Redesign of the output of a backup power supply for meteorological towers in wind farms

Escuela Técnica Superior de Ingeniería (ICAI)

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Julio 201

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Redesign of the output of a backup power supply for meteorological towers in wind farms

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Executive summary

MET Towers are essential in wind farms as they are used to assess wind resource by gathering data from temperature and pressure sensors as well as anemometers and wind speed vanes. MET towers require a reliable power supply and an independent backup system in order to reliably gather wind data.

The current design for the power supply at the Silver Star wind farm implements 2-12V batteries in series as the primary source of power with a battery charger keeping the batteries charged up. This system is flawed as it does not really provide a backup system and the failure of one of the batteries renders the MET tower useless.

The MET tower requires three different outputs from the power supply used for the networking (24 Vdc), the datalogger (12 Vdc) and the sensors (5Vdc).

The scope of the whole project is to redesign a backup system that provides energy for the MET tower for at least 48 hours. This project is going to be focused in the redesign of the output subsystem divided in two parts: the automatic transfer switch that will select the energy source; and the converter system that will convert the input voltage provided by the source to the three different outputs needed.

Automatic Transfer Switch

Three different sources are used to feed the MET tower: the main source that provides energy from the closest aerogenerator to the met tower, a solar source that provides energy from a panel with a small battery connected and the battery bank that provides energy stored previously when the main source was on.

When the main source no longer provide energy, the ATS needs to change to the solar source as fast as possible to assure that any data is lost during the transition. If the energy stored in the solar battery (that is small) or the radiation energy is not enough to power the whole system, then the ATS needs to change to the second redundancy that is the battery bank that has been previously charged with the main source.

In case that the main source comes back, the switch needs to go turn on the main source and turn off the other. Only one source can be powering the MET tower at the same time.

The system selected to implement this is with diodes. Three different voltages are selected for each input depending on the priority of them (25 V for the main source and 24 V for each battery bank). To assure that the solar gets in before the battery bank, in the battery bank input two diodes are connected in series so the drop of voltage of them is 1.4 V instead of the 0.7V that happen in the other cases.

The output voltage is the input voltage minus the drop of voltage across the diode (0.7V approximately). To provide an accurate output voltage converters and regulators are needed.

The design implemented and built in the university, due the budget limitation, changes from two batteries that provides 24 V to one battery that provides 12 V. The design made can be used for both systems.

First, the system is simulated in Simulink, analyzing the correct behavior. Later, it is built in a protoboard and test its performance with real components. Lately, a PCB is design and made with LEDs that indicate the state of the input and a fuse used to protect the switch in case of high currents.

Converter System

According to the requirements provided by BP the output voltages needed are 24 V for the network, 12 V for the datalogger and 5V for the different sensors in the tower. The output voltage provided by the ATS is always around 24 V but is not accurate so a system that regulates this voltage and then decrease it is needed.

To decrease the voltage the method selected is by using buck converters. Buck converters step down voltage in an efficient way by using the energy stored in an inductor and switching every period of time. Depending on how long the switch is on and off (the duty cycle) the output voltage will change.

The standard configuration of the buck converter includes one switch (commonly used a MOSFET controlled by a PMW signal) and a diode. After simulations it is shown that when substituting the diode by another MOSFET the efficiency of the buck converter increases as the losses on the diode nearly disappear. The main problem of using this configuration is the increase of risk of using to MOSFET. If dead time is not selected properly, both can be on and causing a short-circuit and the circuit to break.

Once the configuration of each buck converter is selected, then the way of connecting them is chosen. When connecting both buck converters in parallel (decreasing from 24 to 12 and 24 to 5) the losses are higher in the second buck converter that if both converters where connected in cascade (from 24 to 12 and 12 to 5). By simulations in Simulink it is shown that even that the risk of connecting both of them in cascade is higher, because if one breaks both break, the efficiency is higher so is profitable.

To select the values for the buck converter an optimization of the system is made. The objective of this problem is to reduce the losses of the system, so they are studied for the configuration selected previously (two synchronous buck converters connected in cascade). Main losses happen in the inductor and in the switch, so the lost power equation is obtained and by using optimization methods for a non-linear inequality constrains problem. Finally, the values tend to go the boundary so other factors such cost and space are used for selecting the values of the components.

Finally, a schematic and PCB design is made ready for implementation. There are two different parts: the power part where a regulator stabilizes the input voltage coming from the ATS to provide a constant voltage of 24 V for the networking, and the two synchronous buck converters connected in cascade that provide the 12 and 5 output voltage.

In the other hand, the signal part is controlled by the TM4C123 Launchpad that creates a PMW signal for each buck converter and, with the help of a MOSFET driver, two different complementary signals with a deadtime comes from it, controlling the MOSFETs. The output signals are used as inputs in the TM4C123 so a PID controller can be implemented.

Due to budget limitation, the design built as a prototype in the university changes from the original for BP. The ATS remains the same but the output voltage provided by it is 12 Vdc so one regulator is bought to maintain it constant, a boost converter is used to step up the voltage to 24 vdc and a buck converter is used to decrease to 5V.

Resumen

Las torres meteorológicas son esenciales en los parques eólicos ya que se utilizan para la recolección de datos como temperatura, presión o dirección y velocidad del viento. Estos datos son de gran importancia para el correcto funcionamiento del parque y que la energía producida sea la máxima posible. Es por ello por lo que un sistema secundario que asegure la alimentación de la torre en caso de fallo del primario es necesario.

El diseño actual en "*Silver Star Wind Farm*" al sur de Dallas cuenta con dos baterías de 12 V conectadas en serie con la alimentación primaria por lo que se mantienen cargadas todo el tiempo. El Sistema actual se encuentra con el fallo de que no se trata de un sistema secundario, ya que un fallo en la batería provocaría la suspensión del sistema. Es necesario que el sistema de tres voltajes diferentes a la salida: 24 V para la conexión de red, 12 V para el datalogger y 5 V para los diferentes sensores.

El principal objetivo del proyecto en general es el rediseño de este sistema secundario para que la torre meteorológica esté alimentada por 48 horas al menos. Este proyecto se focaliza en el rediseño del sistema de salidas divido en dos partes: el interruptor de cambio automático que cambiará automáticamente entre las diferentes fuentes dependiendo de si pueden proveer suficiente energía y los convertidores que transformaran el voltaje de entrada acorde a las especificaciones de BP.

Interruptor de cambio automático

Se utilizan tres diferentes fuentes para alimentar la torre: la principal fuente de alimentación es el aerogenerador mas cercano que suministrará energía durante todo el tiempo. En caso de fallo la segunda Fuente seleccionada con prioridad es la solar, compuesta por un panel y una pequeña batería que actúa para almacenamiento y regulador de voltaje. Por último, en caso de fallo de este sistema porque le radiación solar no sea suficiente o se haya descargado la batería, entrará la batería principal que permanecerá encendida hasta su total descarga o hasta que se recupere alguna otra fuente de alimentación (solar o principal).

El sistema implementado esta compuesto por diodos. Cada entrada tendrá un voltaje diferente (25 V para la principal y 24 V para las baterías). Debido a las características de este elemento, solo el voltaje superior (si están conectados en paralelo) será el que cambie el estado del diodo. Para diferenciar entre la solar y la batería, en esta segunda se conectan dos diodos en serie para que la caída de voltaje en los diodos sea de 1,4V en vez de 0,7 como el resto.

El voltaje de salida del sistema será correspondiente al voltaje de entrada menos la caída de voltaje en el diodo, por lo que será 24.3V para la principal, 23.3V para la solar y 22.6V para la batería (dos diodos conectados en serie).

Debido a la limitación del presupuesto, el prototipo diseñado en la universidad difiere del sistema real, ya que solo hay una batería que produce 12 V. En este case hay que variar los voltajes de entrada del interruptor, pero el diseño de este no varía.

Finalmente, el diseño se simula con la ayuda de Simulink para comprobar su correcto funcionamiento. Mas tarde, el Sistema es testeado en el laboratorio y posteriormente se diseña una PCB en la que se incluyen diodos LED que indican el estado de las diferentes entradas y un fusible como método de protección contra altas corrientes.

Convertidores

De acuerdo con las especificaciones dadas por BP se necesitan tres voltajes diferentes: 24 V para la conexión de red, 12 V para el dataloger y 5 V para los diferentes sensores. El voltaje provisto por el interruptor se encontrará en torno a los 24 V pero un sistema que lo ajuste será necesario así como uno que decrezca el voltaje de la manera más eficiente posible.

El método elegido para disminuir el voltaje es mediante el uso de convertidores de reducción o buck. Estos convertidores decrecen el voltaje de manera eficiente utilizando la energía almacenada en la bovina. Dependiendo del tiempo que permanezca abierto o cerrado el interruptor (denominado ciclo de trabajo) el voltaje de salida cambiará.

La configuración más estándar de este convertidor cuenta con un condensador y una bovina como elementos para guardar la energía y un interruptor (comúnmente un MOSFET controlado por una señal PMW) y un diodo para cambiar el estado del circuito cuando está abierto y cerrado. Tras las simulaciones queda demostrado que al sustituir el diodo por otro MOSFET la eficiencia del sistema aumenta. Pero con ello también aumenta el riesgo de fallo ya que en caso se que ambos se encuentren cerrados (ON) se produce un cortocircuito, por lo tanto, la implementación de un deadtime en este tipo de configuración va a ser necesaria.

Después de elegirse como estará compuesto cada convertidor buck, es elegido la forma de conectarse entre ellos. Cuando se conectan en paralelo (disminución de 24 a 12 y de 24 a 5) en el segundo caso las perdidas son mayores que si ambos estuvieran conectados en cascada (de 24 a 12 y de 12 a 5). Mediante simulaciones en simulink se demuestra que, pese a que el riego de conexión en cascada sea mayor, resulta mas eficiente este tipo de conexión.

Para seleccionar los valores del sistema se ha utilizado un proceso de optimización. El objetivo es reducir las pérdidas del este tipo de configuración (dos convertidores síncronos buck conectados en cascada) al mínimo. Tras ser analizadas y obtenidas las ecuaciones se resuelva el problema utilizando métodos de optimizaciones para este tipo de problemas. Se concluye que los valores tienden a acercarse a los limites puesto que la frecuencia y el valor de la bovinas al aumentar al infinito las pérdidas se reducen a cero. Por lo tanto, otros métodos para elegir las variables como coste y espacio entran en juego.

Finalmente se diseña el circuito final. Se pueden distinguir dos partes: la parte de potencia y la de señal. Por esta primera circula la corriente que será transmitida a la torre meteorológica y está compuesta por los MOSFET, bovinas y condensadores de gran tamaño. La entrada será la salida del interruptor automático y las salidas serán los 24 V tras pasar por un regulador, y 12 y 5 V tras ser el voltaje disminuido.

Por otro lado, está la parte de señal. Mediante el Launchpad TM4C123 de Texas Instrument se van a crear dos señales PMW (una para cada convertidor).

Estas señales irán a un driver que encargará de crear la complementaria con su correspondiente deadtime y ampliar la amplitud de la señal para que la entrada g del transistor la puede leer. Por lo último los voltajes de salida (12y 5 V) será entradas en el controlador para implementar un PID que controle el ciclo de trabajo.

Debido al límite de presupuesto, los voltajes cambian en el prototipo hecho para la universidad respecto al modelo diseñado para BP. El voltaje se encuentra alrededor de 12 V por lo que será necesario un regulador para mantenerlo constante, un convertidor buck para decrecerlo a 5 V y un convertidos boost para incrementar el voltaje hasta 24 voltios.

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1. Introduction

Meteorological towers (MET towers) are essential in wind farms to measure different data to control the satisfactory performance of the full system. For doing that some sensors are in this towers that need different power supply.

The goal of the whole project is to create a backup system that provides enough energy to this tower for, at least, 48 hours. Three different output are needed for the different sensor: 24 Vdc for the networking, 12 Vdc for the data logger and 5 Vdc for the sensors. This project is focused on the design of the output system of the project that is divided in two different subsystems.

The first part is an automatic transfer switch (ATS). This device automatically selects the input power that will feed the system by with a priority of sources selected previously: the main source, the solar source and the batteries. It is implemented by using diodes.

The second part is the conversion part. The output voltage provided by the ATS is 24 Vdc. To meet the requirement of the MET tower this needs to be decreased to 12 and 5 Vdc to feed correctly the sensors. Two buck converters are implemented to achieve this.

Due to budget limitation, there are two different designs: one provided to BP according to the specifications of the original MET tower and the prototype built for the university demonstration, where only one battery is used providing an input voltage of 12 V instead of the 24 V of the design.

2. Design Problem Statement

MET Towers are essential in wind farms as they are used to assess wind resource by gathering data from temperature and pressure sensors as well as anemometers and wind speed vanes. MET towers require a reliable power supply and an independent backup system in order to reliably gather wind data.

The current design for the power supply at the Silver Star wind farm implements 2-12V batteries in series as the primary source of power with a battery charger keeping the batteries charged up. This system is flawed as it does not really provide a backup system and the failure of one of the batteries renders the MET tower useless.

With a reliable backup system, the MET tower can provide a constant stream of data for BP Wind Energy to continue performing power performance testing and budget predictions. A robust design would allow for the backup system to operate and supply power to all MET tower equipment for at least 48 hours while the primary power source is offline and switch back to primary power when it comes back online.

2.1. Project Deliverables

The main deliverable is a system that provides three different sources of power (5Vdc, 12Vdc, 24Vdc) from a main AC source as well as a battery and solar backup source. The system includes several hardware subsystems to achieve the conversions needed.

For our design to be successful, it must follow the parameters listed in Table 1.

Subsystem	Specifications	Functionalities
Energy Storage	2x12V, at least 72Ah (Lead Acid)	Will provide power during backup operation.
Battery Charger	10A, Float mode	Will keep batteries at Float voltage (13.62) to maintain their life.
DC Voltage Conversion	Buck converter: 24V-12V and 24V-5V.	Will be used to provide all DC voltages (5V and 12V)

AC-DC Voltage Conversion	120-25V transformer, AC-DC rectifier	Will be used to take the main power (120V) and convert it 25Vdc.
PV	24V, 10A	Will be used as secondary battery charger and main voltage source when solar is ideal.
Status Display	Graphical User Interface (tentative)	Microcontroller will output system information to display.
System protection	5A, 10A, 20A circuit breakers	Will be used to cut off power to system if current limits are exceeded.

Table 2.1. Design Parameters

3. Design problem solution

The section outlines the design choices and reasoning for the BP Wind Energy MET tower power supply according to the requirements provided by them. The final solution implemented will be the one that assure more time of reliable data from the MET tower by using the less power. This means that during all the steps of the design two properties of the system are going to been taken care:

- **Reliability**: It is very important that the all the redundancies of the system do not fail in case the main power breaks. A robust system that assure feeding the MET tower is essential for the good behavior of the system.

- **Efficiency:** During all the design process al the elements are going to be selected to obtain the less losses. Optimization of the values in the existing ranges is necessary to obtain the best performance. This means that all the design is going to be focus on reducing the losses of each subsystem.

3.1. General

The main scope of the project is make sure that the MET tower does not loose data when occurs a failure in the main alimentation system. There always need to be a backup energy system that feed the MET tower when the main source fails.

For solving this issue some solutions can be implemented to provide reliable energy. It is important to choose the optimal method in terms of efficiency and cost.

- **Energy Generation**: A power source that provides enough energy to the system can be used. Renewable energies are the best solution for a buck up system and solar panels are the typical solution used.

  Solar panels can produce electricity by its own and give it to the MET tower or store it in some batteries that would work when the electricity is cut off. The main advantages of this system are its simplicity, the low need of maintenance compared to other renewable energies, the high reliability in Texas (located in the South of United States the solar radiation is high) and the initial cost is low unlike other renewable energies such hydraulic or wind.

  The advantages of using an energy source is that there is no limit of energy produced as it depends on the source (wind, sun…). In the other hand the low reliability is its main disadvantage as they cannot assure a constant production of electricity (production depends on foreign factors).

- **Energy storage**: Using a system that stores the energy is the other option. The use of batteries can provide a reliable back up system as they can be charged by the main source and provide enough electricity for an estimated amount of time.

  The advantage is its high reliability as it is going to provide constant electricity during all the time estimated, but is it limited by the capacity of the system (appearing a time limitation).

The best way to implement a backup system would be to design a combination of both ways.

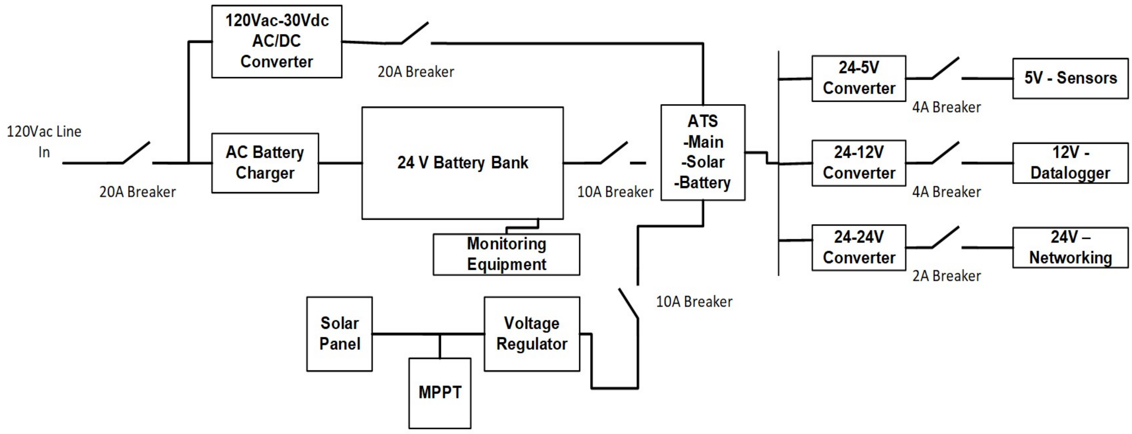

Figure 3.1.. Block design of the full system

The final design selected is a backup power supply system with two redundancies. The primary redundancy is the solar panel, and the secondary redundancy is the 24V battery bank.

As long as main power is constantly being provided, the backup system will never need to come online. When the main power system is functioning properly, power flows from the 120Vac line into the AC/DC converter, into the Automatic Transfer Switch (ATS), and ultimately to the load.

However, in the case of a main power outage, the ATS will initially allow power to be provided by the solar panel and its smaller 18Ah battery. This battery is used simply as a voltage regulator to steady the output voltage of the solar panel to a constant 24V. The voltage regulator is essential to our design as it ensures a constant voltage output from our solar panel, regardless of the weather conditions. This smaller battery can provide power for about 12 hours of continuous use.

In the case that the solar panel battery is completely discharged, and the main power remains offline, the secondary redundancy will come online. The secondary redundancy is the larger 108Ah, 24V battery bank. This battery bank will be responsible for providing power to the MET tower equipment until there is enough sun to recharge the smaller battery or the main power comes back online. The MET tower equipment requires three voltages to be provided: 5V, 12V and 24V.

In order to do this, three DC/DC converters are selected to obtain the output voltages. The way of connection between them will be selected lately.

It is important to constantly monitor the power supply and ensure the proper amount of voltage and current is being delivered to the loads. The MET tower equipment gather data continuously, roughly every 5 seconds, so downtime in the power supply would have disastrous effects. To facilitate the maintenance of the power supply, telemetry has been designed to display voltage and current readings for each output and monitor the charge of the battery.

3.2. ATS

3.2.1. Analysis of ATS

It has been implemented an Automatic Transfer Switch (ATS) in order for our power supply to switch between the main source, solar source and 24V battery source. The figure below represents the circuit schematic of the three-source automatic transfer switch.

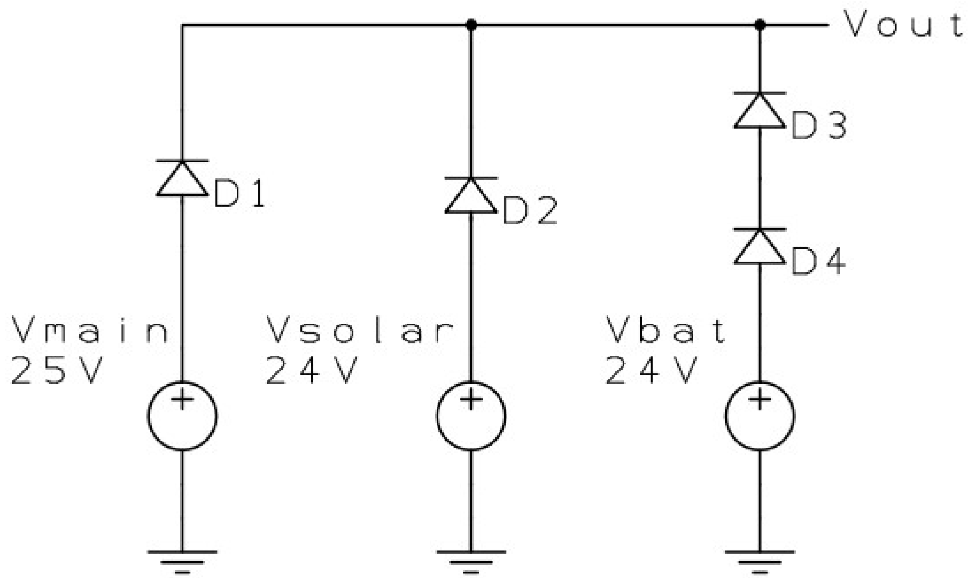

Figure 3.1.2 Circuit Diagram ATS

For the switch to function correctly, the main source voltage needs to be higher than the solar panel battery, and the solar panel battery needs to have a higher voltage than the larger battery.

The sources must be configured this way so that when the main source is on, the other two diodes are reverse biased. This prevents any current from flowing through them, and effectively disconnects the solar panel source and battery source. When there is a main power outage, the same mechanism is used to activate the solar panel battery and leave the larger battery to be used as the last resort. As opposed to the other sources, for the larger battery source we decided to use two diodes to ensure the voltage difference between the solar panel battery and larger battery is sufficient enough to activate proper switching in the ATS. Without this second diode, the voltage drops between the solar panel battery and larger battery were approximately the same, resulting in both sources providing power simultaneously.

With this current design of the ATS, our system is able to efficiently switch between sources in a short period of time, assuring reliable data. Since the MET tower equipment gather data approximately every 5 seconds, there is no risk of losing data if the main power goes offline. This satisfies BP's requirement of having minimal downtime in the case of a power outage.

3.2.2. Simulations of the ATS

To simulate the good performance of the ATS previous to the design of the PCB and building of the switch a model in Simulink is made.

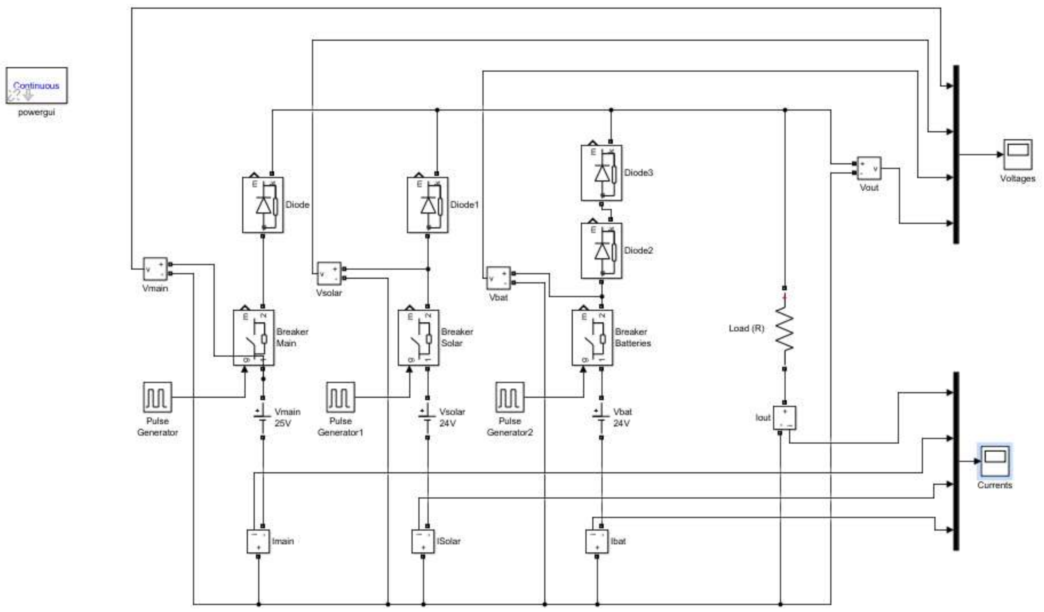

Figure 3.3. Simulink Diagram ATS

The model represents the same circuit like in the previous scheme of the ATS. Each branch represents each redundancy of the design. On the left is the main voltage with 25V, in the middle the solar power that supplies 24V and the battery that provides 24V. Due to the drop of voltage on the diodes (~0.7V) there is a difference between both branches ensuring that the solar gets in before the battery, so two diodes are connected in series causing a drop of voltage of 1.4V.

- <u>Voltages</u>

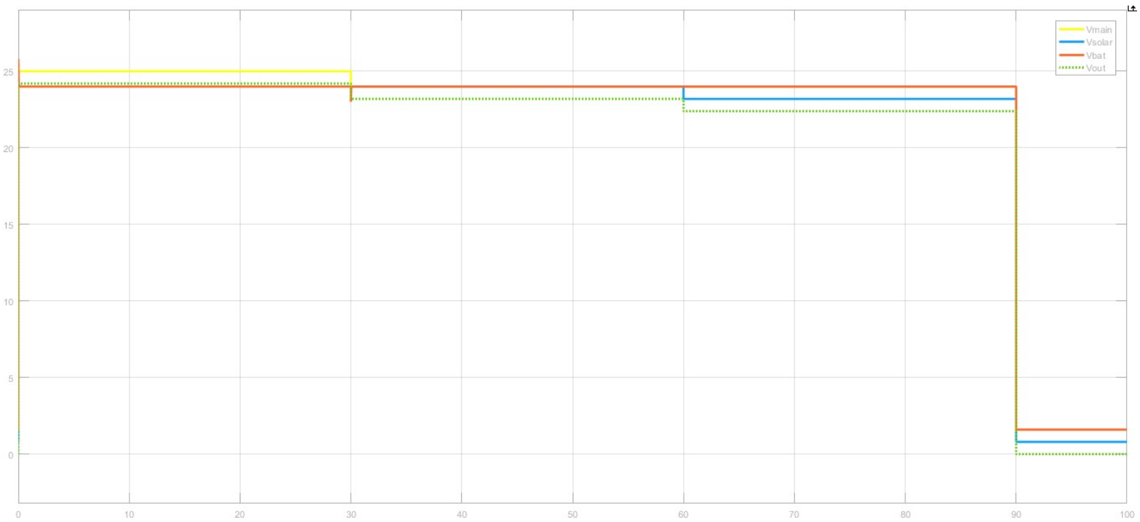

Figure 3.4. Output voltages of ATS (Yellow-Vmain, Blue-Vsolar, Red-Vbat, Green-Vout)

In the simulation there are four different periods:

- During the first 30 seconds (0s-30s) all the sources are ON. The maximum voltage is provided by the main source of 25V and the other sources are providing 24V so due to the difference voltages between them only the diode of the main is on. The rest of them are off, outputting the system a voltage of 24.3V (there is a drop of voltage in the diode).
- During the next 30 seconds (30s-60s) the switch one turns OFF simulating the main source breaks remaining two different voltage sources (solar and battery). If the solar can provide enough power to the system, then the power is provided by it. The output voltage during this period is 23.3V (there is lost due to the drop of voltage in the diode).
- During the last 30 second of the simulation (60s-90s) the main power remains broken and the solar cannot provide enough power to feed the system. Switches 1 and 2 are OFF and the only one that remains ON is the battery. All the power is provided by the battery and the output voltage is 22.6V (due to the drop of voltage in the two diodes).
- During the last period (90s-100s) all the switches are off what means that any of the sources can provide enough power. In this case the output voltage of the system is 0 because the buck up system cannot longer provide enough energy to feed the system, causing that the sensors stop sending data.

The voltage represented in the plot is between the anode of each diode and ground. Even that the switches turn of there is a difference voltage between ground and the anode that is not cero, this have to be taken in account for the design.

- <u>Currents</u>

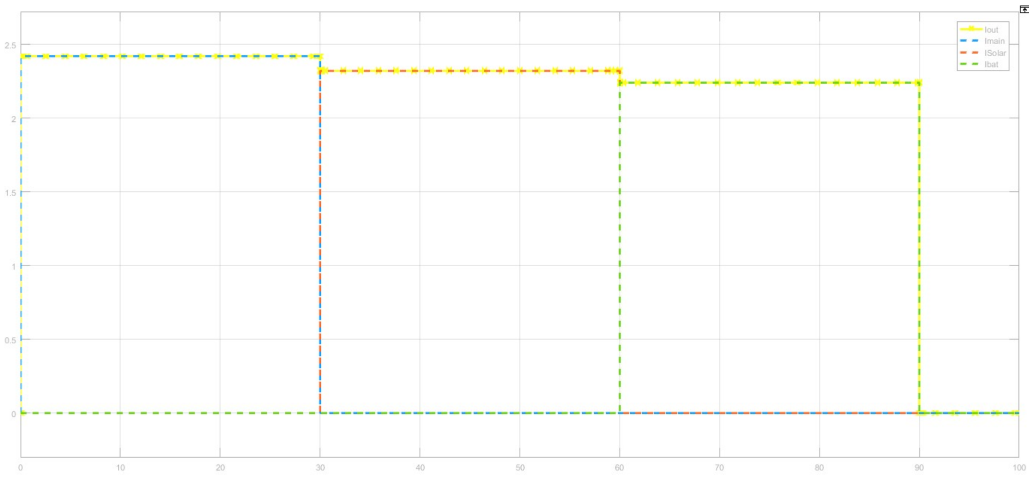

Figure 3.5. Simulation of currents during operation of ATS (Yellow-Iout, Blue-Imain, Red-Isolar, Green-Ibat)

The simulation of the currents it is done simulating the same four periods like the voltages.

- In the first period (0s-30s) all the sources are on but the only one providing power is the main. The current in this case is given by the main source so the output current is the same as the main.
- During the second period (30s-60s) the main breaks and the power is supplied by the solar. Then the output current is the same as the one provided by the solar. The current is not the same that the one provided by the main because, even that the power resistor remains the same if the voltage decrease, due to Ohm's Law, the current must decrease with it.
- In the third stage (60s-90s) the power is supplied only by the third redundancy and the currents provided by the main and the solar are 0.
- When all the sources turn off (90s-100s) there is no current in the circuit causing the system to stop working.

3.2.3. PCB Design

To implement the design a PCB model is designed with Eagle to be printed lately.

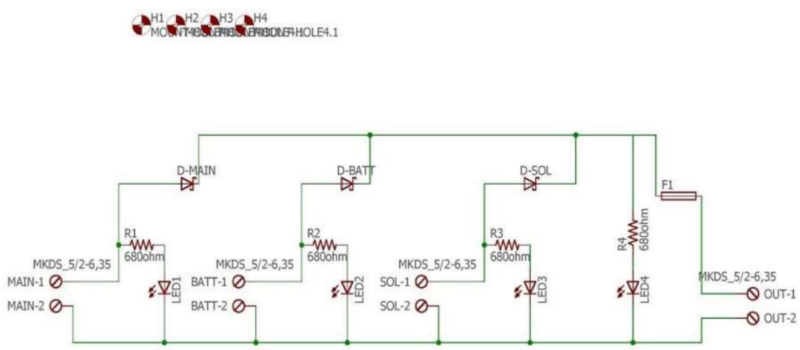

Figure 3.6. Schematic Design with eagle of the ATS

In the schematic of the ATS three different inputs are implemented to connect the three different sources and one output to connect the regulator that will connect with the buck converters.

A small implementation has been added to the PCB design. One LED is connected to each input to indicate what outputs are ON and what outputs are OFF. If the LED is lighting it means that the source is working, independently if it is providing energy or not. But, if the LED is off this means that that source is not working as expected so the energy is being provided by the next one in the priority.

It is also implemented in the output a fuse. In case there is a short-circuit, to prevent that the current goes too high causing damage in the components, a fuse is added so if the current exceeds a limit of 3A it will break closing the system.

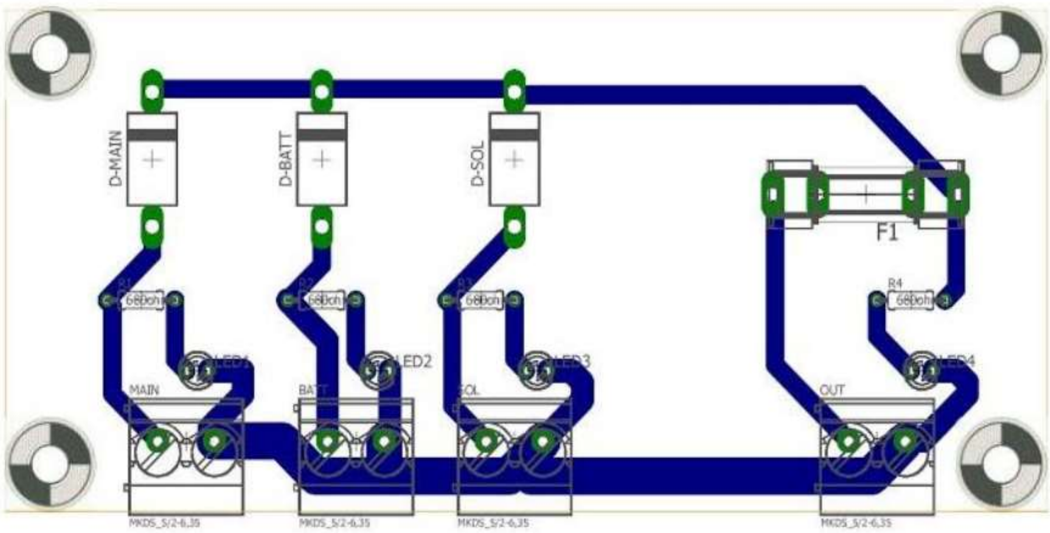

Figure 3.7. Final PCB design of the ATS3.1.i

Later, the PCB design is made. Four holes are done in the corners to make it easier to connect it to the box with screws and the three inputs are connected on the left and the output on the right.

3.3. Buck Converter

3.3.1. Analysis of a buck converter

The buck converter is a device used to decrease DC voltage in an efficient way. The main reason of using this type of converter when compared to other systems to decrease DC voltages like voltage divider is its higher efficiency.

The buck converter has a capacitor and an inductor as elements for storing energy. The output voltage is going to be function of the duty cycle (D) provided by the switching frequency of the MOSFET.

During all the calculus and simulation, we are going to assume that the buck converter is working in CCM (Continuous conduction mode) but it is going to be study the case when it is not working on it.

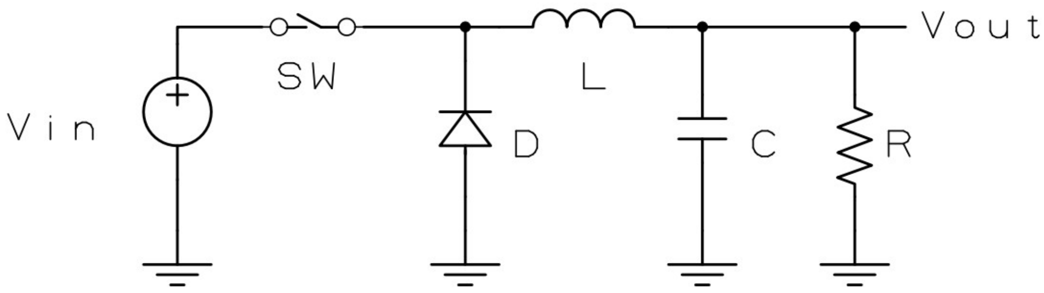

Figure 3.8. Basic scheme of the normal design of a buck converter

The process for obtaining the output voltage of the converter is obtaining the drop of voltage across the inductor depending on the position of the switch (closed or open).

- **Open switch**: When the switch is opened the only energy in the circuit is the one provided by the inductor, so the circuit can be modeled as the figure below.

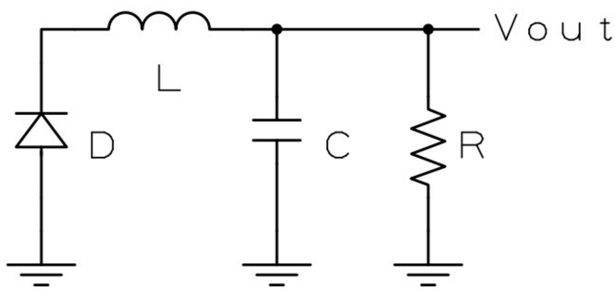

Figure 3.9. Model of the buck converter when the switch is opened

During one period the switch is opened only for (1-D)*T seconds. If a drop of voltage is assumed in the diode as it would happen in a real diode, the output voltage of the converter is the sum of the drop of voltage across the diode and the output voltage. In an ideal buck converter, the drop of voltage can be neglected as the order of magnitude is lower than the other voltages.

$$V_L = V_D + Vo$$

- **Closed switch**: When the switch is closed, the diode is going to change to OFF and it can be modeled as an open circuit that last D*T seconds.

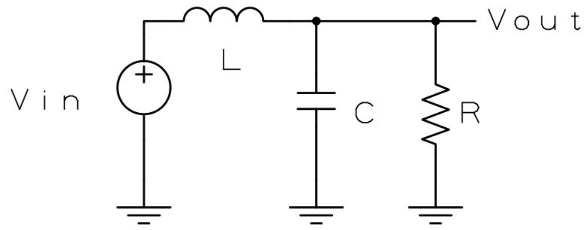

Figure 3.10. Model of the buck converter when the switch is closed

When the buck converter is operating in this mode, the output voltage is the sum of the input voltage and the one across the inductor (during this stage the inductor is charging). In an ideal converter the losses in the switch can be neglected, but when modeling a real buck converter, they have to be considered even if they are very low compared to other voltages in the equation.

$$V_L = V_{in} - V_s - V_{out}$$

When matching both equations we obtain that the output voltage can be obtained by:

$$V_{out} = DV_{in} - DV_s - V_D(1 - D)$$

With the assumptions that there are no losses in the switch and in the diode, the output voltage can be reduced to the equation of the ideal buck converter.

$$V_{out} = DV_{in}$$

Applying the power balance in an ideal buck converter the currents are:

$$P_{in} = P_{out} \rightarrow I_{out} = \frac{I_{in}}{D}$$

The main objective of the project is to develop a system that will obtain three different voltages (24Vdc, 12Vdc and 5Vdc) from one input voltage (24Vdc) reducing to the minimum the losses, it is necessary to consider losses in all the elements to optimize the values of the elements that assure the best performance. For the calculations to obtain the inductor and the capacitor we will use the simplify model (without losses).

3.3.1.1. Currents in all the circuit

To obtain the currents at all the points we are going to work according to the same process in previous point. Assuming two states of the buck converter (switched opened and closed) the behavior of the currents can be modeled in two ways. Once the current through the inductor is obtained, the rest of the currents in the circuit can be calculated.

The current in the inductor is:

$$V_L = L\frac{di_L}{dt} \rightarrow V_L = L\frac{\Delta I_L}{\Delta t}$$

When the switch is opened the incremental of time is (1-D)T and when the switch is closed DT so the current is:

$$Open \rightarrow \Delta I_L = \frac{V_D + V_{out}}{L} DT$$

$$Closed \rightarrow \Delta I_L = \frac{V_{in} - V_S - V_{out}}{L}(1 - D)T$$

Two different slopes appear in the current across the inductor due to the switching. When the current is increasing the inductor is being charged by the input voltage (switched closed) but when the slope is decreasing all the energy stored previously is given to the output and the capacitor. This ripple is going to be mainly absorbed by the capacitor so the output current that we are going to have is supposed to be clean. In a real buck converter this is not going to be possible as the capacity of the capacitor should be infinite. As higher as the capacitor is, less ripple will pass through it.

The main value used is the rms value of the current obtained by the next equation:

$$I_{L,rms}^2 = I_{avg}^2 + \frac{1}{12} I_{pp}^2 = I_{out}^2 + \frac{1}{12}(\Delta I)^2$$

Following the steps taken when calculating the current through the inductor the other currents in the circuit are calculated the same way.

- <u>Input current:</u> the input current is going to be different depending on the position of the switch. When the switch is open there is no input current (this side of the circuit is an open circuit) but when it is closed, the input current is supposed to be the same as the inductor. This means that there is only going to be current during D*T seconds as shown in the plot below.
  The rms value is

$$I_{rms}^2 = D\left(I_{avg}^2 + \frac{1}{12}I_{pp}^2\right) + (1-D)*0 \rightarrow \; I_{rms} = \sqrt{D(I_{out}^2 + \frac{1}{12}(\Delta I)^2)}$$

- <u>Diode current:</u> the shape of current through the diode is similar to the one across the switch. When the switch is closed for (1-D)T seconds, there is no current because the diode is in OFF mode working like an open circuit. But when the switch is closed it can be modeled as voltage source (≈0.7V) and the current will be the same as the decreasing slope of the inductor.
  The rms value is:

$$I_{rms}^2 = D*0 + (1-D)\left(I_{avg}^2 + \frac{1}{12}I_{pp}^2\right) \rightarrow \; I_{rms} = \sqrt{(1-D)(I_{out}^2 + \frac{1}{12}(\Delta I)^2)}$$

- <u>Capacitor current</u>: the objective of the capacitor is absorbing the ripple voltage in the output. This means that the current will be a function only of the ripple current of the inductor, not having an average component like in the previous ones.

$$I_{C,rms}^2 = I_{avg}^2 + \frac{1}{12}I_{pp}^2 = 0 + \frac{1}{12}(\Delta I)^2 \; \rightarrow I_{C,rms}^2 = \frac{1}{12}(\Delta I)^2$$

3.3.1.2. **Ripple Voltage**

In an ideal converter, the output voltage and current do not have a ripple. But this is not true in a real world. We are trying to minimize them as possible. The size of the inductor is related to the ripple of the current and the size of the capacitor to the ripple of the output voltage. As a first approximation, we are going to select the values of the inductor and the capacitor to satisfy the condition of a ripple for a first approximation.

- <u>Inductor current</u>

The main purpose of the inductor in the circuit is to store the energy that would be released to the load when the switch is opened, and the main source is disconnected. We obtain the formula of the ripple current as it has been done before.

$$\Delta I_L = \frac{V_D + V_{out}}{L}DT \; \rightarrow if \; V_D \approx 0 \; \rightarrow \Delta I_L = \frac{V_{out}}{L}DT$$

With that formula we can obtain the value of the inductor when, after making some substitutions, we will obtain the equation. We are going to select that the current ripple should not be more that 10% of the output current. The value of the inductor will be related to the input and output voltage that our system will be designed and with the frequency.

$$L = \frac{V_o^2}{V_{in}\, f \Delta I}$$

In the case of the first buck converter needed, the input voltage is 24 V and the output expected is 12 V. By assuming ideal conditions and a frequency supported by the microcontroller (100 KHz) the ripple current will be 10% of the output current.

$$I_{out} = \frac{V_{out}}{R} = \frac{12}{10} = 1.2A \;\rightarrow\; \Delta I = 0.1 * I_{out} = 0.12A$$

$$L = \frac{V_o^2}{V_{in}\, f \Delta I} = \frac{12^2}{24 * 100KHz * 0.12} = 0.0005\, H \;\rightarrow L = 0.5\, mH$$

With this value we can have a first approximation of the value expected for the inductor. A better optimization to reduce losses in the system will be done lately.

- <u>Output voltage ripple</u>

The average capacitor current is zero during the switching the period. This idea is used to obtain the ripple voltage. The ripple voltage rises from minimum to maximum during charging period and the opposite when discharging.

$$\Delta V_{out} = \frac{\Delta Q}{C} = \frac{\frac{1}{2}\frac{T}{2}\frac{\Delta I_L}{2}}{C} = \frac{T\, \Delta I_L}{8C} = \frac{\Delta I_L}{8Cf}$$

The output voltage ripple is selected following similar requirements like the current ripple, it cannot be higher than a 1%. The requirement here is stricter because for most of the devices the DC voltage needed must be accurate to prevent harmonics and noise that can interferes con signal processing. In this case the sensors need a clean DC voltage to prevent interferences in the data.

$$V_{out} = 12V \;\rightarrow \Delta \mathrm{V} = 0.01 * 12 = 0.12\mathrm{V}$$

Obtaining that the value of the capacitor is:

$$C = \frac{\Delta I_L}{\Delta V_{out} 8f} = \frac{0.12}{0.6 * 8 * 100KHz} = 1.25\ \mu F$$

The value obtained is low and any other value higher than that one would be enough for the design. When increasing the capacitor, the voltage ripple will decrease obtaining a cleaner output. For precise systems where noise is a problem, big capacitors would be needed.

3.3.1.3. Simulation and plot

For next representations of currents and voltages in the buck converter the values used for the simulation are:

C = 1.25 uF

L = 0.5 mH

f = 100 KHz

R = 10Ω

With help of Simulink a previous version of the buck converter is simulated according to the values obtained.

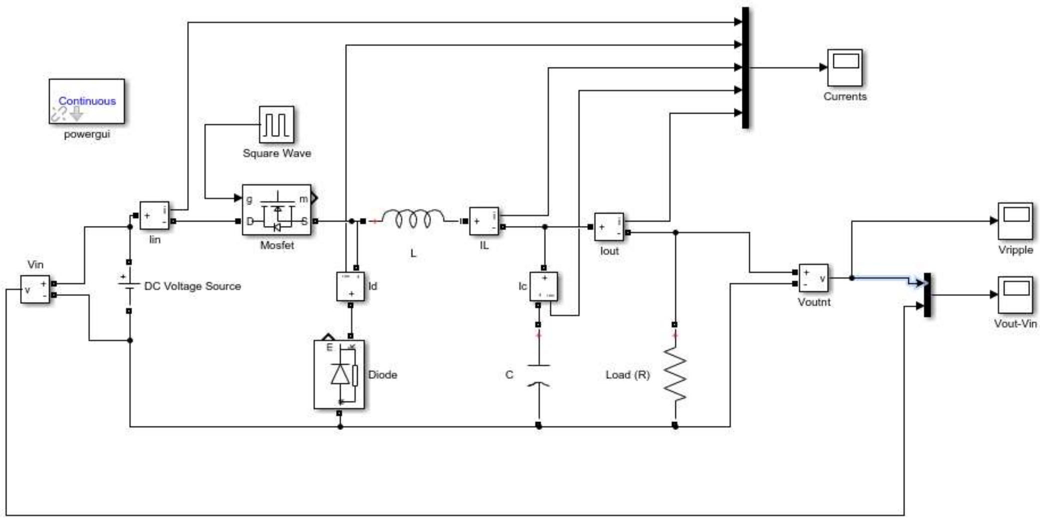

Figure 3.11. Simulink model for the simulation of the behavior of a buck converter

It is possible to obtain the graphs of currents and voltages at all the points of the circuit interesting.

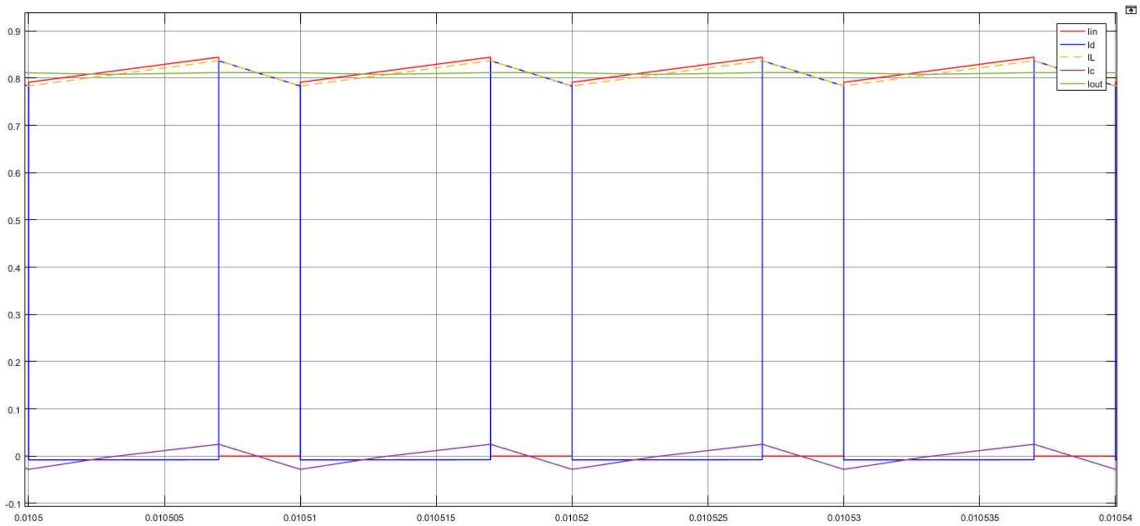

Figure 3.12. Currents and voltages in the buck converter (Red-Iin, Blue-Idiode, Yellow-Iinductor, Purple-Ic, Green-Iout)

In the figure all the currents are displayed according to the values obtained previously.

- <u>Inductor current</u>: The average value of the inductor current matches with the output current of the circuit and the current ripple is as expected (0.12A). The duty cycle applied is 70% of the period, so during the 70% of the period the current is increasing until reaches its maximum. In this point the switch open changing the mode of the buck converter and the rest of the period (30%) the inductor is providing energy.
- <u>Input current</u>: The input current nearly matches the inductor current when the switch is closed (there are some derivations in the switch) that produces an offset between the input current and the inductor current. When the switch in open, the current is 0 during the last period of duty cycle because no power is being provide by the main source.
- <u>Diode current</u>: The current through the diode follows the opposite pattern than the switch. When it is opened, the current matches the one of the inductor but when it is closed the diode changes the state turning off and no current is passing.
- <u>Capacitor current</u>: The average value of the energy stored in the capacitor is 0. This means that the capacitor absorbs all the current produced by the inductor cleaning the output current. The ripple is the same that inductor but neglecting the offset, so the average value is 0.

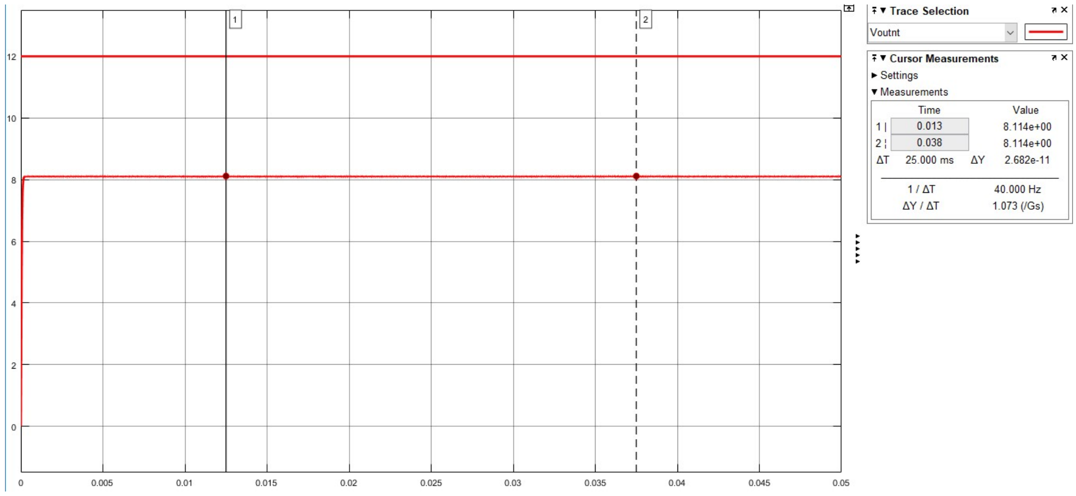

Figure 3.13. Output voltages in the buck converter (Vin=12V; Vout=8.114V)

It is interesting to notice the output voltage of the buck converter. According to the formula of an ideal buck converter, for a duty cycle of 70% the output voltage should be 8.4 V. By contrast, the output voltage obtained is 8.114 V. There are losses due the diode, switch and the rest of elements that are not shown in the ideal model. To obtain the better performance of the buck converter these losses should be considered.

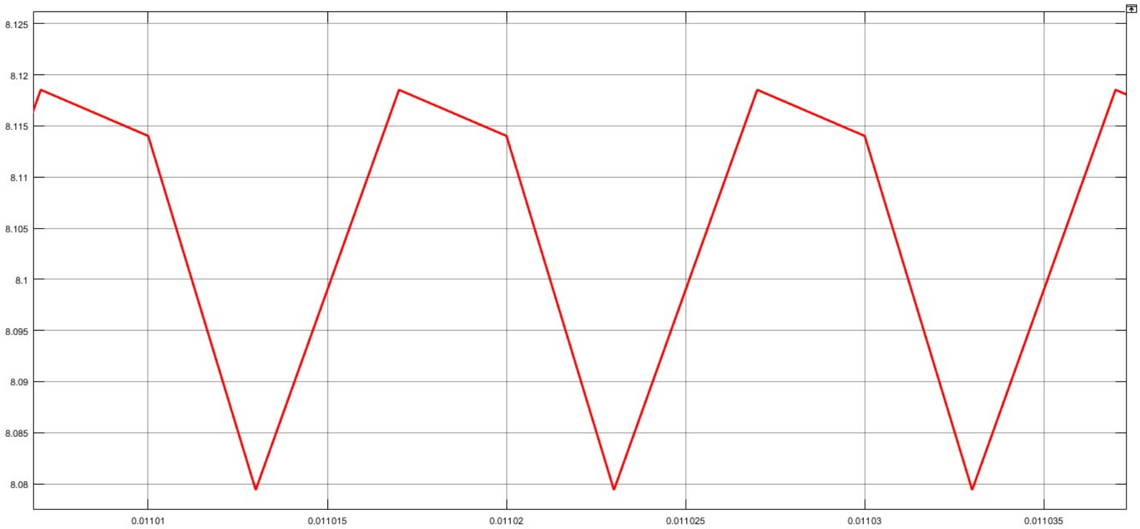

Figure 3.14. Ripple in the output voltage

The voltage ripple obtained is very low, according to expected it is only 0.12 V as expected. For this model we can consider that this enough, but the circuit would have a better response if the value of the capacitor is increased. Increasing the capacitor barely increase the losses in the circuit so the limitation for choosing it will be budget, ratings and space.

3.3.1.4. Mode of operation of the inductor

Another important requirement for the buck converter is that it has to be working in continuous conduction mode (CCM). Depending on the value of the inductor, the average value of the current across the inductor will vary. If the L is too small, the current will have a flat spot at zero and the buck converter will start working in discontinuous conduction mode (DCM).

The inductor is not the only responsible of the change of operation. It occurs when high loads or low operating frequencies decrease the average voltage or increase the current ripple that eventually the value of the current hits 0 during the switch-open state.

To obtain the value of L in the boundary between mode we are going to assume that the minimum of the current ripple is 0.

$$|\Delta I_L| = \frac{V_{out}}{L}(1-D)T \rightarrow \Delta I_L = 2 * I_{out,boundary} = \frac{V_{out}\,(1-D)}{L_{boundary} f_{sw}}$$

$$L_{boundary} = \frac{V_{out}\,(1-D)}{2 * I_{out,boundary} f_{sw}}$$

In the extreme case, the output voltage must be maximum and the output current minimum, what means that the duty cycle is 0.

$$D = 0 \rightarrow L_{boundary} = \frac{V_{out}}{2 * I_{out,boundary} f_{sw}}$$

For the values used previously and the output current that is similar to the one obtained before, we can obtain the minimum value of the inductor that will maintain the buck converter working in CCM.

$$L_{boundary} = \frac{V_{out}}{2 * I_{out,boundary} f_{sw}} = \frac{8.4}{2 * 0.84 * 100KHz} = 50\ mH$$

When simulating the limit is lower than expected. In this model a los of factors that are relevant have been neglected, getting a result of a similar order of magnitude but higher than the one given by the simulation.

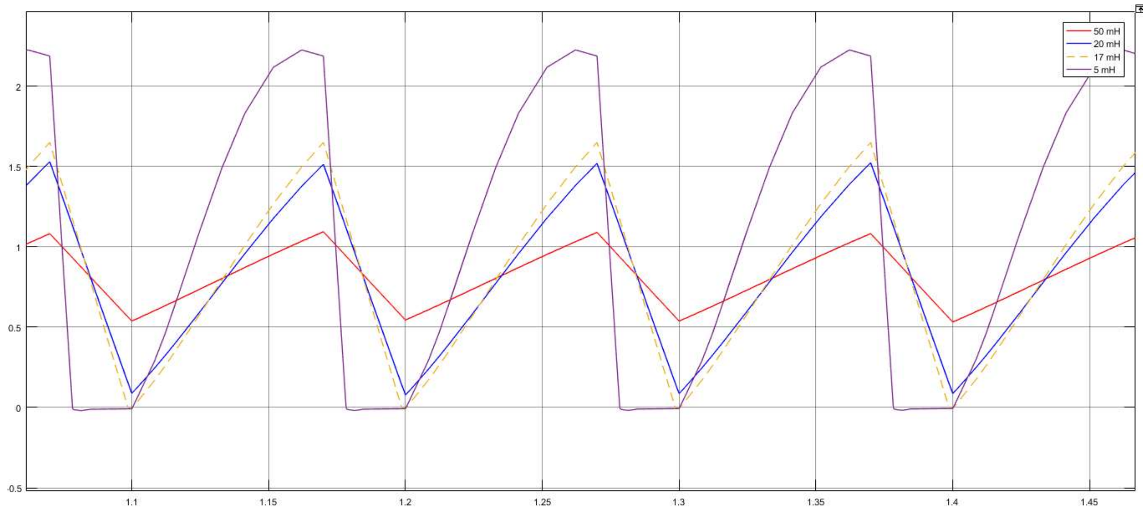

Figure 3.15. Limit for CCM (Continuous conduction mode)

In the picture the output current is plot for different values of L. For the value obtained with the formula the current is as expected, but the limit is reached when the value of L is 17 mA. Below this point, the rest of the values of L create DCM mode and during some part of the period there is no current flowing in the circuit.

3.3.3. Synchronous vs. asynchronous

To switch the best option is to choose a MOSFET. This type of transistor is commonly used for switching because it can be controlled by voltage. For doing that, a PMW input to the MOSFET is going to be the responsible for changing the state of the MOSFET opening and closing the switch.

One of the main requirements of the full installations is its durability. The energy stored and produced by the buck up system is limited, so it is important to minimize the losses as much as possible to give a superior performance.

Losses are produced by main components like the inductor, the switch and diode. When increasing the frequency of switching the losses of every component are going to decrease. This means a reduction of budget and space.

Another option to minimize losses is to substitute the diode by a MOSFET. When the diode is ON the drop of voltage on it is 0.7V approximately, what causes that the output voltage decreases, and the duty cycle needs to be higher than the one calculated when assumed ideal conditions.

Both, diode and MOSFET, have two states (ON and OFF). This means that every diode can be substituted by a MOSFET controlled by voltage. The mains advantage of changing it is that the drop of voltage in a diode is always around 0.7V whether the drop of voltage in the MOSFET depends on the current and the internal resistor that has in ON mode.

This resistor is very low, (around 30 mΩ in a normal MOSFET) so, even if the current is high, is always going to be less than the diode.

The main differences between using a diode and a MOSFET are in the following table:

	DIODE	MOSFET
eff	Low	High
Noise	Low	Switching noise (higher)
Design	Simple	Complicated
Number of elements	Low	High

Table 3.1. Differences between using diode and MOSFET

Even that there are several disadvantages when using the MOSFET in terms of complication of design, requirement of more parts and an increase of the budget, the advantages of using it make the substitution profitable.

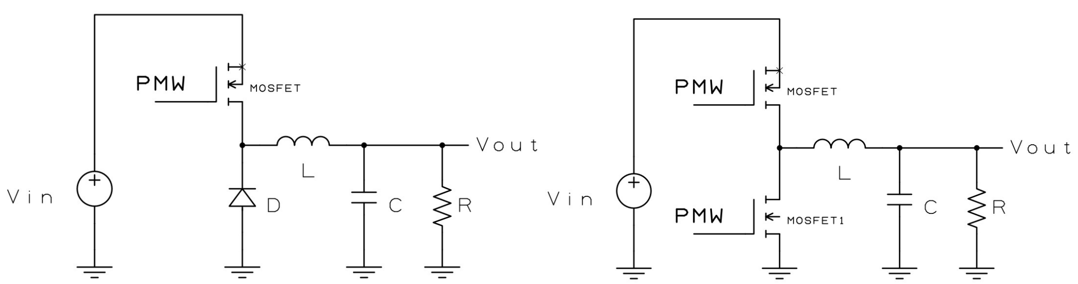

Figure 3.16. Circuit diagram of the two models of buck converter, using diode and MOSFET

Apart of the complexity incorporated to the design, adding another MOSFET in parallel with the previous one creates a potential risk of short circuit. If they are ON at the same moment a shortcircuit is created in the circuit damaging all the buck converter. Dead-time between when switching is needed to prevent this.

Simulink is used to simulate the performance of both models and compare them. In the model below are two different circuits. The top one is the correspond asynchronous buck converter with the diode and the one in the bottom is the synchronous.

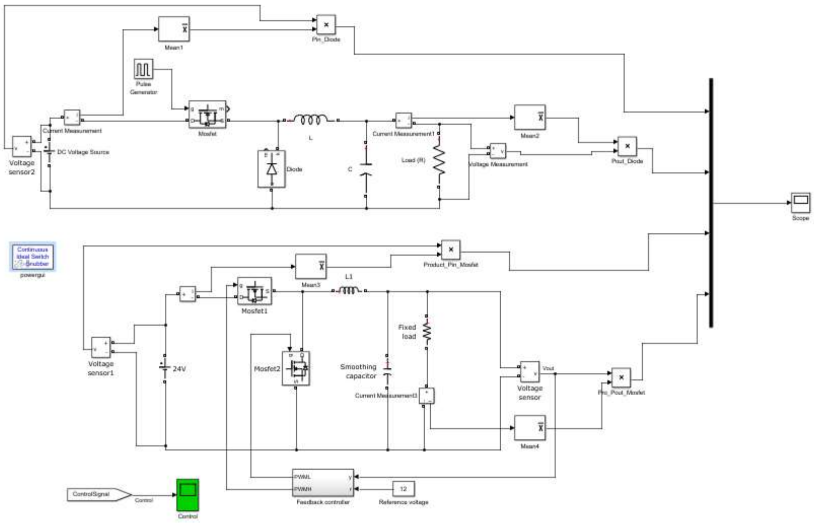

Figure 3.17. Simulink Diagram for comparing using diode and MOSFET

To compare the performance of the circuit what is going to be compared is the efficiency of the two designs by comparing the input and output power.

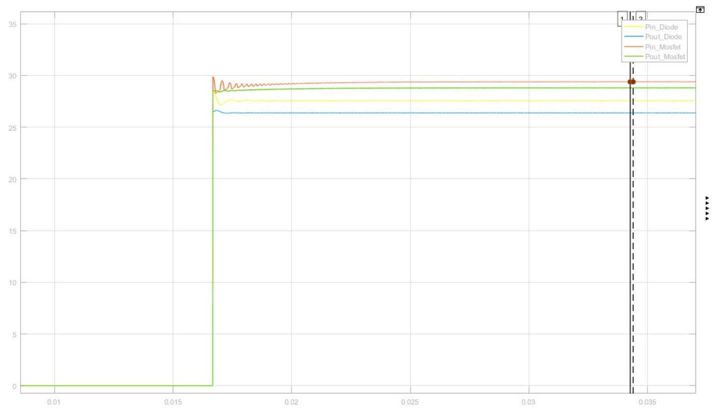

Figure 3.18. Output and input power in the two models (Yellow-PinDiode, Blue-PoutDiode, Red-PinMosfet, Green-PinMosfet)

The values obtained are shown in the table below:

	Pin(W)	Pout(W)	Efficiency (%)
Asynchronous	27.56	26.37	95.682
Synchronous	29.38	28.81	98.060

Table 3.2. Efficiency compared in the two models

In both models the values of all the components are the same. As it was expected, when comparing the efficiency of both model the asynchronous buck converter has a lower efficiency than the synchronous. Like it has been explained before, when using a diode, the drop of voltage on it produces higher losses in the output and more energy is wasted compared to use a synchronous.

In the Simulink model can be seen that the complexity of using the synchronous, even that it provides a better performance, is higher. So, the model selected for the design is a synchronous buck converter.

3.3.4. Parallel vs. Cascade

The input voltage of the power system is 24 V produced by two batteries of 12 V each in series and there are three outputs: 24 Vdc, 12 Vdc and 5 Vdc. To supply all of them at least two buck converters are needed. How to connect them can change the performance and efficiency of the circuit.

- <u>Parallel Connection</u>

The first way to connect both buck converters would be in parallel as shown in the diagram below.

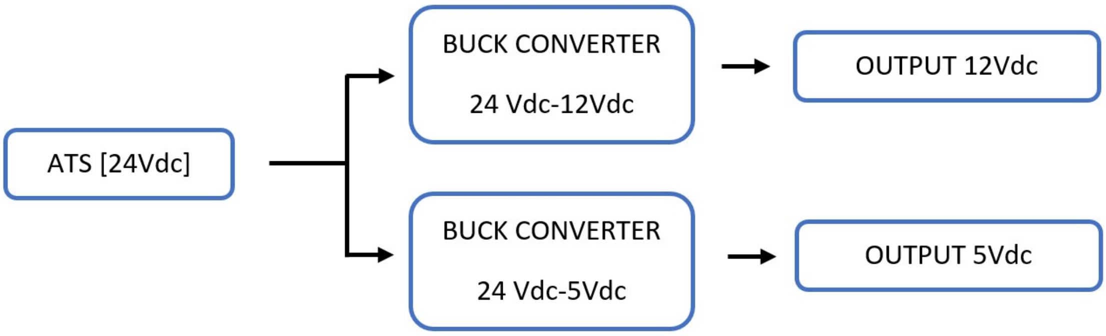

Figure 3.19. Block Diagram of the connection of the buck converters in parallel

The input voltage for both is the 24 Vdc provided by the ATS. Each one with its own duty cycle decrease the voltage until reach the value expected of the output.

The main advantages of this connection are:

- Risk Reduction: When connecting both elements in parallel, in case of failure of one converter, the other group of sensors are not affected by it. The risk that all the system fails due to the output converter is reduced creating a reliable design.
- Less current: The current passing through each buck converter is lower. The current depends on the load, so if only one load is connected less current will pass through each buck converter. This means that the risk of damage in the circuit decreases and all the components needs to fit better requirements. The current supported by the inductor and MOSFET is lower that reduces the cost of each buck converter.

The main disadvantage:

- More losses: When increasing the duty cycle the losses of the circuit increase. The second output of 5V decrease from 24 V to 5 V, decreasing the total efficiency of the system.

- <u>Cascade Connection</u>

Instead of connecting both elements in parallel they can be connected in cascade as shown in the diagram below:

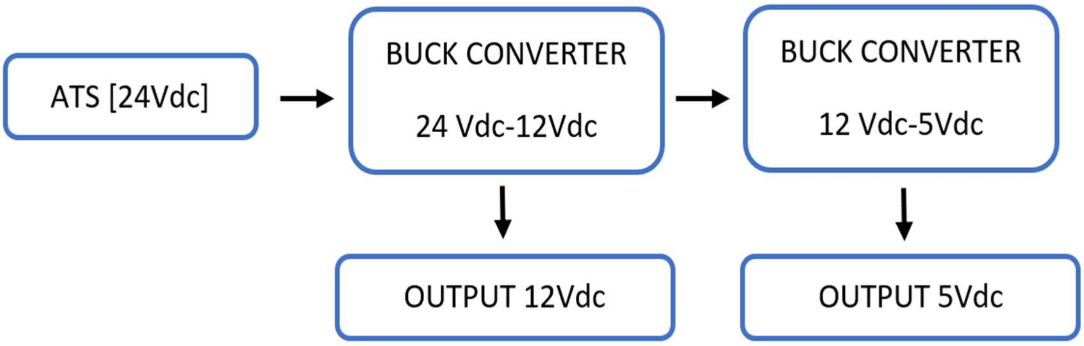

Figure 3.20. Block Diagram of the connection of the buck converters in cascade

There is only one input voltage from the ATS of 24 Vdc that is connected to the input of the first buck converter. The first one decrease the voltage until 12 V that is one of the voltages needed by the meteorological tower. This output voltage is connected in series with the input of the second buck converter with output 5 V. Instead of transforming from 24V to 5 V like in the parallel connection, this buck converter only must decrease the voltage from 12V to 5V.

The main advantage is:

- High efficiency: The duty cycle needed by the first converter is the same but the one of the second is lower than connected in parallel. The efficiency in this connection is higher.

The disadvantages are:

- High currents: Series connection between them produces that the first buck converter supports the sum of its current and the one of the second one. Higher currents means that the components of the first converter need to support them, increasing the rating and the cost of the first buck converter. Furthermore, high currents can potentially damage some elements in case there is a surge.
- Risk reduction: Both buck converters are related. If a failure occurs in the first one the second one would stop working as well because there is not a input voltage. The risk of connecting them in cascade is higher than if they were connected in parallel.

- <u>Parallel-Cascade</u>

The last way of connecting them is a mix of both as shown in the diagram below.

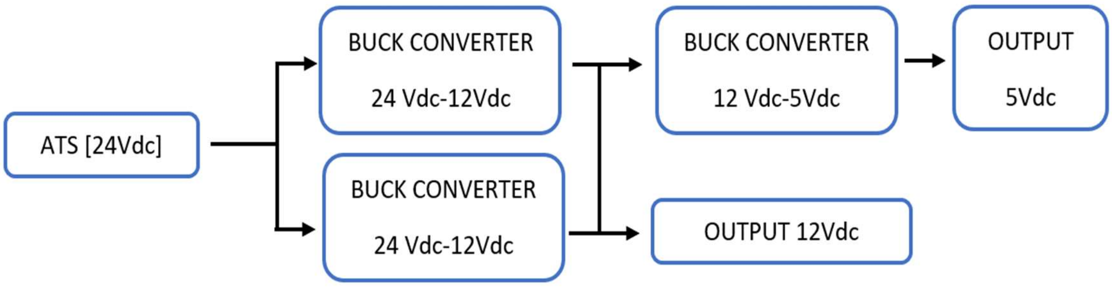

Figure 3.21. Block Diagram of the connection of the buck converters in parallel and cascade

The way they are connected is by connecting two buck converters from 24V to 12V in parallel between them with one buck converter from 12 to 5 V in series. Is a mix of them because it takes the advantages of both methods.

- Risk of failure is reduced with this method. In case one that the first buck converter fails the other will operate in normal conditions and the second converter would still working.
- The total current passing through the first buck converter is reduce compared to the method in cascade. The connection in parallel between them divides the current between them, producing that only it goes half of the total current on each.
- The current requested for the second converter is similar in all the models (the output does not change) but in this case the current flowing in the first buck changes. The losses in each buck converter are less than the second case because, even that the duty cycle remains constant, the current in the elements is the same that means less losses.

In the other hand presents a problem of cost. Duplicating the first converter increase the cost of the system as it requests more components.

3.3.4.1. Simulation of methods

In order to choose the more appropriate method a simulation with Matlab is done to compare what method is more efficient. The values used for all the simulations are the same used in previous calculations of the Simulink.

- <u>Simulation in Parallel</u>

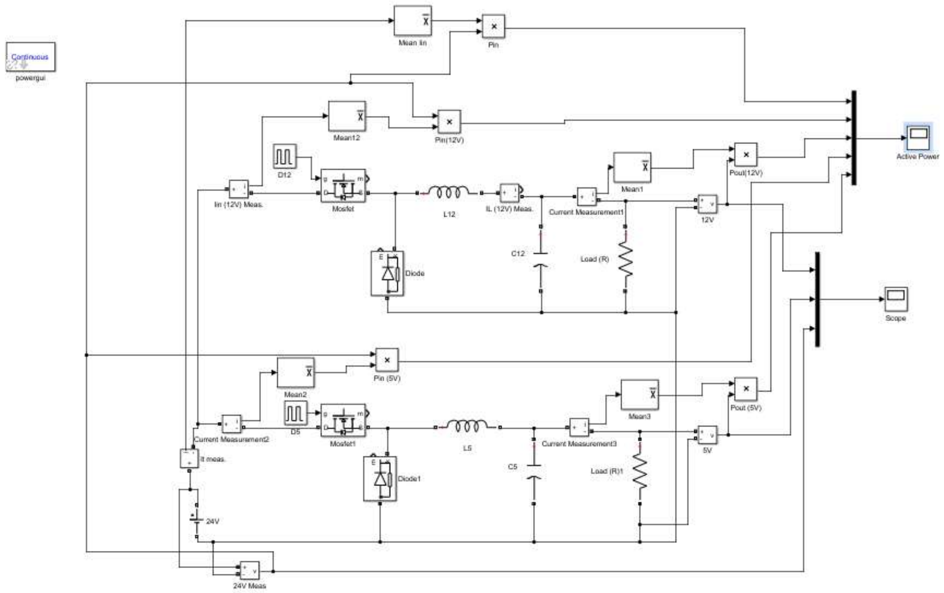

Figure 3.22. Simulink Diagram of the connection of the buck converters in parallel

The diagram in Simulink is the represents the diagram above. In the top is the 24V to 12V buck converter and in the bottom the 12V to 5V . There is only one input source of 24V corresponding to the ATS.

The measurements taken are the input and output power of each buck converter to relate the efficiency of both and compare to the other connections. The input power is measured that as well is the sum of the input powers of each buck converter.

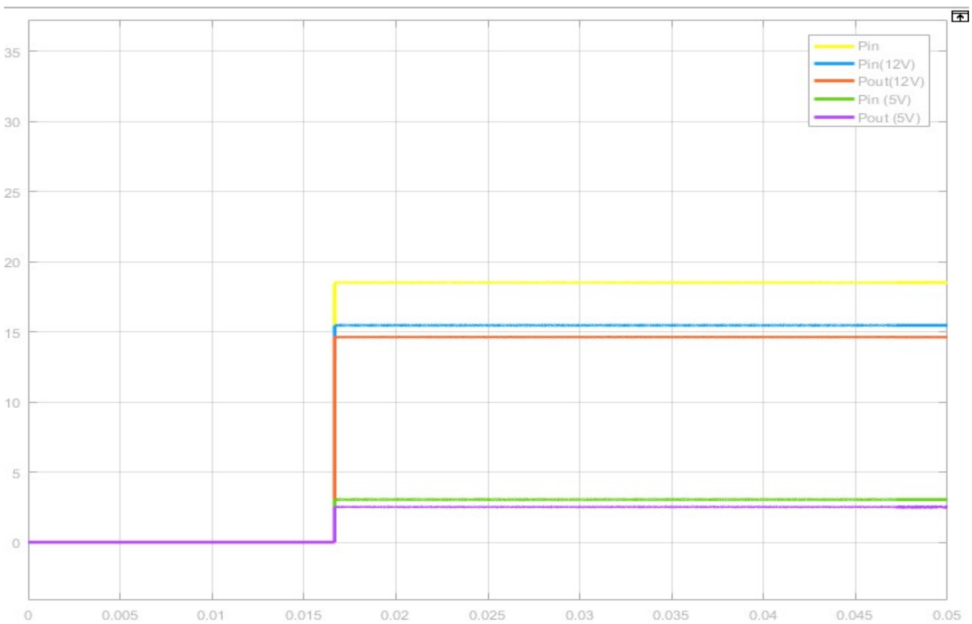

Figure 3.23. Output power of the simulink of buck converter connected in parallel (Yellow-TotalPin; Blue-Pin12V; Red-Pout 12V; Green-Pin5V; Purple-Pout5V)

- <u>Simulation in Cascade</u>

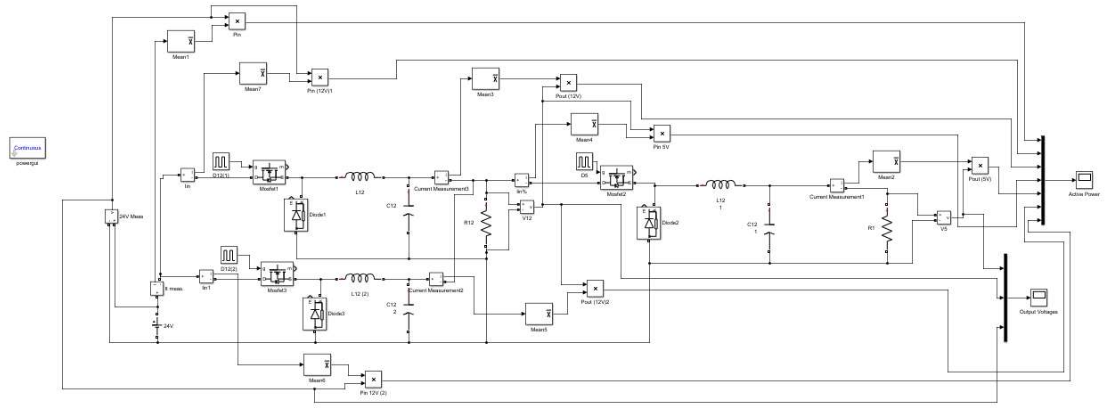

Figure 3.24. Simulink Diagram of the connection of the buck converters in cascade

The diagram for the figure shows the Simulink used to simulate the system of the converters connected in cascade. The input power is only connected to the first buck converter and the second buck converter is connected in parallel with the load of the first one.

In this case the input power of the system is the same as the input power of the second buck converter and there is going to be to output power related to each buck converter.

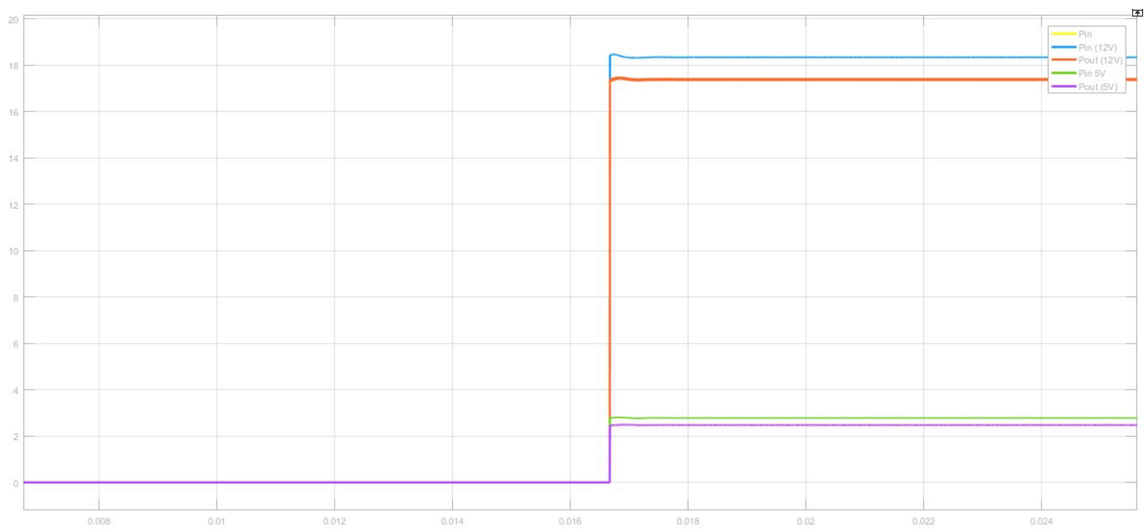

Figure 3.25. Output power of the simulink of buck converter connected in cascade (Yellow-TotalPin; Blue-Pin12V; Red-Pout 12V; Green-Pin5V; Purple-Pout5V)

- <u>Simulation of combination</u>

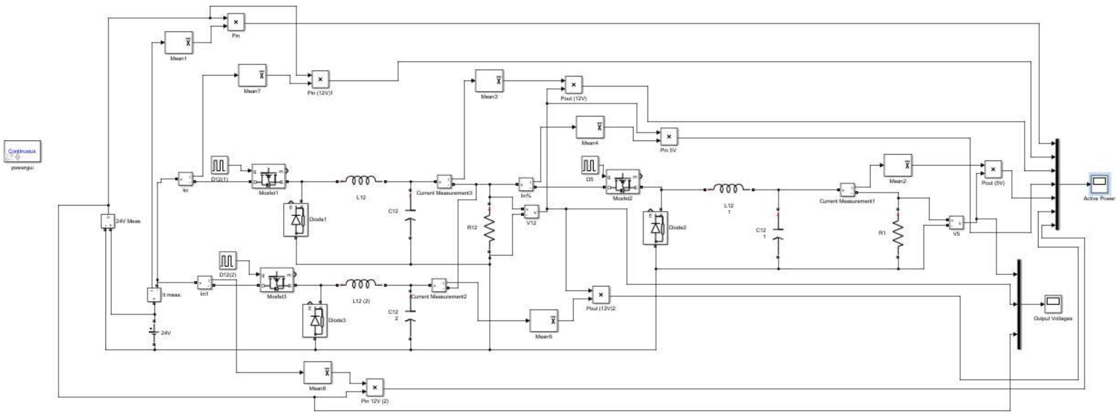

Figure 3.26. Simulink Diagram of the connection of the buck converters in cascade and parallel

In the last simulation there are two converters connected in parallel to the input power instead of one. The output of 12 V is connected to both converters at the same time, obtaining the current from both buck converters.

The main problem of connecting to buck converters in parallel is that the output voltage has to be exactly the same to do not create a voltage difference between in the output. This can unbalance the circuit and damage it. Using this technique increases the risk of it if a prevention system is not implemented. The system used in the ATS with diodes can be used like prevention.

The measurements taken in this case are the total input voltage, the input voltage of each buck converter and the 12V and 5V outputs.

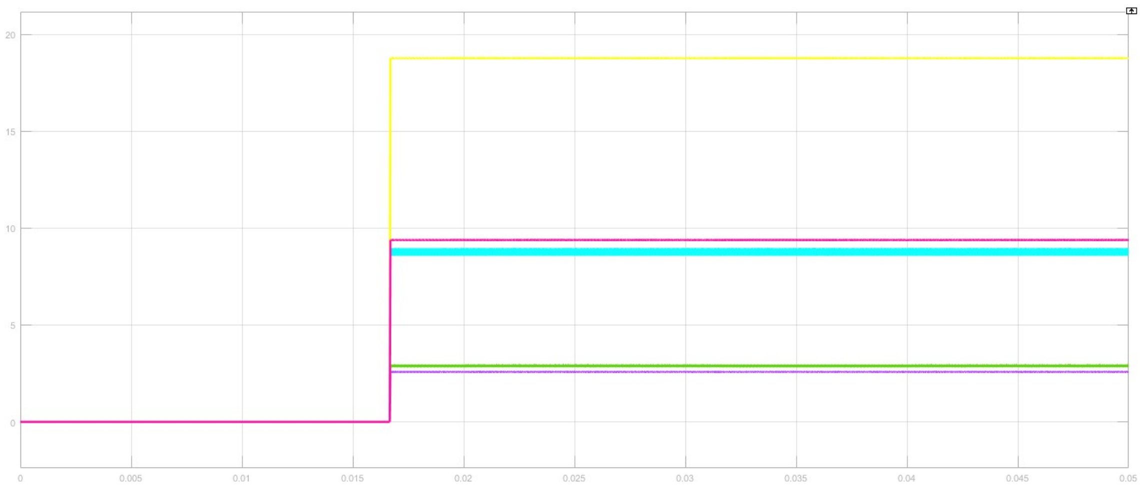

Figure 3.27. Output power of the simulink of buck converter connected in cascade and parallel (Yellow-TotalPin; Pink-Pin12V; Blue-Pout 12V; Green-Pin5V; Purple-Pout5V)

3.3.4.2. Analysis of different models

	Pin12V1(W)	Pout12V1(W)	Efficiency12V1(%)
Parallel	15.38	14.36	93.368
Cascade	18.33	17.35	94.654
Combination	9.38	8.96	95.522
	Pin5V(W)	**Pout5V(W)**	**Efficiency5V(%)**
Parallel	11.430	10.32	90.289
Cascade	2.770	2.556	92.274
Combination	2.9	2.57	88.621
	Pin12V2(W)	**Pout12V2(W)**	**Efficiency12V(%)**
Parallel	-	-	-
Cascade	-	-	-
Combination	9.38	8.96	95.522

Table 3.3. Efficiency compared between the three different types of connection

With the model in cascade the efficiency of both converters is higher that the others. The best performance of the 24V to 5V buck converter is given by the model of the combinations of both. The current is divided between both producing less losses than the model in cascade.

The biggest disadvantage of using this model is that the cost is higher than the other cases because the amount of material needed and the advantage of using it is not worth it. Higher efficiency is one of the requirements of the design, so the model selected for the model is the connection in cascade because the efficiency is higher in the second buck converter.

3.3.5. Optimization of the system

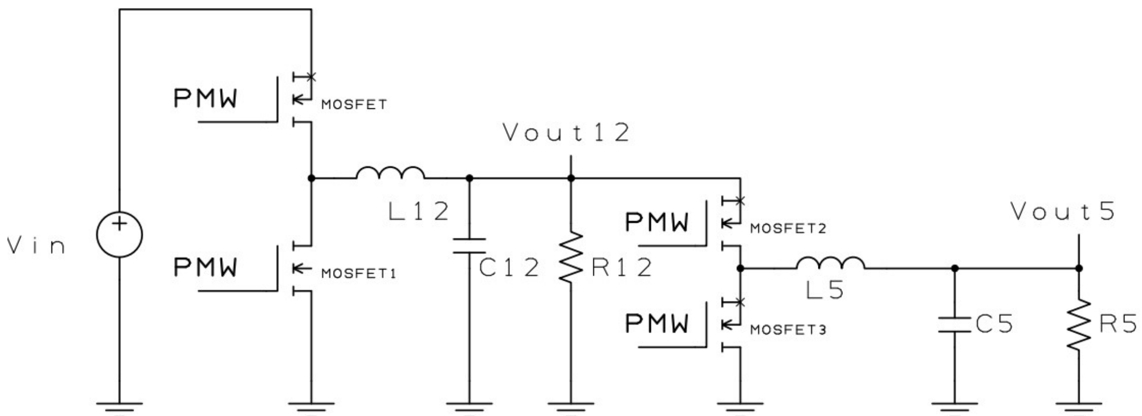

Figure 3.28. Diagram circuit of the final model selected for the output subsystem

The final designed selected is two synchronous buck converters connected in cascade. The input voltage is 24 Vdc provided by the ATS and two output voltages are needs to decrease the voltage from 24 to 12 and from 12 to 5.

Instead of diodes, like a standard configuration of the buck converter, two MOSFETs are used to replace them. As it has been shown previously, the losses are less when substituting the diode with the MOSFET.

3.3.5.1. Formulation of the problem

- <u>Variables and definitions</u>

Some of the values of the elements of the system are fixed but other can vary. Those variables are the ones selected by optimization methods to obtain those that minimize the losses of the system.

- R12 and R5 are fixed -> R12 = R5 = 10Ω
- L12 and L5 are variables of the system
- The switching frequency f12 and f5 are variables of the system.
- The duty cycle of the circuit is considered fixed whether it is not really fixed and depend on some value.

- <u>Objective</u>

The objective of the optimization is to minimize the losses of the hole system. Each loss is calculated for each component.

- Inductor

Losses in the inductor will only be analyzed for one buck converter. When differencing the two different of the state the voltage across the inductor for a synchronous buck converter.

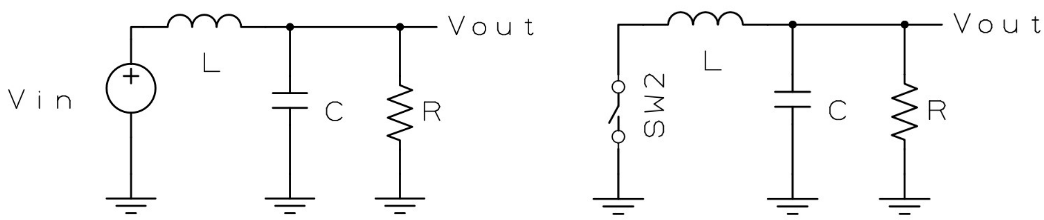

Figure 3.29. Circuit diagram of the states of the buck coverter

The voltage across the inductor in both states is

$$SW1\ CLosed\ \rightarrow V_L = V_{In} - V_s - V_{out}$$

$$SW1\ Opened\ \rightarrow V_L = V_o - V_s$$

The lost power in the inductor is the product of the voltage across it and the current. From the equation before the average current across the inductor is:

$$V_L = L\frac{di_L}{dt} \rightarrow V_L = L\frac{\Delta I_L}{\Delta t}$$

In the two different states the current is:

$$Open \ \rightarrow \ \Delta I_L = \frac{V_{out} + V_s}{L} DT$$

$$Closed \ \rightarrow \ \Delta I_L = \frac{V_{in} - V_S - V_{out}}{L}(1 - D)T$$

Finally obtaining that the average current across the inductor in a synchronous buck converter is:

$$I_{RMS} = \sqrt{I_{out}^2 + \frac{\Delta I^2}{12}} = \sqrt{\left(\frac{V_{out}}{R}\right)^2 + \frac{\left(\frac{(V_{out} + V_s)D}{Lf}\right)^2}{12}}$$

The total power consumed by the inductor is obtaining with the product of the average current and the average voltage:

$$P_L = V_L I_L = (V_{out} + V_s) * \sqrt{\left(\frac{V_{out}}{R}\right)^2 + \frac{\left(\frac{(V_{out} + V_s)D}{Lf}\right)^2}{12}}$$

With the simulations of Simulink the shape obtained of the power across the inductor is trapezoidal. The voltage across the inductor is similar to a square wave and the current is triangular. In the plot can be distinguished both states of working.

- SW1 Opened and SW2 Closed: The inductor is working as a source feeding the output so the power is positive.
- SW1 closed and SW1 Opened: In this stage the inductor is being charged so it is working like a resistor, so the power in negative.

The positive or negative is given by the criteria used, the important thing is to notice that there is a change of behavior on it. Is producing power and consuming.

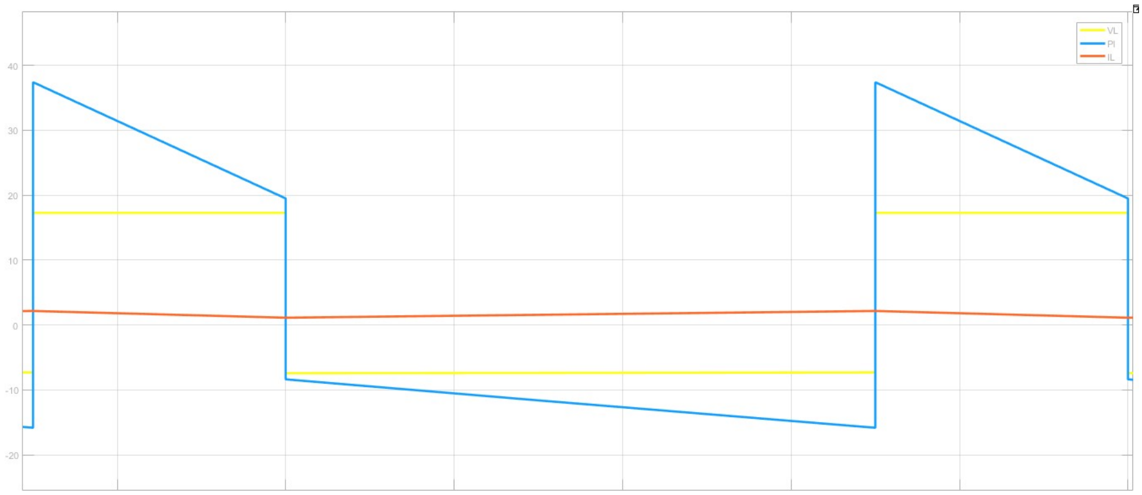

Figure 3.30. Power lost in the inductor

- Switch

In the switch are to kind of losses: the ones introduced by the dead time in the switching period ante the ones that occurs during all the time that buck converter is working. For this optimization the first ones are not analyzed because they are in a lower order of magnitude compared to the second ones.

The high switch or switch 1 is only having losses only during the first period of the duty cycle. The power is the product of the voltage and the current like in the inductor:

$$I_{rms\_HS} = \sqrt{D(I_{out}^2 + \frac{1}{12}(\Delta I)^2)} \rightarrow P_{Cons\_HS} = I_{rms\_HS}^2 \, x \, R_{ds}$$

$$P_{Cons\_HS} = \; R_{ds} * \left(D(I_{out}^2 + \frac{1}{12}(\Delta I)^2)\right)$$

For the second switch the same formula is applied but only for the other part of the period:

$$P_{Cons\_LS} = \; R_{ds} * \left((1-D)(I_{out}^2 + \frac{1}{12}(\Delta I)^2)\right)$$

The power lost during the dead time:

$$P_{DT} = V_{SD}(I_L T_{D1} + I_L T_{D2}) * f_{sw}$$

Knowing the three different losses the total power consumed by the switch is the sum of all of them:

$$P_{sw} = P_{Cons\_HS} + P_{Cons\_LS} + 2P_{DT}$$

$$P_{sw} = R_{ds} * \left(D\left(I_{out}^2 + \frac{1}{12}(\Delta I)^2\right)\right) + R_{ds} * \left((1-D)\left(I_{out}^2 + \frac{1}{12}(\Delta I)^2\right)\right) + 2V_{SD}(I_L T_{D1} + I_L T_{D2}) * f_{sw}$$

The losses due to the dead time are neglected because they are smaller that the other, obtaining that the power consumed by the switches is:

$$P_{sw} \approx R_{ds} * \left[\left(D\left(I_{out}^2 + \frac{1}{12}(\Delta I)^2\right)\right) + \left((1-D)\left(I_{out}^2 + \frac{1}{12}(\Delta I)^2\right)\right)\right] = R_{ds} * \left(I_{out}^2 + \frac{1}{12}(\Delta I)^2\right)$$

The objective to minimize is:

$$P = P_{L,12} + P_{L,5} + P_{sw}$$

$$P = (V_{out12} + V_s) * \sqrt{\left(\frac{V_{out12}}{R12}\right)^2 + \frac{\left(\frac{(V_{out12} + V_s)D_{12}}{L_{12}f_{12}}\right)^2}{12}} + (V_{out5} + V_s)\sqrt{\left(\frac{V_{out5}}{R5}\right)^2 + \frac{\left(\frac{(V_{out5} + V_s)D_5}{L_5 f_5}\right)^2}{12}} + R_{ds} * \left(I_{out12}^2 + \frac{1}{12}(\Delta I12)^2 + I_{out5}^2 + \frac{1}{12}(\Delta I5)^2\right) +$$

NOTE:

$$V_S = I_s R_{ds} = R_{ds} * \sqrt{D(I_{out}^2 + \frac{1}{12}(\Delta I)^2)}$$

- Equality Constrains

The equality constrains of the problem are:

$$g(x) = \begin{pmatrix} g_1(x) \\ g_2(x) \end{pmatrix} = \begin{pmatrix} V_{out12} & - D_{12} * (24 - V_s) \\ V_{ou} & - D_5 * (12 - V_s) \end{pmatrix}$$

- Inequality constrains

The inequality constrains are the barrier that the variables do not have to overpass.

- The value of the inductor has to be possible to obtain so it is limited in a range:
-

$$h_1(x) = \begin{pmatrix} h_{1,1}(x) \\ h_{1,2}(x) \end{pmatrix} = \begin{pmatrix} L_{12} \\ L_5 \end{pmatrix} \in (100 * 10^{-9}, 0.05)$$

- The value of the inductor needs to be a number between 0 and 1:
-

$$h_2(x) = \begin{pmatrix} h_{2,1}(x) \\ h_{2,2}(x) \end{pmatrix} = \begin{pmatrix} D_{12} \\ D_5 \end{pmatrix} \in (0,1)$$

- The value of the frequency needs to exist in a range where the microcontroller can work. The specifications of the microcontroller used in the design (TM4C123) can work until 2 MHz but for safety reason the maximum is set to 500 KHz.
-

$$h_3(x) = \begin{pmatrix} h_{3,1}(x) \\ h_{3,2}(x) \end{pmatrix} = \begin{pmatrix} f_{12} \\ f_5 \end{pmatrix} \in (0,500KHz)$$

- Final Formulation

Finally, the problem that is going to be solved by optimization methods is:

$$\underset{x \in \mathcal{R}_{++}}{min} \{f(x) \mid g(x) = 0, h(x) \leq 0\}$$

3.3.5.2. Resolution of the problem

The vector of variables of the system is:

$$x = \begin{pmatrix} L_5 \\ L_{12} \\ D_5 \\ D_{12} \\ f_5 \\ f_{12} \end{pmatrix}$$

In this case the problem to solve is a non-linear inequality constrained optimization that is solved with the help of Matlab. For solving this problems, Matlab requires the objective function, the equality constrain matrix that is the same that previously and the inequality constrains matrix that is reformulated like:

$$L_5 \geq 100 * 10^9 \ \rightarrow \ 100 * 10^9 - L_5 \ \leq 0$$

$$L_5 \leq 0.05 \ \rightarrow \ L_5 - 0.05 \ \leq 0$$

$$L_{12} \geq 100 * 10^9 \ \rightarrow \ 100 * 10^9 - L_{12} \ \leq 0$$

$$L_{12} \leq 0.05 \ \rightarrow \ L_{12} - 0.05 \ \leq 0$$

$$D_5 \leq 1 \ \rightarrow \ D_5 - 1 \ \leq 0$$

$$D_{12} \leq 1 \ \rightarrow \ D_{12} - 1 \ \leq 0$$

$$f_5 \leq 500 * 10^3 \ \rightarrow \ f_5 - 500 * 10^3 \ \leq 0$$

$$f_{12} \leq 500 * 10^3 \ \rightarrow \ f_{12} - 500 * 10^3 \ \leq 0$$

Finally obtaining the following inequality constrain matrix

$$h(x) = \begin{pmatrix} 100 * 10^9 - L_5 \\ L_5 - 0.05 \\ 100 * 10^9 - L_{12} \\ L_{12} - 0.05 \\ D_5 - 1 \\ -D_5 \\ D_{12} - 1 \\ -D_{12} \\ f_5 - 500 * 10^3 \\ -f_5 \\ f_{12} - 500 * 10^3 \\ -f_{12} \end{pmatrix}$$

The initial point selected for the iteration is:

$$x_0 = (100\mu H \quad 100\mu H \quad 0.5 \quad 0.5 \quad 100KHz \quad 100KHz)$$

With three iterations matlab solves the problem giving that the values that optimize this problem are:

$$x^* = \begin{pmatrix} L_5 \\ L_{12} \\ D_5 \\ D_{12} \\ f_5 \\ f_{12} \end{pmatrix} = \begin{pmatrix} 0.05 \\ 0.05 \\ 0.416 \\ 0.501 \\ 100K \\ 100K \end{pmatrix}$$

3.3.5.3. Optimization Conclusion

The values obtained for the optimization of the system are the values expected. In the case of the inductor they are limited by the boundaries imposed. The mathematical interpretation do not consider the physical constrain that the elements have, this is way they tend to go to infinite.

In the equation of the losses across the inductor the inductor and the frequency are in the denominator, which means that the losses will decrease more as these values increase, this is why the limitation of value is the boundary exposed

$$P_L = V_L I_L = (V_{out} + V_s) * \sqrt{\left(\frac{V_{out}}{R}\right)^2 + \frac{\left(\frac{(V_{out} + V_s)D}{Lf}\right)^2}{12}}$$

The ideal values where the losses would be close to 0 would be when the frequency and inductor are inifinite. This values are physically impossible to obtain, so other factors such cost and space should be considered when selecting the inductor and the frequency response of mosfets and drivers for the frequency.

In the case of the duty cycle, this value is not something fixed because the real input and output voltages are not always the same, so this should be modified with the microcontroller and a PID to obtain the more accurate output.

3.3.6. Design

For the final design the PCB designer Eagle is used. The scheme below shows the circuit finally implemented.

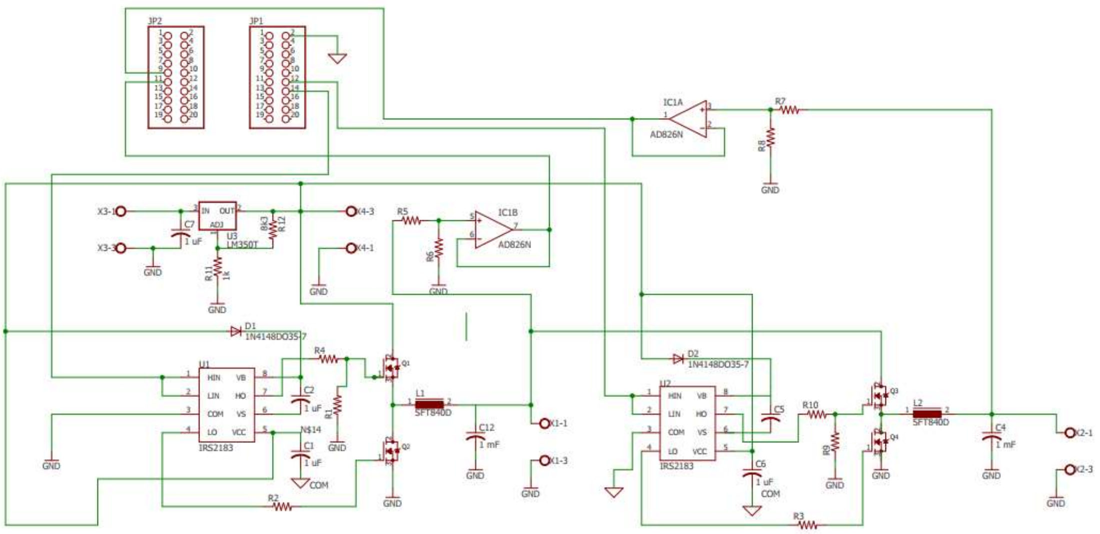

Figure 3.31. Schematic Design of the buck converter

There are two parts of the circuit: the signal part that controls the switching of both buck converters with a microcontroller and the power part composed for the inductor and capacitors that provides the different outputs.

3.3.6.1. Power Design

The input power of the board is supplied by the ATS. This power is always around to 24 Vdc but it is not always it, so a lineal regulator is needed to assure a first output of 24 V. The one selected is the LM350T of Texas instruments because it is able to hold up to 3A, and the overall average current of the system does not exceed 2A. At any case, this regulator should be enough to support the currents needed.

This lineal regulator is adjustable, so the output voltage is function of two resistors

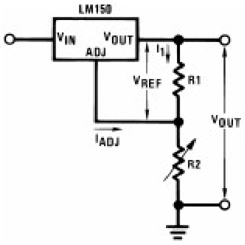

Figure 3.32. Connection of the LM350T

$$V_{out} = V_{ref}\left(1 + \frac{R_2}{R_1}\right) \qquad V_{ref} = 1.25V$$

$$if\ R_1 = 1.1K \ \rightarrow \ R_2 = 20K$$

With these values the output voltage of the lineal regulator is selected for a constant 24 Vdc if the input voltage exists always in a range close to 24V.

To obtain the two other outputs are connected two synchronous buck converters in cascade. The values of the elements are selected according to the optimization process done before and the cost of the different elements, selecting 330uH inductors and 1 mF capacitor to decrease the ripple.

3.3.6.2. Signal Design

The PMW needed for controlling the switching of all the MOSFETS is provided by the microcontroller. The TM4C123 is the one selected for creating the PMW signal needed and to implement the PID. In this part there are different stages:

- Signal Generation: The pins PB6 and PB7 of the launchpad generates two PMW waves with a variable duty cycle and an amplitude of 3.3V.

- Signal Processing: Each of this signals is the input for the MOSFET drivers selected (IRS2183PBF). This device has two functions:
  - Increase the amplitude of the PMW signal until with the voltage that is fed the microchip. This is necessary because the 3.3V is not enough voltage for the GS gate of the transistor to operate. According to the datasheet, it needs at least 5 V-
  - Due to the synchronous configuration of the buck converter used two PMW are needed. This means that the input signal of the second mosfet (the one that is substituting the diode) needs to be the complementary

of the input of the other. In this case a deadtime is needed to prevent shortcircuit, so at the transition time both of signals are.
If during the transition time both of signal are positive, both transistors would be on causing shortcircuit and the failure of the system.

- Control Signal: The drivers from one input generates two different outputs that will be used to control both MOSFETS. Connected to the G gate of the transistor, they are used to control when it is in on and off mode, controlling the PMW signal with the duty cycle sent by the microcontroller. In this case resistors are needed connected to the output to create enough current for the output to work.

- Feedback Signal: connected to the output of each buck converter (to the 12 and 5 V) a feedback signal is connected. A voltage divider made with two resistors is used to decrease the voltage until a voltage that the microcontroller can read. The maximum voltage that the microcontroller can accept is 3.3V so the average value that we will want in both cases is 2V.
To prevent overvoltage instead of providing the voltage directly to the launchpad a operational amplifier is connected between the input signal and the microcontroller in buffer configuration (gain one).

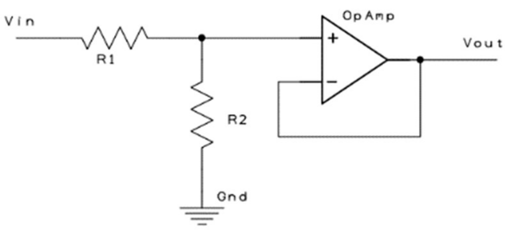

Figure 3.33. Connection of the operational amplifier as buffer

$$V_{out} = \frac{V_{in} * R_2}{R_1} = 2V$$

$$V_{in} = 12V \rightarrow R_1 = 6K \quad R_2 = 1K$$

$$V_{in} = 5V \rightarrow R_1 = 5K \quad R_2 = 2K$$

- PID controller: with the microcontroller a PID systems should me implemented. Depending on the input voltage that receive the microcontroller in pins PE4 and PE5, the microcontroller will change the duty cycle that control the switching frequency of the MOSFETs to provide always a continuous output to the sensors and datalogger

Once all the circuit is design the last step is design the PCB with Eagle.

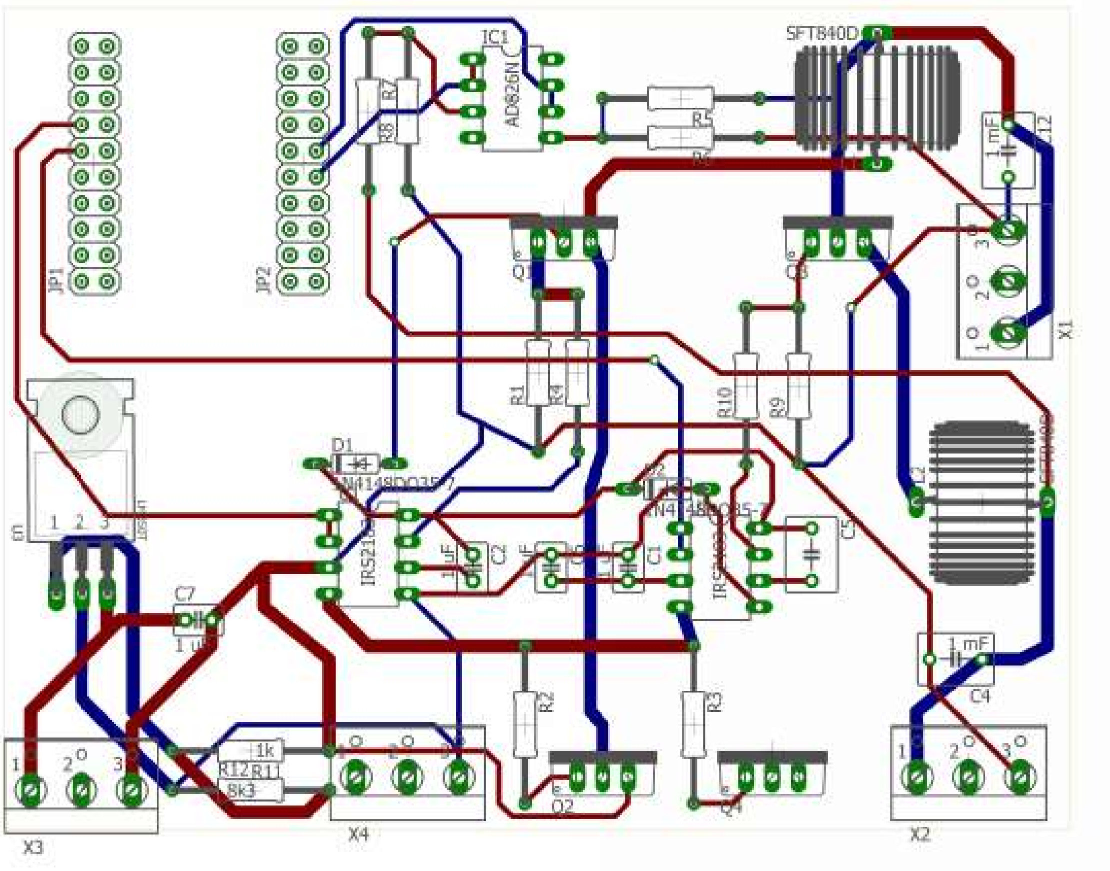

Figure 3.34. PCB Design for the system of two synchronous buck converter in cascade

High currents goes through the design so the thick of the routes is important. The width one are the ones that support high currents and the thicker one are the one for signal processing as the current is small (less than 8 mA).

3.4. Boost Converter

Due the budget limitation instead of two batteries of 12 V each connected in series that would produce an output voltage of 24 V, only one battery of 12 V is going to be used. This means that the whole design of the output system needs to be changed to fit the requirements of BP with a different input voltage.

Instead of two synchronous buck converters in cascade configuration a boost converter is used to increase the voltage from 12 V to 24 V, a regulator to maintain the voltage of 12 V and a buck converter to decrease from 12 V to 5 V. In this section is explained the behavior of the boost converter.

This device is integrated by one inductor and one capacitor as elements for storing energy as shown in the scheme below:

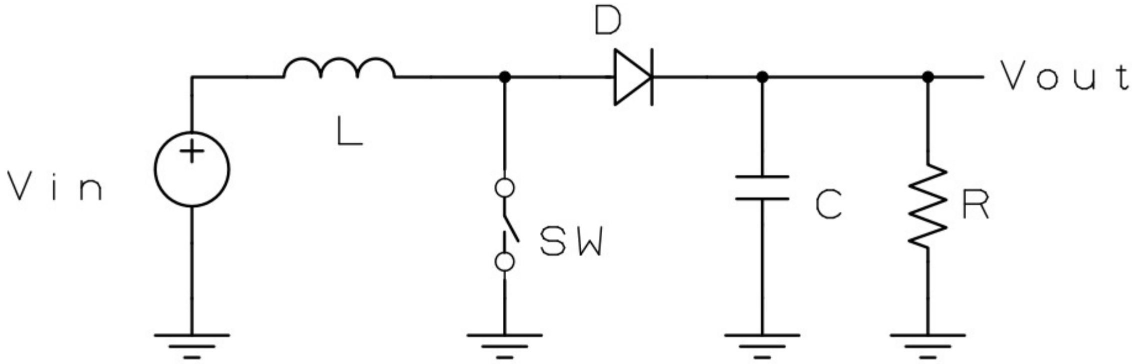

Figure 3.35. Circuit diagram of the basic design of a boost converter

Like the buck converter, it is an efficient way to increase the voltage obtaining a similar output power and input power, with some losses across the diode, the switch and the inductor. The boost converter is an indirect converter. To raise the output

The process to obtain the output voltage is the same that was used in the buck converter: obtaining the voltage across the inductor when the switch is opened and closed.

- **Closed Switch**
  When the switch is closed for D*T seconds the circuit is divided in two different circuits that are not connected because the diode turns off obtaining the next scheme:

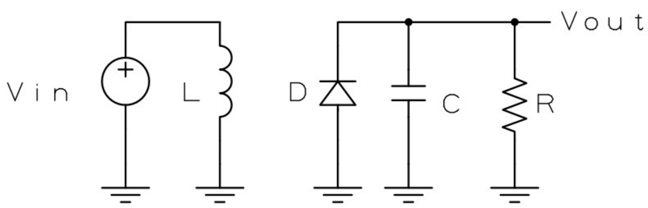

Figure 3.36. Model of the boost converter when the switch is closed

During this stage the inductor is being charged by the input source and the capacitor is the one supporting the load. The voltage across the inductor in this case is the same that the input source:

$$V_{in} = V_L$$

- **Open Switch**
  When the switch is opened it can be substituted like and open circuit obtaining the circuit below.

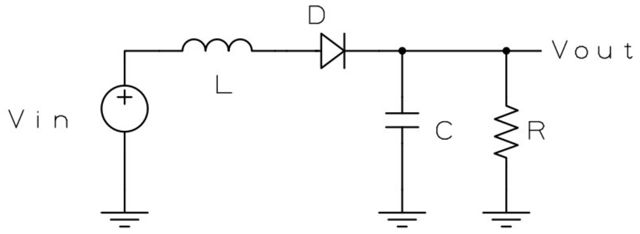

Figure 3.37. Model of the boost converter when the switch is open

  During this period the inductor is being discharged while is providing energy to the load. This means that the main source and the energy stored in the inductor when the switch is closed is feeding the load for (1-D)*T seconds.

$$V_{in} - V_L - V_d = V_{out}$$

  The boost converter is an indirect converter. To raise the output voltage, L must charge. But doing so disconnects the load from the source causing the load voltage to initially fall rather than rise.

Then the average DC voltage is obtained when joining the two equation and knowing that the average inductor voltage in one period is 0:

$$V_L = D * T * V_{in} + (1 - D) * T * (V_{in} - V_{out} - V_{d)} = 0$$

$$V_{out} = \frac{V_{In}}{1 - D} - V_d$$

Assuming the ideal case where there are no losses across the diode the output voltage would only be function of the input voltage and the duty cycle:

$$V_{out} = \frac{V_{In}}{1 - D}$$

3.4.1. **Analysis of currents**

Once the average output voltage is obtained the next step is to find the currents in the circuit. The first step is obtaining the ripple current of the circuit.

To find it is used the same procedure, finding the current across the inductor when the switch is closed and when the switch is opened knowing the differential relation between the current and voltage in an inductor.

$$V_L = L\frac{di_L}{dt} \rightarrow V_L = L\frac{\Delta I_L}{\Delta t} \rightarrow \Delta I_L = \frac{V_L * \Delta t}{L}$$

When the switch is opened the incremental of time is (1-D)T and when the switch is closed DT so the current is:

$$Open \rightarrow \Delta I_L = \frac{V_{in} - V_{out} - V_d}{L} DT$$

$$Closed \rightarrow \Delta I_L = \frac{V_{in}}{L}(1-D)T$$

Two different slopes appear in the current across the inductor due to the switching. When the switch is closed for D*T seconds the inductor is being charged by the main source so the slope of the current at this point is positive. Otherwise, the inductor is working as an energy source feeding the load so as it discharges the slope of the current is negative.

The main value used is the rms value of the current obtained by the next equation:

$$I_{L,rms}^2 = I_{avg}^2 + \frac{1}{12}I_{pp}^2 = I_{In}^2 + \frac{1}{12}(\Delta I)^2$$

It is very similar to the equation of the current of the inductor of the buck converter because the shape of the wave is the same. The different s the average component that in the first case was the output current and now, due to the circuit design of the boost converter, is the input current.

Following the steps taken when calculating the current through the inductor the other currents in the circuit are calculated the same way.

- Input current: the input current changes depending on the position of the switch. When the switch is opened there is no input current (because it is working like an input circuit) but when it is closed, the input current is the same like the inductor. This means that there is only going to be current during D*T seconds as shown in the plot below.

  The rms value is

$$I_{rms}^2 = D\left(I_{avg}^2 + \frac{1}{12}I_{pp}^2\right) + (1-D)*0 \rightarrow \; I_{rms} = \sqrt{D(I_{in}^2 + \frac{1}{12}(\Delta I)^2)}$$

- Diode current: the shape of current through the diode is similar to the one across the switch. When the switch is closed for (1-D)T seconds, there is no current because the diode is in OFF mode working like an open circuit. But when the switch is closed it can be modeled as voltage source (≈0.7V) and the current will be the same like the decreasing slope of the inductor.
  The rms value is:

$$I_{rms}^2 = D*0 + (1-D)\left(I_{avg}^2 + \frac{1}{12}I_{pp}^2\right) \rightarrow \; I_{rms} = \sqrt{(1-D)(I_{in}^2 + \frac{1}{12}(\Delta I)^2)}$$

- Capacitor current: the objective of the capacitor is absorbing the ripple voltage in the output. When the switch is closed the current across the capacitor is the output current but when it is opened there is a influence of the ripple current.

$$I_{C,rms}^2 = DI_{Out}^2 + (1-D)\left[(I_{In} - I_{out})^2 + \frac{1}{12}(\Delta I)^2\right]$$

3.4.2. **Analysis of ripple voltage**

Due to the switching of the system the output voltage is not totally clean. Like it happens in the buck converter, there is a ripple voltage in the output that, depending on the value of the capacitor, is bigger or smaller.

Contrary what happens in the inductor, the average voltage in a capacitor is 0 during the switching period.

$$\Delta V_{out} = \frac{\Delta Q}{C} = \frac{I_{out}DT}{C} = \frac{I_{out}D}{Cf}$$

3.4.3. Plot and simulations

To test the circuit is going to be used simulations made with Simulink. To select the values of the components the procedure used is the same like in the buck converter: assuming a good percentage value for the ripple current and voltage and, using the equations for the boost converter obtained before, find the best value for the boost.

- Value of the inductor: The value assumed for a good current ripple is a 10% of the inductor current. During all the calculations an ideal buck converter is going to be assumed, so the efficiency in assumed 100% having the same output power that input power. This is only used to obtain the value of the components for the simulation, no the real values of the input and output power.

$$\Delta I_L = \frac{V_{in} - V_{out} - V_D}{L} DT \rightarrow if\ V_D \approx 0 \rightarrow \Delta I_L = \frac{V_{in}}{L}(1-D)T \rightarrow L = \frac{(1-D)V_{in}}{\Delta I_L f}$$

$$P_{in} = P_{out} \rightarrow \Delta I = 0.1 * I_{in} = 0.1 * \frac{V_{out} * I_{out}}{V_{in}} = \frac{0.1 V_{out}^2}{R * V_{in}} = 0.192\ A$$

$$L = \frac{0.1\ V_{out}^2\ (1-D)\ V_{in}}{R\ V_{in}\ f} \rightarrow L = 28.8\ \mu H$$

- Value of the capacitor: Is assumed that the value of the output current is good enough when it is only 1% of the output voltage. Same assumption of ideal converter is used to obtain the value of the capacitor.

$$C = \frac{I_{out} D}{\Delta V_{out} f} = \frac{V_{out} D}{0.1 * V_{out} R f} = \frac{D}{0.1 R f} = \frac{0.5}{0.1 * 10 * 100 * 10^3} = 5 \mu F$$

Compared to the values obtained with the buck converter these are smaller. Any case, these values can only be used for a first approximation and for a simulation. The best values should e obtained optimizing the losses of the boost converter as did in the buck converter.

For the simulations and plot is going to be used models of Simulink. The values used for the simulation are:

R = 25 Ω
L = 30 μH
C = 0.1 mF
f = 100 KHz
D = 52.5% (0.525)

The diagram used is shown in the picture below.

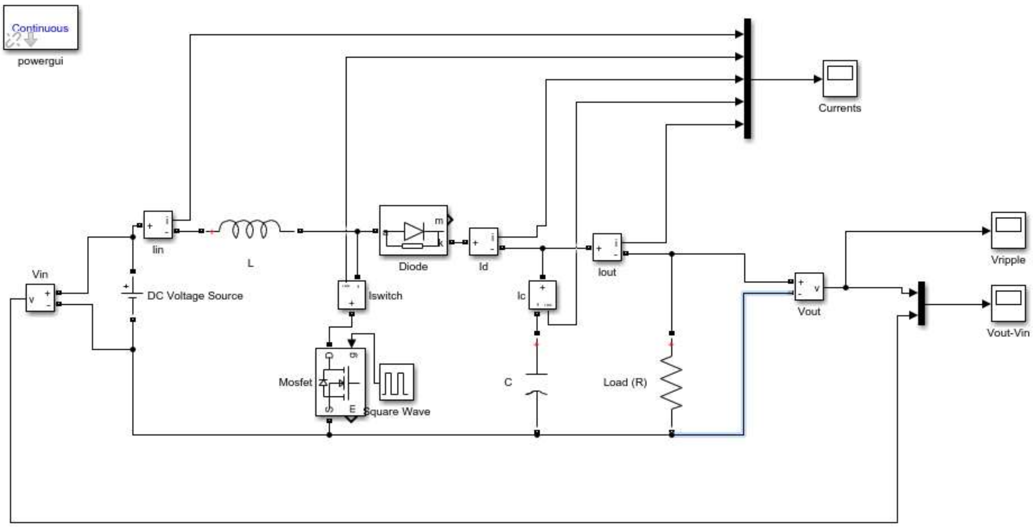

Figure 3.38. Simulink Diagram of the boost converter

In the simulations three different behaviors of the boost converter are recorded: currents, output and input voltage and ripple voltage.

- **Currents**
  In the simulation all the possible currents of the circuit are going to be measured.

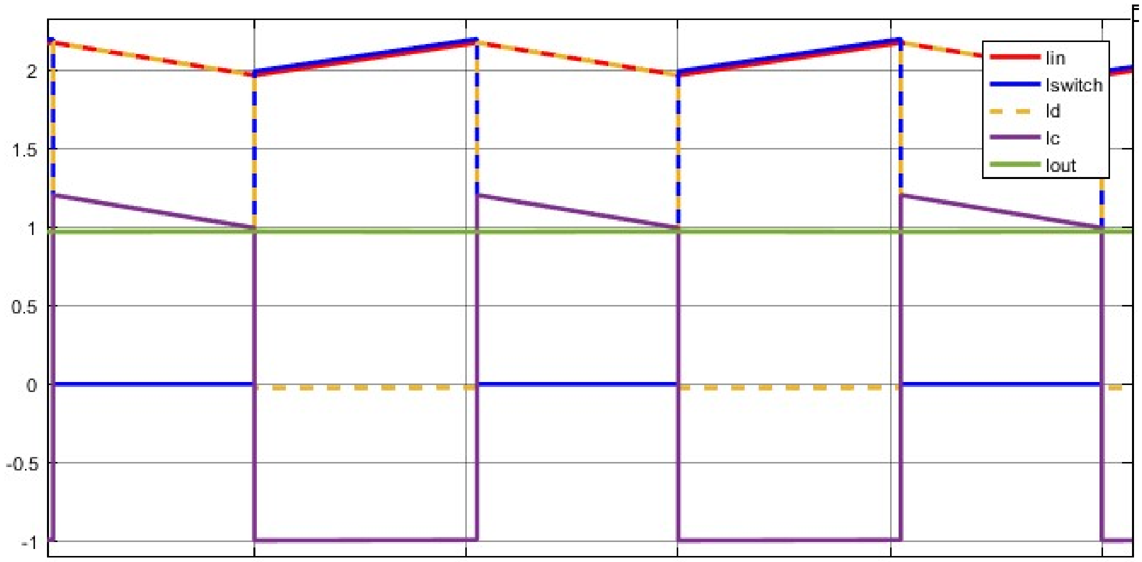

Figure 3.39. Currents in the boost converter (Red-Iin; Blue-Iswitch; Yellow-Id; Purple-Ic; Green-Iout)

- The input current is the same current that the inductor current. Represented in red in the simulation it can be seen that increase for nearly half of the duty cycle and decrease for the rest of the period, showing when the inductor is charging and discharging.
  When measured, the maximum value of the input current is 5.156 A and the minimum value 4.957 A, obtaining an average value of 5.1560 A and a ripple current of 0.199 A. When assuming ideal conditions for the boost converter, the value calculated was 0.192A (10% of the input current of 1.92A), so it is assumed that ideal model works closer to the real one.
- The current across the switch is divided in two periods. In the first part, when the switch is closed, the current across the switch is the same as the inductor because it is working like a short-circuit. When the switch is opened, there is no current through the switch and the value is 0, getting that there is only current in the first part of the period.
- The current across the diode works the opposite of the switch current. When the switch is closed, the diode is in off state blocking the current of the inductor pass through it, obtaining that no current is passing trough it. In the other case, when it is open, it changes to on state and the diode current is the same as the input current.
- Capacitor current is more complex that the others. When the switch is closed the capacitor is discharging into the load so the current in this state is the same value that the output current but negative (due to the way it is measured). When the switch opens, the capacitor is absorbing all the ripple current of the input current, getting an average value of the difference between the input and output current.

- **Voltages**

  The next measurement recorded is the relation between the input and output voltage. For an ideal boost converter the value of the duty cycle should be 0.5, but due to the losses in some values to obtain 24 V in the output the duty cycle need to be higher. For this simulation the value used of the duty cycle is 0.525.

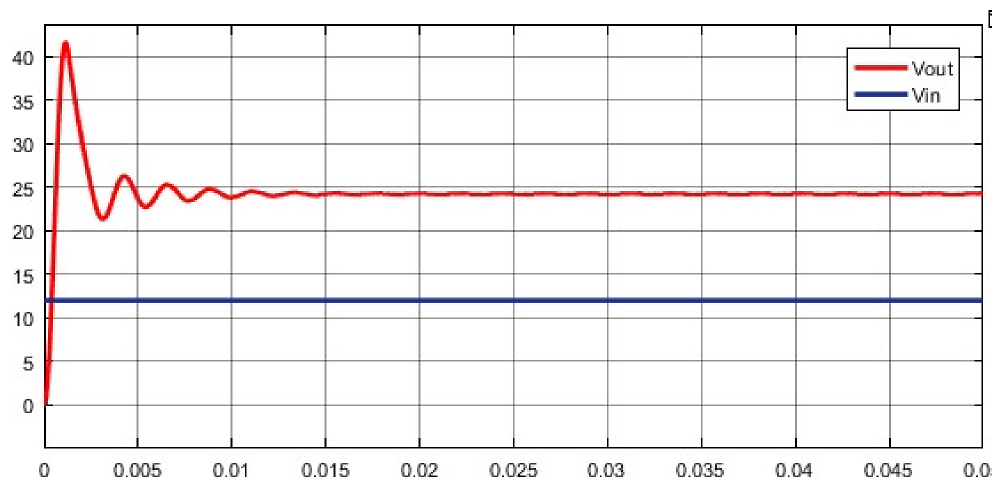

Figure 3.40. Output voltages of the boost converter (Red-Vout, Blue, Vin)

During the steady state the value of the output voltage is 24 V with the ripple. In the transient state a peak close to 42 V is reached according to the simulation. For the selection of the boost converter this needs to be considered and the range is checked in the datasheet.

- **Ripple Voltage**
  The last measurement is the ripple voltage.

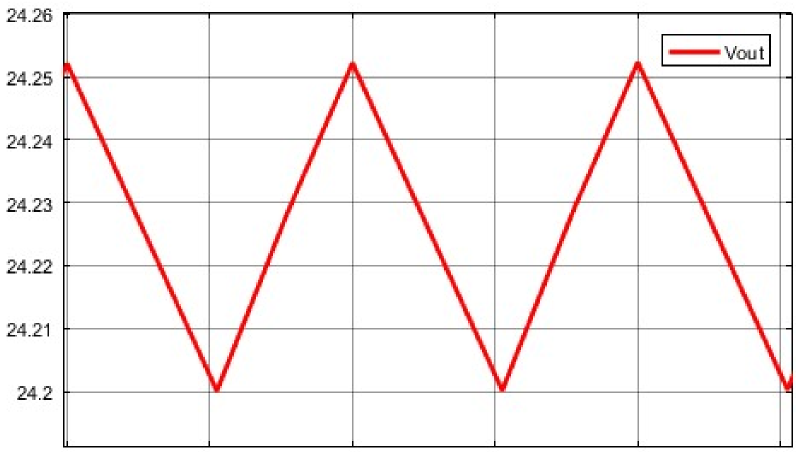

Figure 3.41. Ripple in the output voltage of the boost converter

With the values selected the value expected was 1% of the output voltage. So, if the output voltage is 24V, the ripple voltage should be around 0.24V. When measuring during the simulation, the ripple obtained is 0.05V. The capacitor value used for the simulation is 0.1 mF, much bigger than the one obtained with the calculations of 0.005 mF. This explains why the calculation differs from the simulation.

4. Design implementation

4.1. General implementation

For the prototype built the design changes from the original made for the MET tower in BP. Due to budget limitation only one battery is used in the design what makes the need of changing the design of the output system.

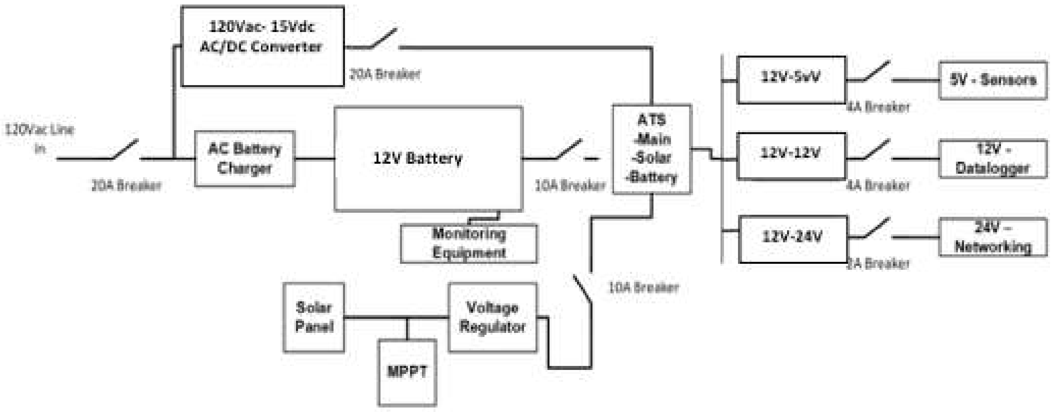

Figure 4.1. General Design of the system

Only one battery of 12 V is used what means that the operation point of the ATS need to change from 24 V to 12 V and the whole output subsystem needs to change with it. The final implementation of the whole system is shown in the picture below.

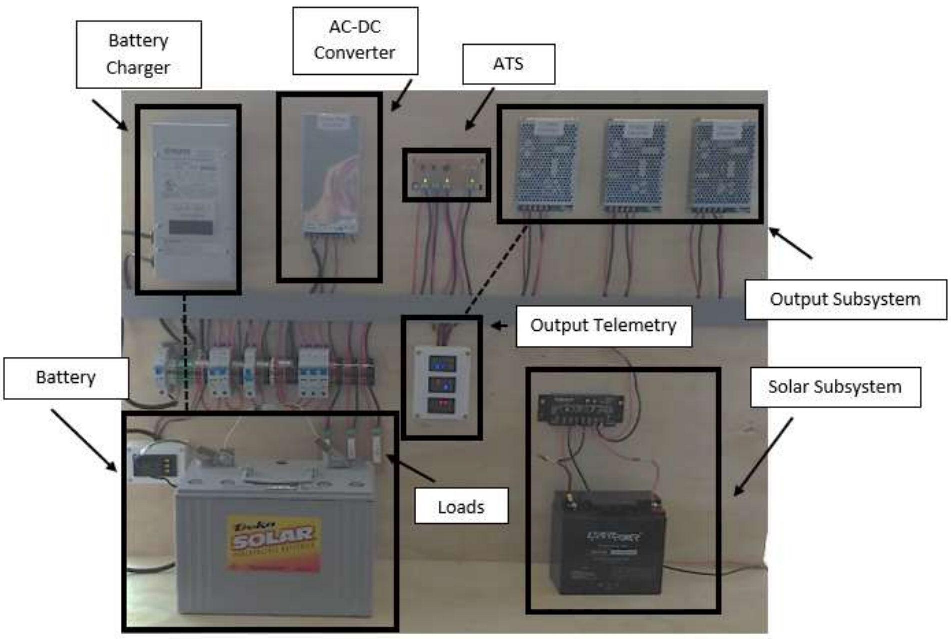

Figure 4.2. System built for the university

Instead of using the data logger and sensors used in the original meteorological tower which are very expensive, three power resistors are implemented in the final design to simulate the power required by the different outputs. The whole system is checked providing a good performance, with the battery of 96 AH selected it is able to provide up to 72 hours , that can be extended to 12 hours more with the battery of the solar panel. In the best scenario, where the sun is providing enough energy to power all the system, the outputs would not require any energy stored in the battery and all of it will be provided by the sun.

This means that the whole system can provide up to 84 hours of backup energy.

4.2. ATS

The ATS is the automatic transfer switch that changes between the sources depending on the input voltage that receive. A priority is selected previously, so if one source runs off the next one in the priority line get ins feeding the sensors.

t is working with the same principles as the original design, the only thing that changes is the input voltages that receive and the output voltage. The PCB design made previously for the wind farm can still be used for the prototype.

4.2.1. Testing

For the testing, prior to build the PCB, the model is tested in the laboratory with a protoboard and sources. Due to the limitation of the laboratory only two sources can be tested at the same time because only two power sources can be connected and there are only two oscilloscope probes. This does not alter the results of the test.

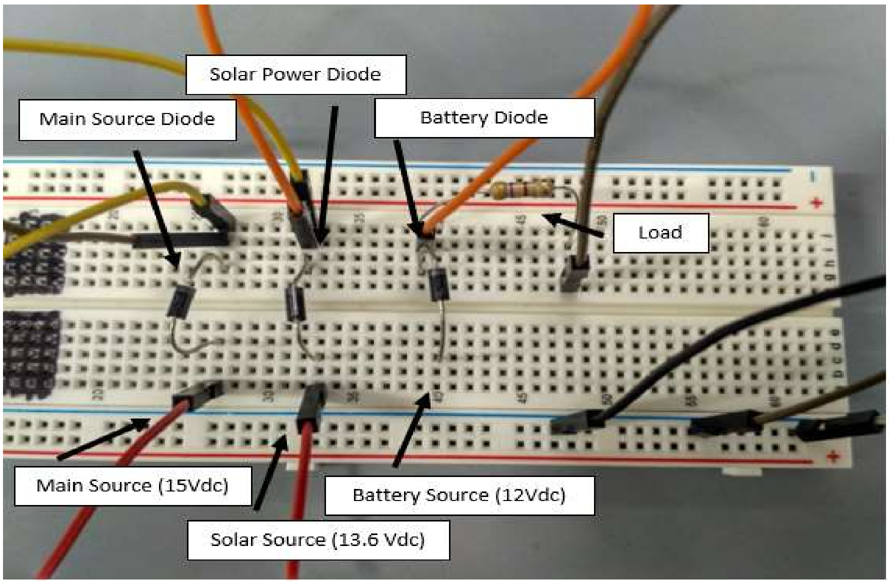

Figure 4.3. Circuit built in lab for first test

For testing the correct performance of the switch, we test the full circuit in the four possible ways that it can operate:

- Full system is working fed by the main source
  The diode connected to the main source is in ON state and the drop of voltage across it is around 0.7V (0.664V). The other diodes are in OFF state and any current is passing through them. The voltage across them is the difference between the main voltage minus the forward voltage of the diode and the different voltage of the source.

$$V_{d1} = V_f \quad [V_f = 0.7V]$$

$$V_{d2,d3} = (V_{Main} - V_f) - V_{source}$$

The forward voltage is a special characteristic of each diode, so it is not exactly 0.7V. The output voltage of the system will be provided by the main source, so the expected output voltage would be defined as:

$$V_{out} = V_{main} - V_f$$

The figures show the measured before each diode during the experiment relatively to ground (the voltage of the source). The first measurements (V1) are the source voltages (V_{main},V_{solar} and V_{bat} respectively).

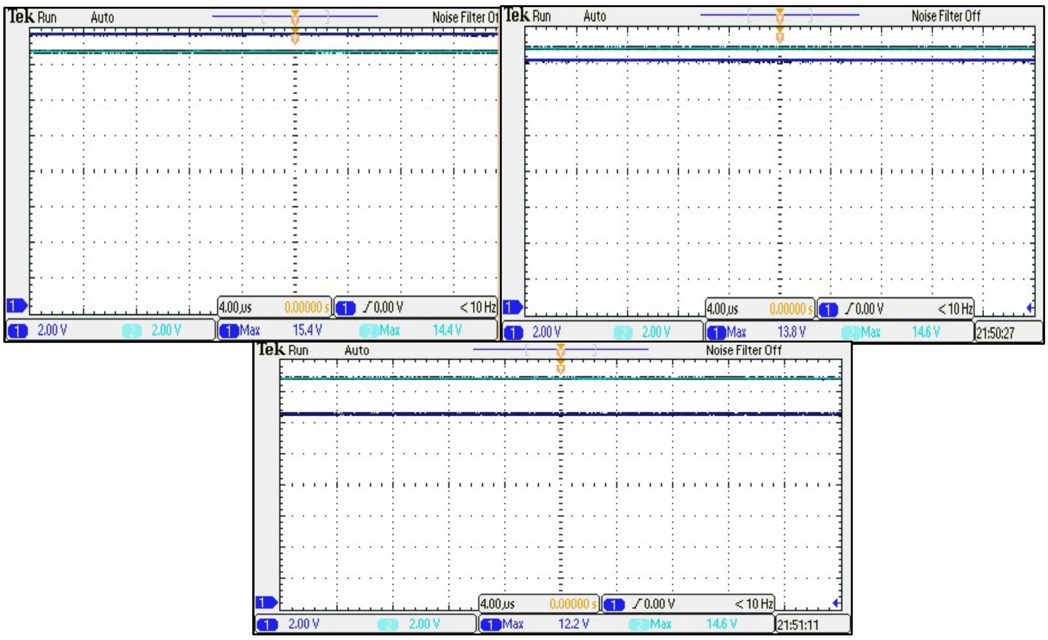

Figure 4.4. Output voltage (light blue) vs. Input voltages (dark blue) (Vmain-Left Top; Vsolar-Right Top; Vbat-Bottom)

The current obtained in this stage is only through the main source and is 0.03A. The diode working on this stage is the first one and the drop of voltage in the diodes is as expected with the previous formulas.

- <u>Main Power off</u>
  If the main power runs off, the system is fed by the solar subsystem. Diodes 1 and 3 are off and diode two turns on. The expected voltages on each diode follows the next equation:

$$V_{d1} = 0 - (V_{solar} - V_f)$$

$$V_{d2} = V_f$$

$$V_{d3} = V_{bat} - (V_{solar} - V_f)$$

The output voltage expected is the difference between the voltage provided by the solar and the forward voltage across the diode according to following equation:

$$V_{out} = (V_{solar} - V_f)$$

In the scopes taken the input voltage of the different source is V1 and the output voltage is V2. In the top figure there is no input voltage, but the output voltage is the voltage of the solar minus the forward voltage across the diode. This output voltage is the same in the three scopes as expected, what means that the diode that is on is the solar and the rest of them are off.

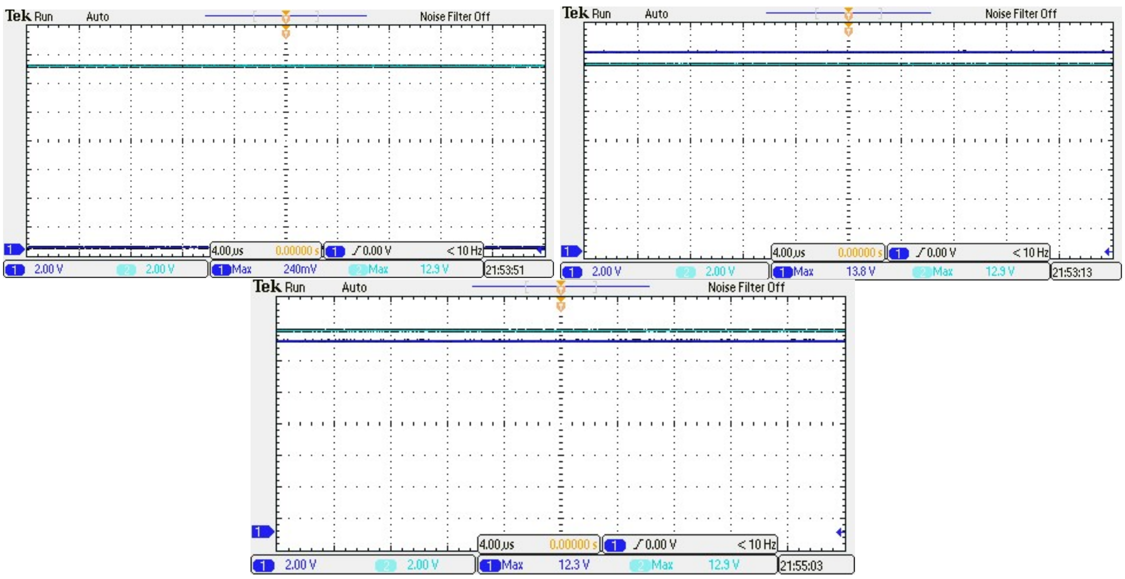

Figure 4.5. Output voltage (light blue) vs. Input voltages (dark blue) (Vmain-Left Top; Vsolar-Right Top; Vbat-Bottom)

During this state the current drawn by the system is 0.026 A. It has decrease because the voltage has decrease but the load remains the same.

- <u>Running on batteries</u>
  When the solar is not reliable anymore the system runs on the main batterie. The diodes 1 and 2 will be in OFF mode while the third diode is ON. The voltage across each diode will follow similar rules like other states:

$$V_{d1,d2} = 0 - (V_{bat} - V_f)$$

$$V_{d3} = V_{bat} - V_f$$

The output voltage should be the difference between the voltage of the battery and the forward voltage of the diode.

$$V_{out} = V_{main} - V_f$$

In the scopes V1 is the source that in the first two cases is cero due that neither the main or the source are providing energy, so al the system is working on the battery power. The current measured is 0.023A.

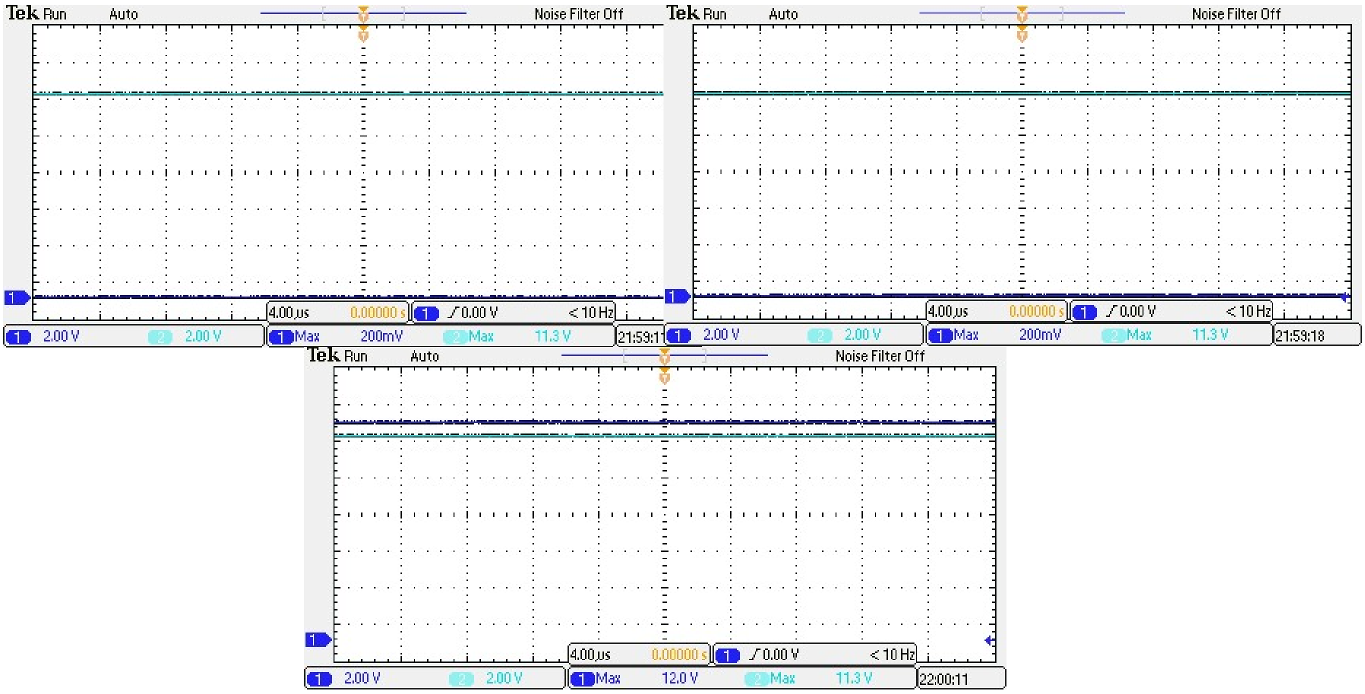

Figure 4.6. Output voltage (light blue) vs. Input voltages (dark blue) (Vmain-Left Top; Vsolar-Right Top; Vbat-Bottom)

Once is checked the performance of the ATS and that the output voltages are as expected the next step is to measure the accuracy of the switch when changing stage by studying the step response of the diode.

The step response of the system is studied for the change between the four different stages of the system, obtaining three different responses.

- <u>Main source turns off</u>

Due to elements that store energy of the voltage source when turning the power off is not possible to obtain a step as it would be preferable. Instead of that a lineal input is obtained. For the study of the real response of the system when the sources turn off this is what is going to be studied.

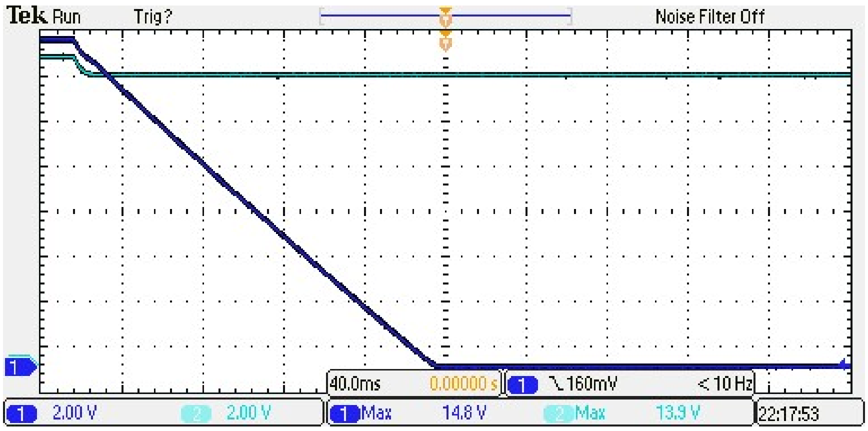

Figure 4.7. Time response of the ATS when the main source turns off

In the picture the voltage 1 is represents when the main source turns off. Instead of a switch, in the lab a power source is being used, so the time of switching is slower (180ms) but the response of the diode is good and fast without any oscillation.

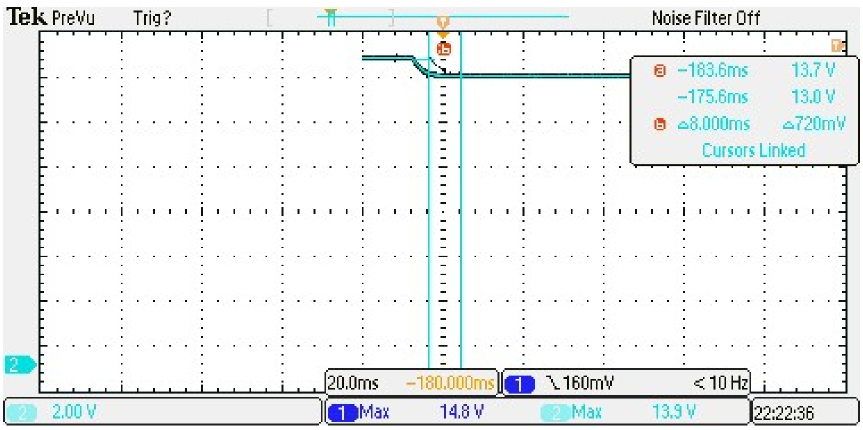

Figure 4.8. Time of switching when the ATS when the main source turns off

With the cursors of the oscilloscope is measured that the time that it takes for the system to change from one output voltage to another is only 8ms. The frequency of data requested from the MET tower is every minute, so it can be assumed that there is not going to be lost data during the change from the main source to the solar system.

- <u>Solar source off</u>

During this second stage the output voltage has to change from 12.6V to 11.9V. Like it happened in the previous transition, the input of the source when switching off is not a step but linear due to the elements inside the power source.

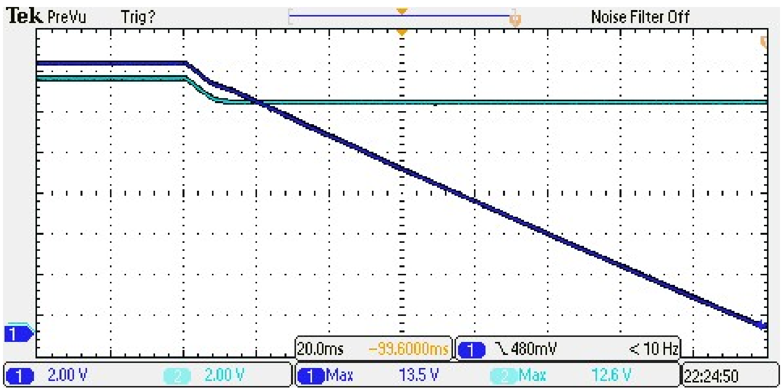

Figure 4.9. Time response of the ATS when the solar source turns off

In the screenshot taken during the second transition the step response of the system respect to the input voltage is good. The output voltage decrease following the input voltage (with a difference of 0.7V) until obtain the input voltage of the battery. From that moment the system stabilizes, and the output voltage is the voltage of the battery minus the forward voltage across the diode. It takes 11.6 ms to finish the transition and, as happened in the previous case, is not considered enough time to lose data so the system is not at risk.

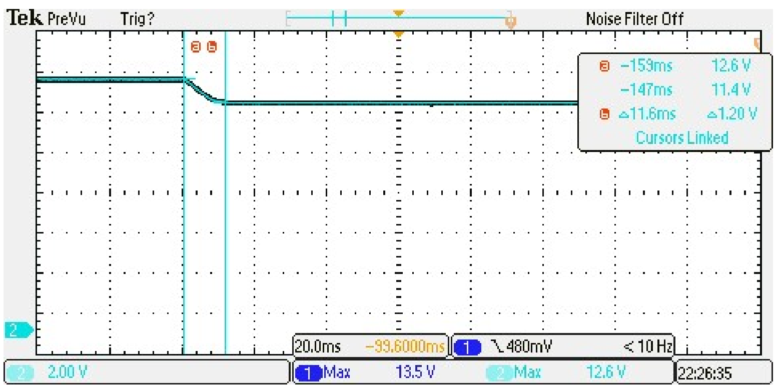

Figure 4.10. Time of switching when the ATS when the solar source turns off

- Battery off

The last transition possible of the system happens when the battery runs out. There is no other input source available (the main source keeps broken and the solar source does not have enough power to provide the system) so the system breaks down producing the lost of data.

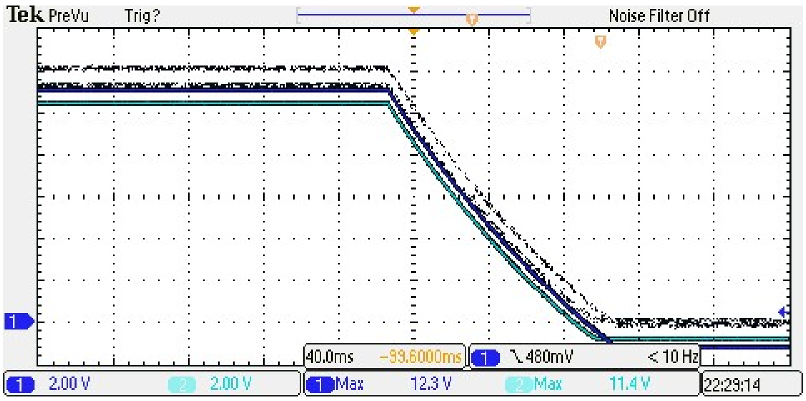

Figure 4.11. Time response of the ATS when the solar source turns off

In the screenshot taken the output voltage follows during all the time the input voltage until it reaches 0. This happens because the voltage in the other sources still 0, so any of the others turns on when need it and the voltage turns 0.

There is a delay of microseconds between the input and voltage but, according to the results obtained, the sensors would stop sending data from the moment the third redundancy turns off. The time that is takes to turns off is 0.111s, but this is higher only due to the linear decreasing input of the source.

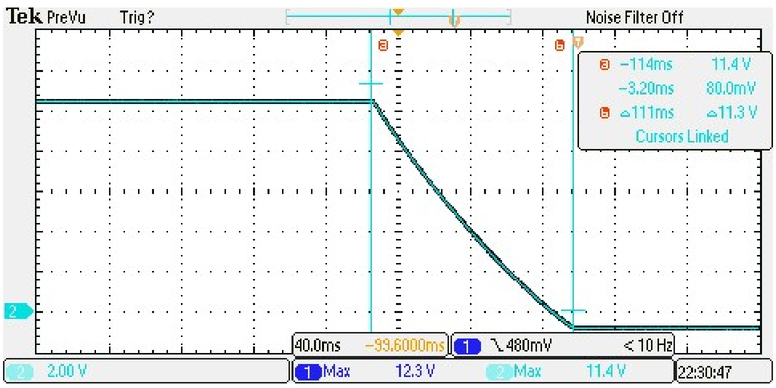

Figure 4.12. Time of switching when the ATS when the battery turns off

4.2.2. Performance

Once the ATS was tested in the lab and the results obtained were as expected, the next step what to build the ATS to incorporate it to the system. Using the design of point 3.2.3. made with Eagle, the PCB was made in the laboratories of the university. Some caution had to be taken in advance.

- The current of the system was expected high (around 2 A) so all the layers had to we wide enough to support the current.
- All the component of the ATS (diode and headers) are more expensive than usual due to the high currents they need to support.

Finally, the ATS implemented in the design is shown in the picture below.

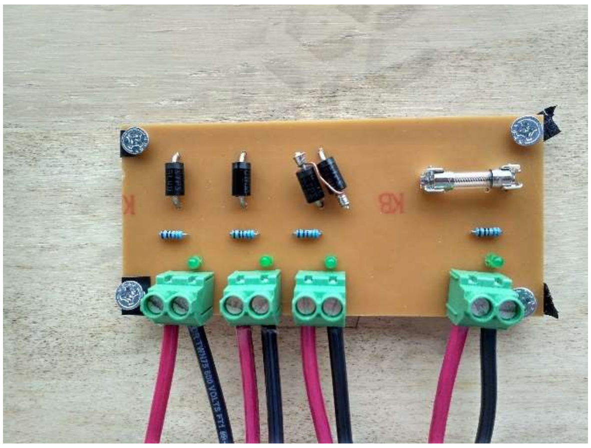

Figure 4.13. ATS built for the university demonstration

Due to the similar voltage obtained between the battery of the solar system and the main battery another diode is added in the third redundancy to assure the priority of the sources.

Condition	V_{D1}	V_{D2}	V_{D3}
All Sources On	0.228V	2.046V	1.401V
Main Source Off	0V	0.365V	0.444V
Main and Solar Off	0V	0V	0.296V

Table 4.1. Voltage across the diodes depending on the state

It is important to notice that, in the ideal case, there is no need of two diodes in the third redundancy because the difference of voltage is high enough to assure priority. In the other hand, when testing the performance of the full system in the real world the output voltage og the main battery was in a range between 13.7 and 13.3 and the one of the solar battery between 13.3 and 12.9. This range is not separated enough to consider that there is no risk with one diode so another diode is used for prevention.

The measurements taken are shown in the next table. It follows the behavior from equation in (4.4.3). The voltage showed are measured across each diode for each state (positive in the cathode and negative in the anode).

Note: Once the switches are turned off there is not ground in that source, what means that the voltage across the diode is 0 because is not connected to ground, so the voltage cannot be negative.

4.3. Buck and boost converter

After the ATS is built and tested that its performance is correct, the next step is building the complete system and connect the outputs.

BP requires three different outputs: 24, 12 and 5 Vdc. With only one input voltage of 12 V provided by the battery. Three different devices are needed to assure the outputs: buck converter to decrease the voltage from 12 to 5 V, a boost converter to increase the voltage from 12 V to 24 V and a regulator to maintain a constant output of 12 V independently of the output voltage provided by the ATS.

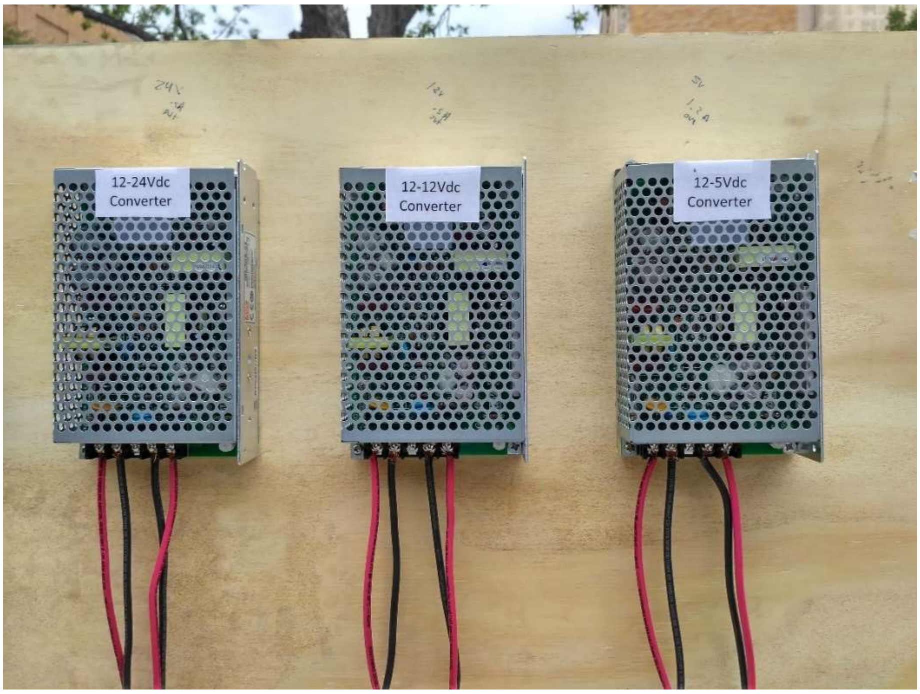

Figure 4.14. Output subsystem for the university demonstration. From left to right (Boost converter, regulator and buck converter)

In the picture are shown the three converters selected to connect the different outputs (Datasheet of them is attached in the appendix). Once the ATS is checked and all the measurements give values as expected the next step is to test the performance of the complete system and its reliability. For doing so, there is a telemetry installed in the circuit that will display the voltage and current.

To simulate the load three resistors are selected according to the approximate value that the different devices (sensor, datalogger and networking) need. The picture below shows the power resistors used od 50Ω for the output of the boost converter, 15Ω for the output of the regulator and 5Ω for the output of the buck converter.

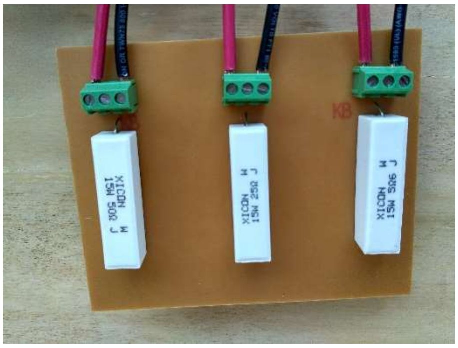

Figure 4.15. Telemetry and loads used in the university demonstration

To prevent having free wires a PCB is designed and made with esthetical purpose but is only used for connecting the power resistors. In the table are shown the requirements of each ideal output. The power dissipated in each resistor is less than the maximum power allowed for them, so they are on the correct range.

Voltage Output	Resistor	Power dissipated (W)	Maximum Power Allowed (W)
24	50	11.52	15
12	25	5.76	15
5	5	5	15

Table 4.2. Power dissipated in each power resistor

The last step is measure the correct performance of the system. Thanks to the telemetry installed for each output is possible to measure and visualize easily the voltage and current across each resistor constantly. The table obtained shows the values measured.

Output Voltage	Resistor	Output Current (Expected)	Output Current (Measured)	Output Power (Expected)	Output Power (Measured)
24	50	0.48	0.48	11.52	11.52
12	25	0.48	0.49	5.76	5.88
5	5	1	0.98	5	4.9

Table 4.3. Output power consumed by the system

Table 5 shows the different voltages measured and expected. Due to the tolerance of each resistor the current can differ a little from expected but the performance of the circuit was as expected.

5. Cost considerations

In this part is going to be explained the cost considerations and the budget expected and used. This section is divided in two distinct parts: in the first one is explained the cost of the ATS that is the same for the BP design and the prototype built, and in the second part the output subsystem that is different between the two different designs.

5.1. ATS

The cost consideration for the output subsystem of the design is shown in the table below.

AUTOMATIC TRANSFER SWITCH					
COMPONENT	**REFERENCE**	**DESCRIPTION**	**QUANTITY**	**PRICE/UNIT**	**TOTAL PRICE**
Diode	1N5400	Rectificator Diode 3A/50V	3	0.13	0.39
Led	L-53GD	Diode Led Green, 5 mm, 5-32mcd	4	0.14	0.55
Resistor	2W-680R	Resistor: metal oxide; THT; 680Ω; 2W; ±5%; Ø5x12mm; Sal: axiales	4	0.08	0.30
Terminal Block	DG128-5.0-02P14	CB terminal block; angled; 5mm; ways:2; on PCBs; 2.5mm2; 24÷12AWG	4	0.19	0.76
Fuse	FUSE 0.001.2510	Fuse: fuse; time-lag; ceramic; 4A; 250VAC; 5x20mm; SPT	1	0.24	0.24
				TOTAL($)	**2.25**

Table 5.1. BOM of the ATS

The simplicity of the PCB design makes the ATS a cheap and efficient solution for the design. It can also be used for both systems, independently of the input voltages that are used, what makes it a versatile option compared to other automatic switching system more complex. To this cost of material should be added the working time for the ATS.

Name	**Hourly Rate**	**Total Hours Invested**	**Total Labor**
Ismael Martin Martin	35	15	525

Table 5.2. Working expenses for building ATS

Given a total price for the ATS of

Section	**Total ($)**
Components	2.25
Labor	525
Grand Total	527.25

Table 5.3. Total price for building the ATS

5.2. Output subsystem design

For the output subsystem there are two different cases: the first design is used to be implemented in the BP windfarm and the second is the components used in the prototype built for the simulation.

5.2.1. Design For BP

In the first design, the output system consists in one input and three output design that should output 24, 12 and 5 V precisely with a 24 Vdc input. In the table below is detailed the list of materials used for the design:

OUTPUT SUBSYSTEM					
COMPONENT	**REFERENCE**	**DESCRIPTION**	**QUANTITY**	**PRICE/UNIT**	**TOTAL PRICE**
Mosfet	STP160N3LL	MOSFET N-channel 30 V, 0.0024 Ohm typ., 160 A, STripFET(TM) VII DeepGATE(TM) Power MOSFET in a TO-220 package	4	1.14	4.56
Mos. Driver	IRS2183PBF	Gate Drivers HALF BRDG DRVR 600V 10 to 20V 1.4A	2	3.19	6.38
Inductor	HCTI-330-5.2	Fixed Inductors HIGH CURR TOROIDAL INDUCTOR 330 UH	2	2.31	4.62
Capacitor (1mF)	EEU-FS1H102L	Aluminum Electrolytic Capacitors - Leaded 50VDC 1000uF 10000H 12.5x35mm	2	1.66	3.32
Microcontroller Launchpad	TM4C123	Texas Instrumentn Microcontroller Launchpad	1	13.95	13.95
Terminal Block	DG128-5.0-02P14	CB terminal block; angled; 5mm; ways:2; on PCBs; 2.5mm2; 24÷12AWG	4	0.19	0.76
Regulator	LM350T	3A Adjustable regulator	1	3.12	3.12
Capacitor (1uF)	CY1P-1U	Condensador: cerámico; X1,Y1; 1uF; Y5P; ±10%; THT; 10mm; Ø:7mm	6	0.16	0.93
Operational Amplifier	INA122P	Amplificador operativo; 120kHz; 2,2÷36V; Canales:1; DIP8	1	6.62	6.62
Resistor	2W-1R	Resistor: metal oxide; THT; 1Ω; 2W; ±5%; Ø5x12mm; Sal: axiales	2	0.08	0.15
Resistor	2W-100R	Resistor: metal oxide; THT; 100Ω; 2W; ±5%; Ø5x12mm; Sal: axiales	2	0.08	0.15

Resistor	2W-1K	Resistor: metal oxide; THT; 1K; 2W; ±5%; Ø5x12mm; Sal: axiales	5	0.08	0.38
Resistor	2W-8K3	Resistor: metal oxide; THT; 8K3; 2W; ±5%; Ø5x12mm; Sal: axiales	1	0.08	0.08
Diode	1N5400	Rectificator Diode 3A/50V	2	0.13	0.26
				TOTAL ($)	**45.29**

Table 5.4. BOM of the output subsystem designed for BP

The total cost of the materials is $45.29. Like in the previous case, this is not the final cost of the project of the output subsystem part. There is an extra cost applied to the hours of work detailed in next table. In this hours are included the researching time for solution, the simulation, optimization values and search of components and the design on schematic and PCB.

Name	**Hourly Rate**	**Total Hours Invested**	**Total Labor**
Ismael Martin Martin	35	100	**3500**

Table 5.5. Working expenses for building the output subsystem designed for BP

This should give a total cost of the project of:

Section	**Total ($)**
Components	45.29
Labor	3500
Grand Total	**3545.29**

Table 5.6. Total price for building the output subsystem designed for BP

The final price estimated with the price of components and the total payment for the hours of labor of the project is $5295.29.

5.2.2. Design for UT

The second design made is a simpler design to built in the University. Due to the budget limitation affording another battery to provide 24 Vdc is not possible. This means that the whole system is redesigned to be implemented in a prototype that instead of providing 24 Vdc provides 12 Vdc as the input for the output subsystem and the same three outputs that in the previous case.

Three different converters are selected to provide the voltages. They are bought and mounted. The table below shows the total price paid for the components.

OUTPUT SUBSYTEM					
COMPONENT	**REFERENCE**	**DESCRIPTION**	**QUANTITY**	**PRICE/UNIT**	**TOTAL PRICE**
Boost Converter 12V-24V	SD-50B-24	Isolated DC/DC Converters 50.4W 24V 2.1A Input 19-36VDC	1	31.09	31.09
Regulator 12V-12V	SD-50B-12	Convertidores CC/CC aislados 50.4W 12V 4.2A Input 19-36VDC	1	31.09	31.09
Buck Converter 12V-5V	SD-50B-5	Isolated DC/DC Converters 50W 5V 10A Input 19-36VDC	1	28.79	28.79
				TOTAL ($)	**90.97**

Table 5.7. BOM of the output subsystem designed for university demonstration

In this case the hours of labor used for this design are less because there is no need to design the interior of any converter, only to search for the components that provides the best performance and fit the requirements of the system. The table below shows the total cost implemented of this part of the project.

Name	Hourly Rate	Total Hours Invested	Total Labor
Ismael Martin Martin	35	15	525

Table 5.8. Working expenses for building the output subsystem built for university demonstration

Inside this hours are included: searching for component, order of components, built of the output subsystem and test of performance.

When including the final design for the project built in the UT.

Section	Total ($)
Components	45.29
Labor	525
Grand Total	**570.29**

Table 5.9. Total price for building the output subsystem built for university demonstration

5.3. Final cost analysis and considerations

In this part is explained the differences between the whole output system (ATS and converters) and provide a final estimation cost for the whole project:

Part	Cost BP	Cost UT
ATS	527.25	527.25
Output Subsystem	5295.29	570.29
Total	**5822.54**	**1097.54**

Table 5.10. Total expenses for this project for BP or UT

6. Conclusion

This project can be divided in two different parts: the design made for the original MET tower for BP and the design made for building as a prototype in the UT. Both them can be devided again in two parts: the ATS (same design for the two different models) and the output subsystem that changes depending on the input voltage. The average input voltage for the prototype built for UT is 12V whether for the original system of BP in the windfarm in Dallas is 24 V (two batteries connected in series).

The automatic transfer switch (ATS) changes between the different input sources depending on the voltage that they supply. A priority is selected depending on the output voltage provided by each source, first by the main source, then the solar source and finally the battery bank.

The switching is made by using diodes and depending on the input voltage of each source it will turn on and off the diode. The simplicity and the good time-response of the system gives makes this mechanism a good option for both designs.

The switch is designed, simulated, tested a prototype in the laboratory and finally designed in a PCB. It works as expected providing a good performance with a enough fast response to assure that any data is lost during the switching.

For the output susbsytem, as mentiones before, two different designs are made. Th

For the original design of BP, where the output voltage of the ATS is 24 V due to batteries connected in series, after different simulations the design that provides a best performance and a higher efficiency for the output subsystem is two synchronous buck converters in cascade that decreases the voltage from 24 to 12 Vdc and from 12 to 5 Vdc. It is used a synchronous system controlled with a microcontroller that receives a feedback and changes the duty cycle automatically depending on the output voltage to assure a constant output.

For the prototype made for the university the configuration changes due to that the average output voltage of the ATS is 12V. Due to BP requirements, three output are needed so this voltage needs to be increased to 24 V, regulated to 12 V and decreased with a buck converter to 5V.

The system is designed according to the requirements of BP based on the power needed.

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8. Appendix

8.1. Appendix A: Simulation Code Buck Converter

- Simulation code for normal buck converter

```
%%  SIMULATION FOR BUCK CONVERTER

clc
clear

%Parameters
Vdc=12;
R=10; %Ohm
L=500e-3;
C=1.25e-6;
f=100e3;
D=70;
T=1/f;
```

- Simulation for buck converter in cascade vs. parallel configurations

```
%% BUCK CONVERTER (CASE 1)
%% Simulation In Parallel

clc
clear

%Parameters
Vdc=24;
R=10; %Ohm
L=500e-6;
C=15e-6;
f=100e3;
D12=52.25; %percentege of the periodÇ
D5=45
T=1/f;
%% Simulation In Cascade and Mix

clc
clear

%Parameters
Vdc=24;
R12=10; %Ohm
R5=5;
L=500e-6;
C=1.25e-6;
f=100e3;
D12=52.25; %percentege of the period
D5=45.72;
T=1/f;
```

8.2. Appendix B: Simulation Code Boost Converter

```
%% BUCK CONVERTER

clc
clear

%Parameters
Vdc=12;
R=25; %Ohm
L=300e-6;
C=100e-6;
f=100e3;
D=52.5; % EN PORCENTAJE
T=1/f;
```

8.3. Appendix C: Optimization Code

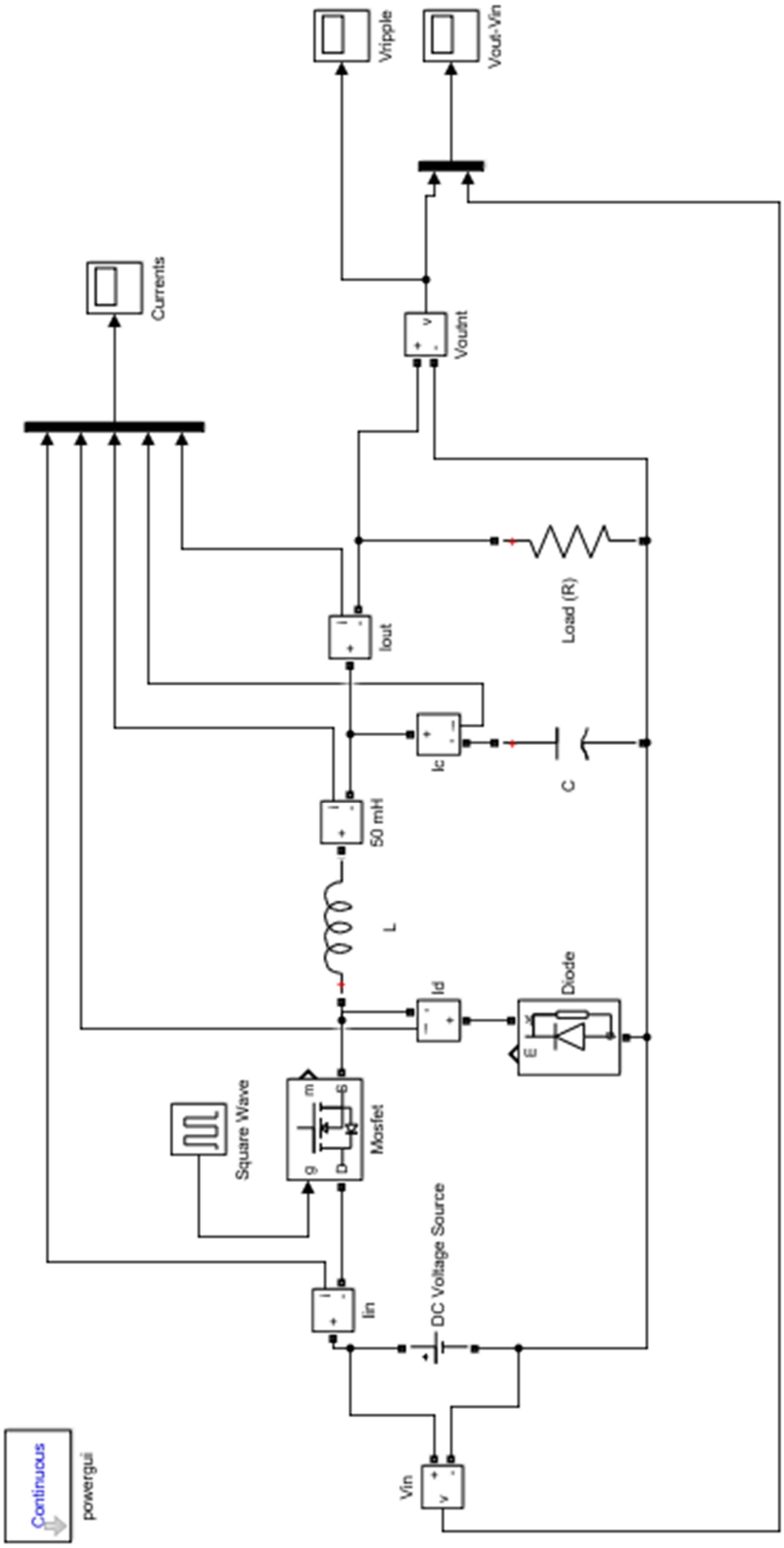
```
%% PROJECT OPTIMIZATION
% Minimization of the losses in two synchronus buck converter in cascade

clc
clear
format long

%Declaration of constants
Vo12 = 12;
Vo5 = 5;
R12 = 10;
R5 = 10;
Rd = 3.2*10^-3;


%Declaration of variables
% x(1) = L5
% x(2) = L12
% x(3) = D5
% x(4) = D12
% x(5) = f5
% x(6) = f12

%Starting guess
x0 = [100*10^-6,100*10^-6,0.5,0.5,100*10^3,100*10^3];

%Optimization
options = optimoptions(@fmincon,'Algorithm','sqp');
[x,fval,exitflag,output] = fmincon(@objfun,x0,[],[],[],[],[],[],...
   @confuneq,options)
output.iterations
```

```
function f = objfun(x)

% Declaration of Constants
Vo12 = 12;
Vo5 = 5;
R12 = 10;
R5 = 10;
Rd = 3.2*10^-3;


% Objective Function
f =
(Vo12+Rd*sqrt(x(4)*(Vo12^2/R12)))*sqrt((Vo12/R12)^2+((Vo12+Rd*sqrt(x(4)*(Vo12
^2/R12)))*x(4)/x(2)/x(6))^2/12)+...

(Vo5+Rd*sqrt(x(3)*(Vo12^2/R12)))*sqrt((Vo5/R5)^2+((Vo5+Rd*sqrt(x(3)*(Vo12^2/R
12)))*x(3)/x(1)/x(5))^2/12)+...

Rd*((Vo12/R12)^2+((Vo12+Rd*sqrt(x(4)*(Vo12^2/R12)))*x(4)/x(6)/x(2))^2/12+...
    (Vo5/R5)^2+((Vo5+Rd*sqrt(x(3)*(Vo12^2/R12)))*x(3)/x(1)/x(5))^2/12);
```

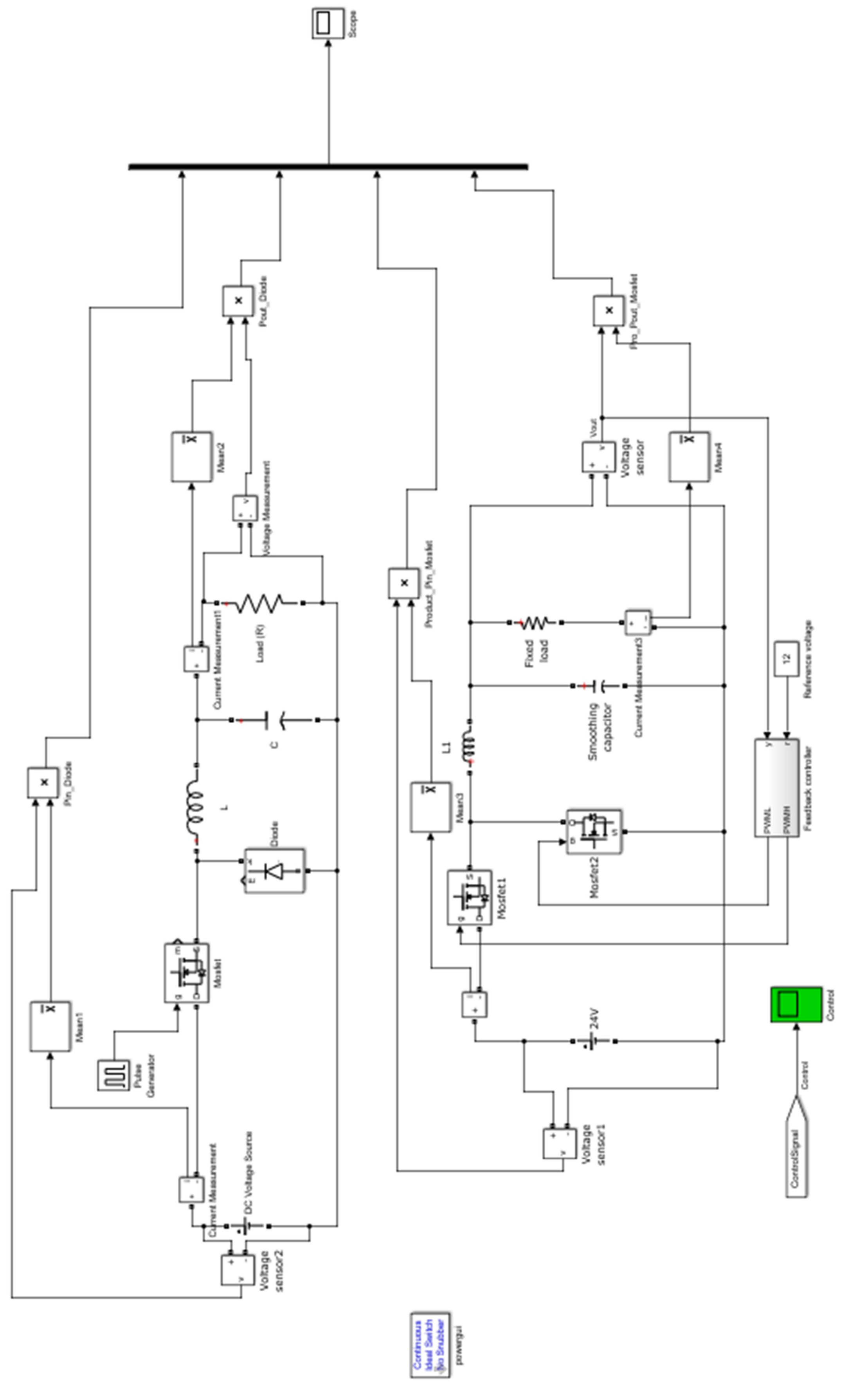
```
function [c,ceq]=confuneq(x)

%Declaration of variables
Vo12 = 12;
Vo5 = 5;
R12 = 10;
R5 = 10;
Rd = 3.2*10^-3;

% Equality constrain matrix
ceq = [Vo12-x(4)*(24-Rd*sqrt(x(4)*(Vo12^2/R12))),
     Vo5-x(3)*(12-Rd*sqrt(x(3)*(Vo5^2/R5)))];

% Inequality constrain matrix
c = [100*10^-9-x(1);
     x(1)-0.05;
     100*10^-9-x(2);
     x(2)-0.05;
     x(3)-1;
     -x(3);
     x(4)-1;
     -x(4);
     x(5)-500*10^3;
     -x(5);
     x(6)-500*10^3;
     -x(6)];
```

8.4. Appendix D: Simulink Diagrams

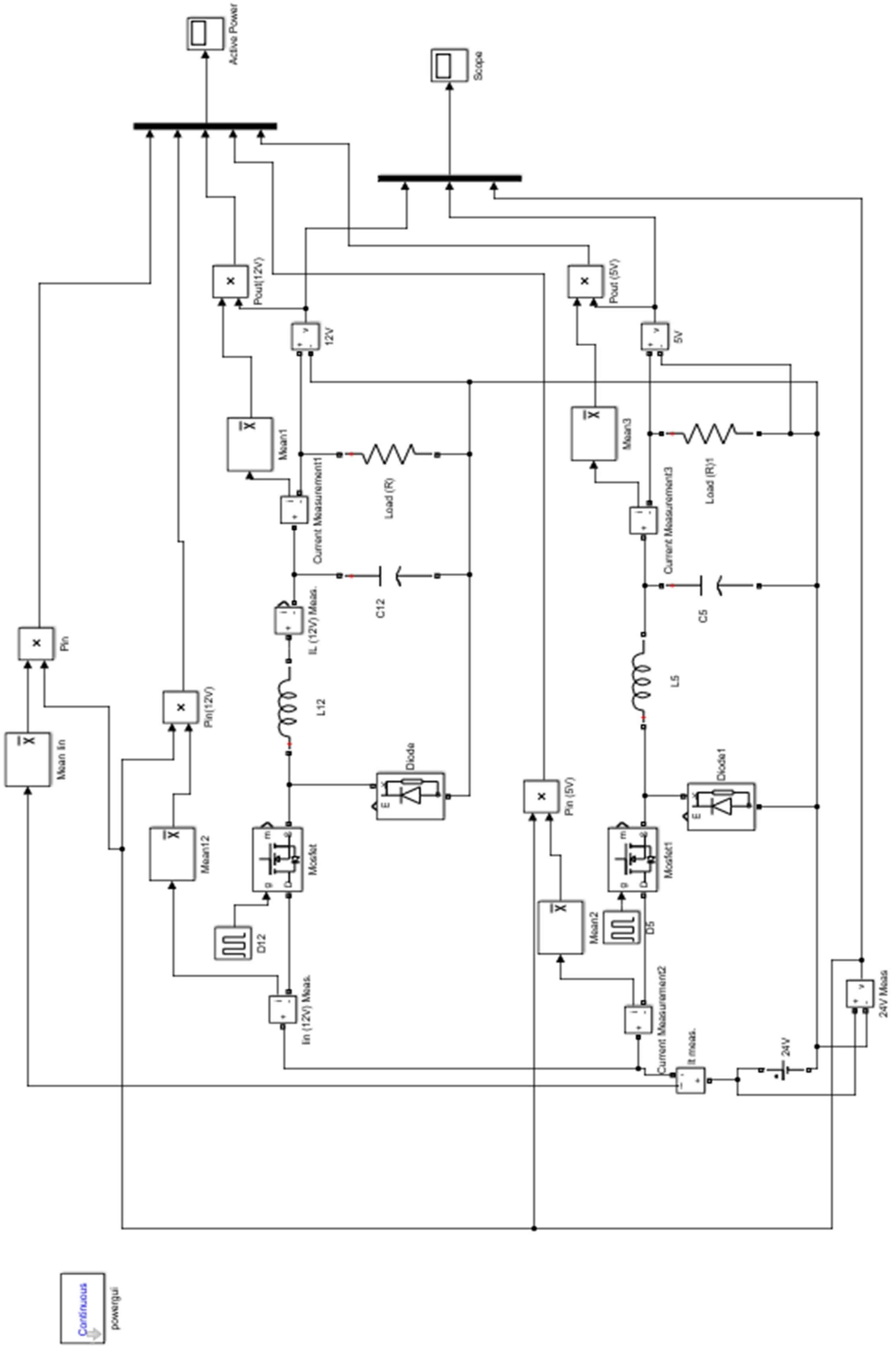
- Normal buck converter configuration



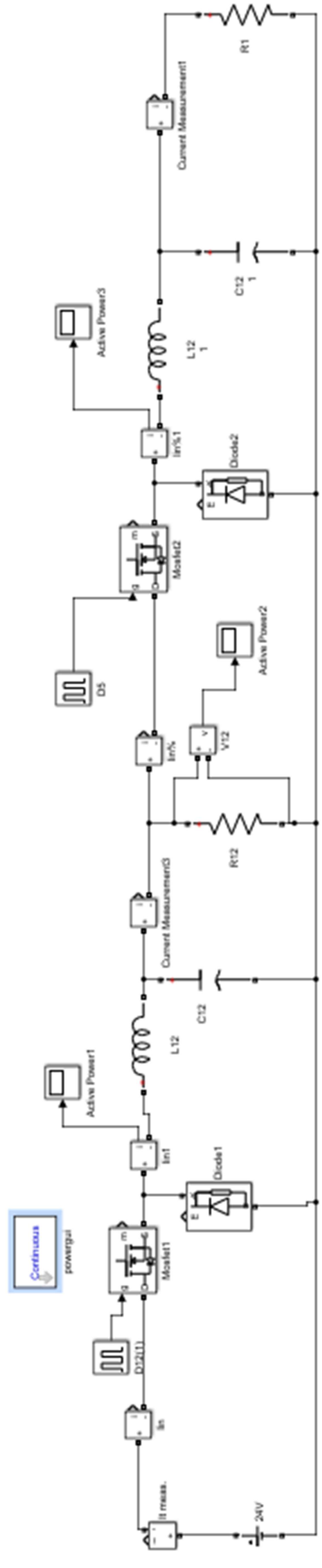
- Asynchronous vs. Synchronous configuration



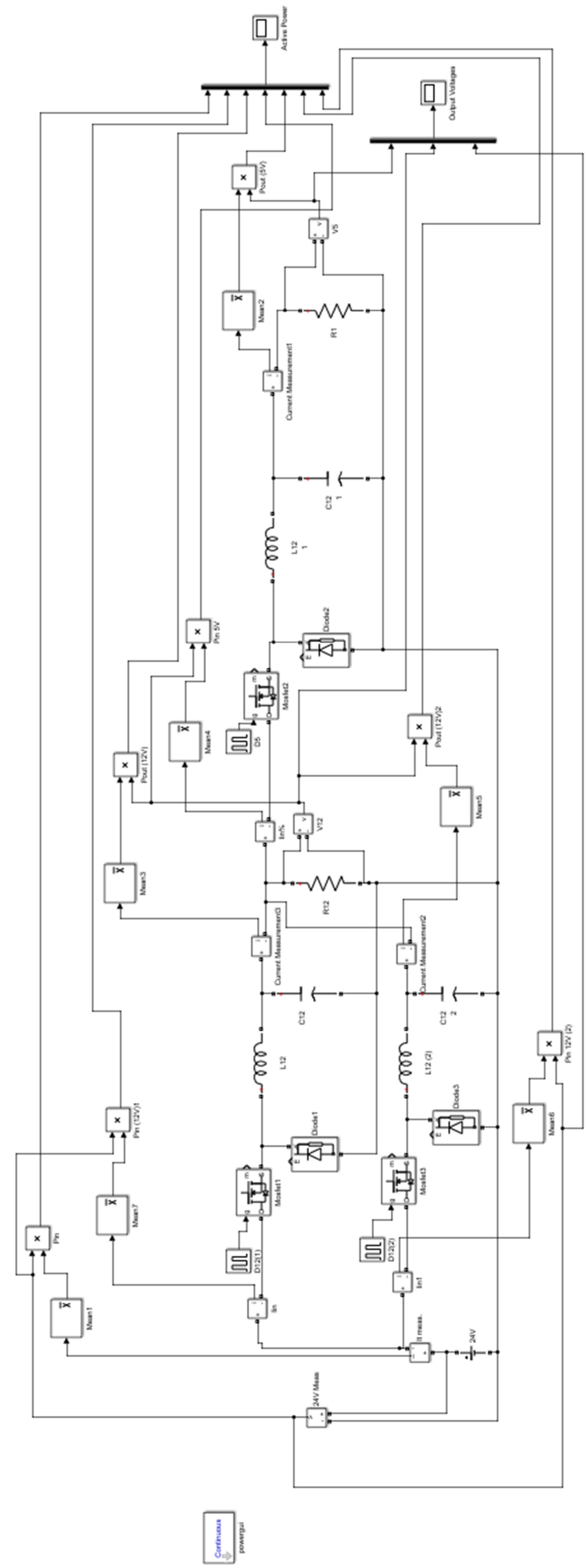
- Parallel Configuration



- Cascade Configuration



- Parallel vs. Configuration



- Simulation of the ATS