comply with the IEEE Code of Ethics. Of the ten that IEEE has listed, the ones that apply to this project are listed below:

- To accept responsibility in making decisions consistent with the safety, health, and welfare of the users, and to disclose promptly factors that might endanger the public or the environment.
- To be honest and realistic in stating claims or estimates based on available data.
- To improve the understanding of technology; its appropriate application, and potential consequences.
- To seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others.

Applied to this project, we have to be responsible and conscious of all the safety concerns and possible hazards that this project can provoke and, doubtlessly, address and solve them along all the design, development and testing stages.

During the design stage we have to be honest with all the statements that we have made and their possible implications when presenting our project. All those statements have to be based on real and trustworthy data or studies. We have to ensure that the bases of our project are solid and reliable.

Moreover, once our project is finished, we have to state clearly the functioning of our system for future students or users.

Finally, we will have to accept and learn from the critics and analysis that our project is going to receive. And credit all the people involved in the design of our project one we will show it in future presentations or in future courses.

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A. REQUIREMENT AND VERIFICATION TABLE

Module	Requirement	Verification	Points
Rectifier	The diodes have to handle a maximum current of 5 +/- 0.2A. The maximum value of the output voltage is 28 +/- 0.5V.	1. Connect the rectifier to the power supply. 2. Measure the maximum input voltage provided by the power supply under the rated conditions with a voltmeter. 3. Measure the output voltage of the rectifier and its ripple with an oscilloscope. 4. Measure the current across all the diodes with a multimeter to confirm that the maximum current is not overpassed.	5
Filter	Corner frequency 10Hz. The voltage ripple has to be less than 0.1V at the rated speed of the alternator 600 rpm (60 Hz). The power losses on the filter have to be less than 3W.	1. Power the filter with a signal generator and produce a sinusoidal signal with a frequency of 60 Hz. 2. Measure with an oscilloscope the output voltage of the filter and calculate the attenuation. 1. Connect the filter to the rectifier 2. Power the system with the workbench at 12V. 3. Attach a resistive load of 1.44 Ohm at the output of the filter. 4. Measure the voltage ripple of the output voltage of the filter with an oscilloscope. 5. Measure the current across the load and its ripple with a multimeter and an oscilloscope. 6. Measure the current and voltage across the resistive elements of the filter and calculate the power losses under rated conditions.	5

DC/DC Buck-Boost Converter	Maximum voltage ripple: 0.5V. Convert input voltage of 25 +/- 2V into a constant 15 +/-1V output voltage.	1. Attach a resistive load of 2.25 Ohm 100W to the output of the converter. 2. Connect the converter to the power supply settle at the rated working conditions. 3. Measure the output voltage and output voltage ripple with a multimeter and an oscilloscope. 4. Measure the maximum output current under rated conditions and we will compare the input power and the output power to calculate the efficiency and the power losses of the converter. 1. Connect the converter to the a DC power supply in the lab and power it with different input voltages. 2. Measure the output voltage of the converter and its response to the input voltage variations with an oscilloscope.	10
Battery Charging Circuit	Charged at a continuous voltage of 15V +/-1V. For a rated current of 1.25 +/- 0.2A A the battery charges in 8 hours.	1. Connect the battery to the system and power the system at the rated conditions. 2. Power the system with 15V DC. 3. Measure the voltage of the battery during the charging process with a multimeter. 4. Measure the charging current and compare it with the theoretical current for the system from the datasheet which is 1.25A. 1. Connect a resistive load of 40W to the battery. 2. Measure the discharging ratio when the battery is fully charged and disconnected from the system to check energy capacity.	10
Temperature Sensor	Measure temperatures between 10 and 60 º, with +/- 1 ºC accuracy.	1. Connect one terminal of the sensor to ground and the other one to a 4.7 K resistor. 2. Connect the other terminal of the resistor to 5V from the Arduino. 3. Connect the point between the sensor and the resistor to an analog port from the Arduino. 4. Run code to obtain the temperature measurement. 5. Verify the displayed temperature corresponds with the expected one by comparing it with the measure of a thermometer.	2.5

Main Microcontroller (Arduino Due)	Read 4 voltages: Output of the temperature sensor, the voltages from the converter and the voltage of the battery. Run the control algorithm	1. Connect each voltage sensor to the following pins: -Temperature sensor pin A0 -Input Voltage Converter pin A1 -Output Voltage Converter A2 -Battery Voltage A3 2. Display in the Serial.display of the Arduino all the voltages and compare them with the real measurements of each of them using a multimeter. 1. To test the control algorithm we will connect the input and output voltage of the converter to analog pins from the Arduino, as described in 1. 2. We will connect one of the PWM pins from the Arduino to a mosfet driver, that will be connected to the gate of the mosfet of the converter. 3. We will then run the control's algorithm, and verify that the output voltage of the converter is 15 +/-1 V.	10
Transmitter and Receiver	Transmit the data between two Arduinos to display it in the LCD display. Receive data within a range of 1 m.	1. To verify the correct transmission between the transmitter and the receiver we will do a simple experiment. We will connect the transmitter pins in the following way: data will go to a digital pin of Arduino Due, vcc to 5V and GND to our ground terminal. The receiver pins will be connected in a similar way: the vcc will be connected to 5V or 3V(noise seems to be reduced when connecting it to 3V), the data pin to an analog input of the Arduino Pro Mini and GND to the ground terminal. 2. Implement the transmitter's and the receiver's code, so that when the transmitter is sending information the LED in the Arduino Due is on, and when it is not, it is off. We will transmit a high or low signal from the transmitter to the receiver. 3. The receiver will be listening to the analog pin, and whenever it receives a high signal it will turn the Arduino Uno's LED on. 4. There might be a slight delay, but both LEDs should turn on and off at the same time.	5

LCD Display	Display the data received from the Arduino Uno.	1. We will make the following connections: -LCD RS pin to digital pin 12 -LCD Enable pin to digital pin 11 -LCD D4 pin to digital pin 5 -LCD D5 pin to digital pin 4 -LCD D6 pin to digital pin 3 -LCD D7 pin to digital pin 2 2. Wire a 10k potentiometer to +5V and GND, with it is wiper (output) to LCD screens VO pin (pin3). A 220 ohm resistor is used to power the backlight of the display, usually on pin 15 and 16 of the LCD connector. 3. We will now use Arduino's LiquidCrystal Library to test the transmission and we will write a code to display "hello world" on the screen, using the function lcd.print("hello, world!").	2.5