NEWTON Deliverable D3.3

Preliminary design report for the power distribution block

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Abstract: This document reports the preliminary design of the Power Distribution Unit (PDU) of the NEWTON instrument. The PDU supplies energy to the Control Unit (CU) and the Sensor Unit (SU) and it is composed by two different blocks, the power module and the AC current source. The power module consists of a DC/DC converter that receives the primary power from the rover and generates the secondary lines that supply the CU and the SU. The AC current source module generates the current to drive the primary winding of the sensor unit. The document includes the preliminary design of the two blocks as well as preliminary validation results.

Keyword list: Planetary Science missions, magnetometry, complex susceptibility, multi-sensor system, Mars, the Moon, power supply, DC/DC converter, Flyback, Full-Bridge, Half-Bridge, Buck, GaN.

Executive Summary

This NEWTON WP3 deliverable D3.3 entitled "Preliminary design report for the power distribution block" describes the preliminary design of the power distribution unit developed for the three prototypes of NEWTON instrument.

With the aim of maximizing the impact of novel NEWTON technology, different prototypes will be developed within the project. Two prototypes (named prototype 1 and 3) will be developed for planetary application, while a slightly (reduced) adapted version of prototype 1 (named prototype 2) will be developed in order to demonstrate the spin-off of the technology between space and non-space fields. The three prototypes share the same architecture while they provide different performance capabilities adapted to different scenarios. The key building blocks of the three prototypes are the same, i.e. Power Distribution Unit (PDU), the Control Unit (CU) and the Sensor Unit (SU).

With regard to the PDU, it supplies the electronic Control Unit and the Sensor Unit and it is composed by two different blocks, the power module and the AC current source. The power module is a DC/DC converter which generates the secondary voltages to supply the control unit and the sensor unit respectively. The AC current source drive the primary winding of the susceptometer. This deliverable describes the preliminary design and stand-alone validation of the PDU for the three prototypes.

This document is structured in different sections. Section 2 reports the architecture of the three prototypes developed within the NEWTON project as well as it describes the main differences between them. Section 3 describes the preliminary design of the PDU for the three prototypes of the NEWTON instrument, while Section 4 reports the proof-of-concept of the preliminary designs. Section 5 gives an overview of the main outcomes obtained from this preliminary design stage as well as it describes the actions planned for the next stage of the project. During this following phase, the final design of the NEWTON instrument will be developed and reported in the next WP3 deliverables which are planned to be delivered in April 2018. Finally, Section 6 presents a summary of the content included in this document as well as the main conclusions obtained from it, and Section 7 provides the referenced bibliography.

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Abbreviations

AC	Alternating Current
ADC	Analog to Digital Converter
B	Magnetic Induction
C	Capacitor
CCM	Continuous Conduction Mode
COTS	Commercial off the shelf
CPU	Central Processing Unit
CU	Control Unit
D	Deliverable
DC	Direct Current
DCM	Discontinuous Conduction Mode
DSC	Digital Signal Controller
DSP	Digital Signal Processor
EDL	Entry, Descend and Landing
E-HEMT	Enhancement mode – High Electron Mobility Transistor
EM	Engineering Model
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EPC	Electronic Power Converters
EU	European Union
FM	Flight Model
GPIO	General-Purpose Input/Output
INTA	Instituto Nacional Técnica Aeroespacial
IRM	Isothermal Remanent Magnetization
L	Inductance
MCU	Main Control Unit
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NASA	National Aeronautics and Space Administration
NRM	Natural Remanent Magnetization
PCB	Printed Circuit Board
PDU	Power Distribution Unit
PFC	Power Factor Correction
PSU	Power Supply Unit
PWM	Pulse Width Modulation
R	Resistance
RDC	Resistor Capacitor Diode
RHPZ	Right Half Plane Zero
RMS	Root Mean Square
SMPS	Switch Model Power Supply
SPI	Serial Peripheral Interface
SU	Sensor Unit
TBD	To Be Determined
TRL	Technology Readiness Level
TTI	Tecnologías de Telecomunicaciones e Información
UART	Universal Asynchronous Receiver-Transmitter
UPM	Universidad Politécnica Madrid
UT	University of Trier

WP	Work Package

1. INTRODUCTION

Magnetic characterization is essential to know the past and present of planetary objects. To make magnetic prospections in-situ requires a magnetic susceptometer (its real:χ' and imaginary:χ''parts) to determine the magnetic structure recorded during the formation of the studied rocks. The previous measures with vector magnetometers to know the total magnetic field (B) and its components (Bx, By, Bz), complete a total study of the planetary exploration.

NEWTON project develops a new portable and compact multi-sensor instrument for ground breaking high resolution magnetic characterisation of planetary surfaces and sub-surfaces through the combination of complex susceptibility and vector measurements. The new instrument includes magnetometer, portable susceptometer, power supply system immune to radiation and a frequency generation system. The goal of the NEWTON project is to achieve a demonstration prototype in a relevant environment (TRL6) in order to make the multi-sensor instrument suitable for boarding in a planetary exploration rover in the short term.

With the aim of maximizing the impact of novel **NEWTON** technology, different prototypes will be developed. Two prototypes (named prototype 1 and 3) will be developed for planetary application, while a slightly (reduced) adapted version of prototype 1 (named prototype 2) will be developed in order to demonstrate the spin-off of the technology between space and non-space fields. This will allow the consortium to simultaneously investigate 1) ground breaking potential for the measurements of parameters of main importance in planetary magnetism with implications to the geological history of the planets by introducing susceptometer technology and new technologies that are immune to radiation in the designs and 2) integrate and explore synergies to industrial spin-off.

The three prototypes share the same architecture while they provide different performance capabilities adapted to different scenarios. The key building blocks of the three prototypes are the same, i.e. Power Distribution Unit (PDU), the Control Unit (CU) and the Sensor Unit (SU). This deliverable describes the preliminary design of the PDU for the three prototypes.

2. ARQUITECTURE OF THE NEWTON INSTRUMENT

In this section, the main features of the architecture of the different prototypes are described highlighting the fundamental differences between them. As already mentioned, NEWTON project is developing three different prototypes for different applications and scenarios, with the aim of maximizing the impact of novel NEWTON technology. The main features of these prototypes are:

- **Prototype 1:** This prototype is designed for planetary exploration missions with the particular case of Martian and Moon's system with an envelope adapted to a rover-mounted payload. This prototype performs in-situ measurements of the susceptibility in a planetary environment combined with vector Natural Remanent Magnetization (NRM) data. This prototype will work in a sweep of continuous frequencies within the range from 1 kHz up to 100 kHz.

- **Prototype 2:** This prototype is a reduced version of prototype 1 implemented on a hand-held device for a rapid and preliminary analysis of surface during prospections on Earth. This prototype performs in-situ measurements of the susceptibility at discrete frequencies. It will be employed to potentiate the impact of NEWTON technology not only in space sector, but also on Earth for civil engineering applications.

- **Prototype 3:** This prototype is an advanced system for the in-situ analysis and full magnetic characterization of drilled samples in the medium term missions with more powerful rovers or to be part of base stations with the particular case of Martian and Moon's systems. This prototype performs in-situ measurement of the susceptibility, demagnetization and isothermal remanent magnetization (IRM) acquisition experiments.

As previously mentioned, the three prototypes share the same architecture while they provide different performance capabilities adapted to different scenarios. The key building blocks of the three prototypes are the same, i.e. Power Distribution Unit (PDU), the Electronic Control Unit (CU) and the Sensor Unit (SU). The SU is at the same time divided in the sensor head, which includes magnetometer and susceptometer, and the proximity electronics.

This document reports the preliminary design of the Power Distribution Unit (in case of Prototype 1 and 2 it also includes an amplifier located in the SU). D3.1 [1] describes the preliminary design and optimization process of the magnetic head including susceptometer head and magnetometer, while D3.2 [2] reports the preliminary design of the Control Unit, and it also includes information about the design of the electronics included in the SU. FIGURE 2 and FIGURE 3 show the architecture of the different prototypes and the corresponding documents where their building blocks are included.

The preliminary architecture of the three prototypes was initially defined and included in the NEWTON deliverable D2.1 [3]. Now, as part of the activities developed within WP3, the architecture has been updated and re-defined. D3.1 [1] includes a detailed description of the architecture of NEWTON prototype 1, prototype 2 and prototype 3 while it also reports the main difference among prototypes. It is recommended to the reader go through section 2 of D3.1 before continuing reading this document.

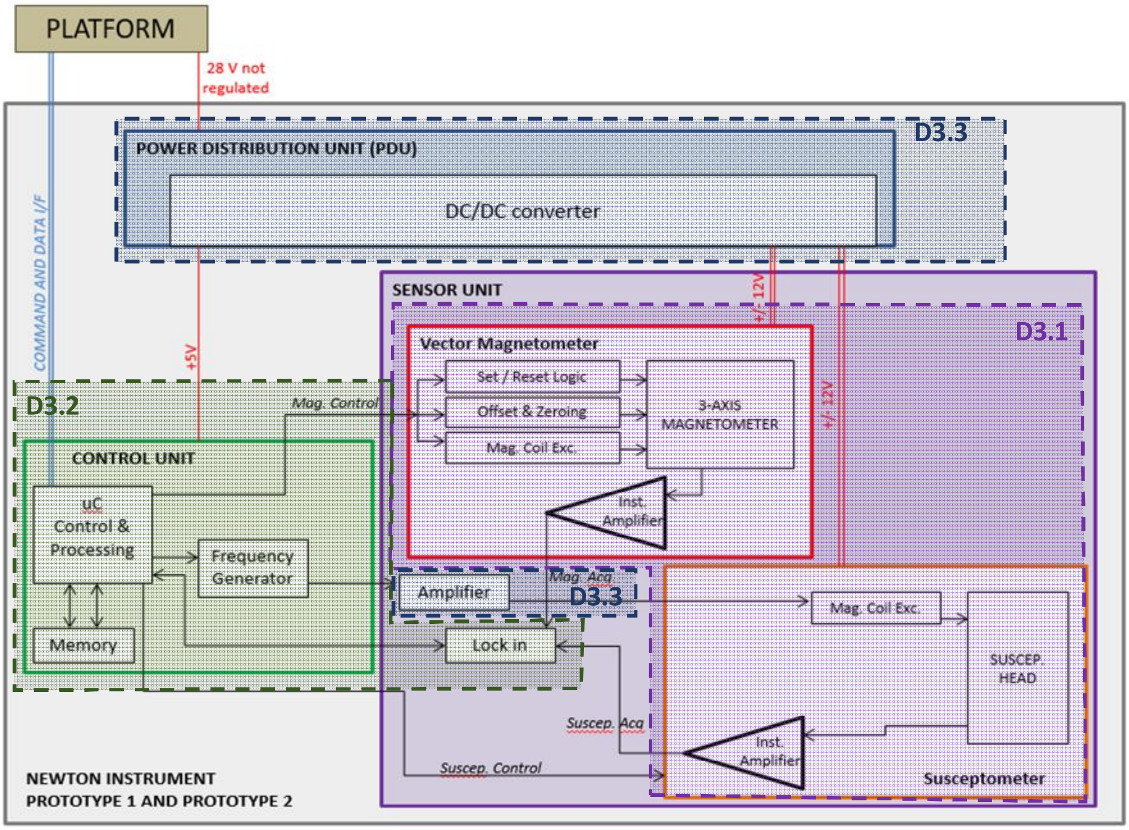


FIGURE 1. Block Diagram of the NEWTON muti-sensor instrument for prototype 1 and prototype 2.

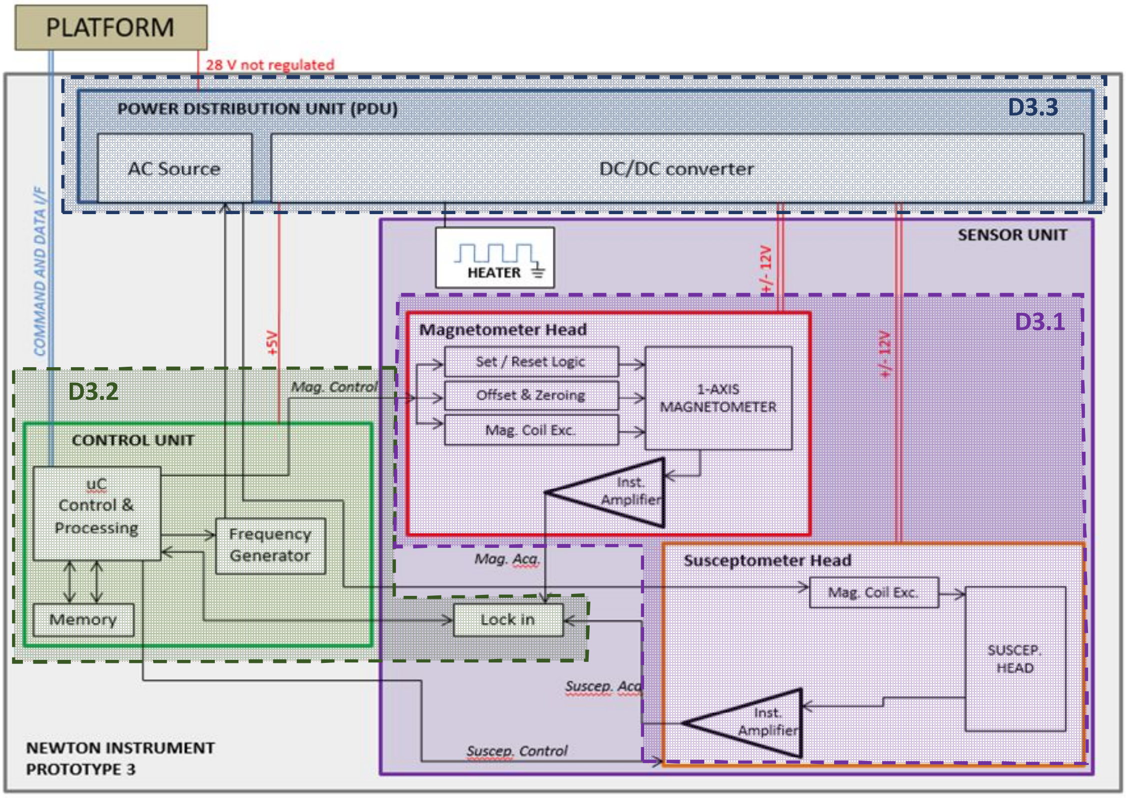


FIGURE 2. Block Diagram of the NEWTON muti-sensor instrument for prototype 3.

3. PRELIMINARY DESIGN OF THE PDU

The power distribution unit of NEWTON instrument supplies energy to the control unit and to the sensors. It is composed of the DC/DC converter and the AC current source.

With regard to the DC/DC converter, it receives the primary power from the rover, 28V not regulated and generates the secondary voltages to supply the electronic control unit and the sensor unit. Although the electrical requirements are the same for the three prototypes, prototype 2 is not devoted to operate on space.

With regard to the AC current source, it drives the primary winding of the sensor unit. In the case of prototype 1 and 2, it is not required to implement an individual AC current source, therefore the generation of the AC current will be implemented as part of the electronic Control Unit and the Sensor Unit. In the case of prototype 3, the demand of the AC current needs and ad hoc development, this is based on a Full-Bridge switching as described in 3.2.

3.1. DC/DC CONVERTER (Prototype 1, 2 and 3)

3.1.1. DC/DC Converter Requirements

Space is a harsh environment with severe radiations and extreme sharp temperature variation over a wide range. The environments encountered by Solar System in-situ exploration missions covers extremes of temperature, pressure and radiation that far exceed the operational limits of conventional electronics, electronic packaging, thermal control, sensors, power sources and batteries. Certain proposed missions would experience extremes in heat flux and deceleration during their entry, descend and landing (EDL) phases, leading to their inclusion as missions in need of technologies for extreme environments [4].

Another important point which should be taken into account in space application is that the energy is limited. Spacecraft and satellites have self contained electrical systems where the power source is usually solar cell arrays. Often, a battery or fuel cell is incorporated. These elements are regulated to form a relatively regulated electrical bus of limited power capacity. The equipment on the spacecraft will then use power supplier, DC/DC converters or EPCs (electronic power converters) to provide power for the many types of equipment on the spacecraft [5]. In this limited energy scenario, it is clear the necessity of saving a maximum of electrical power, in other words, of achieving high efficiency.

Furthermore, an important issue facing space power supply applications is that extreme high reliability must be achieved in a harsh environment with quantities of power supplies that are relatively low which discourages learning curve and experience improvements. Moreover, the size and weight are also limited resources in space applications and directly affect the mission cost. This overview leads to the conclusions that flexibility and reliability of the design of power electronics for aerospace application are mandatory.

The design of the DC/DC converter of the PDU of NEWTON instrument has been developed considering the requirements listed in TABLE 1. These requirements have been defined taking into account the scenarios of application of NEWTON as well as the design requirements defined for the blocks which interface with the DC/DC converter, i.e. the sensor unit and the electronic unit.

As can be seen in the table, prototype 1 and prototype 3 share the same requirements. With regard to the prototype 2, the difference is that NEWTON prototype 2 will operate on Earth in the field of civil engineering application, therefore the requirements associated to the operation on space, i.e. temperature and environmental, are different. In principle, the same design will be adopted for the three prototypes with the peculiarity that the design of prototype 2 is not necessary to be adapted for space applications.

Regarding the requirements associated to the operation in a planetary context, mission requirements have been analyzed at the early stage of the project within the framework of WP2, taking into account the scenarios of application of NEWTON instrument [3]. These requirements have been redefined and updated in D3.1 [1]. Mission requirements have been taken into account during the design of the different key building blocks of the multi-sensor instrument for prototypes 1 and 3.With this regard, we must distinguish between the units and its potential location and consider that the PDU of both prototypes are to be placed within the inner of the rover body, which provides a relative protection against the severe planetary conditions.

It is also important to highlight that, the information included in D3.3 describes the current status of the design of the PDU (preliminary design stage). As WP3 is still on-going until April 2018, this means that, the design can suffer some changes in the following stage of the project before the final design of the PDU. In addition to this, as the design developed at this stage of the project is a preliminary design, the environmental requirements for space applications have been considered, but COTS have been used. For the final design of the PDU, it will be identified/used components with equivalents that are space qualified, in such a way that the final PDU to be developed for prototypes 1 and 3 will make use of components suitable for an EM, but assuring that there is available a space qualified version, that can allow a quick transition to a FM PDU.

TABLE 1. Requirements for the design of the PDU.

Parameter	Prototypes 1&3	Prototype 2	Observations
ELECTRICAL			
Input DC Voltage	+28V (not regulated)	+28V (not regulated)	From the rover/ lander or external batteries
Output DC Voltages	+5V +12V -12V	+5V +12V -12V	+5V are dedicated to supply general electronics (digital output) +12V and -12V should supply the amplifiers of the susceptometer and magnetometer (analogue output)
Output ripple	≤ ±0.5%	≤ ±0.5%	Implies a maximum ripple of 120mVpp at the +12V and -12V outputs, and 50mVpp at the +5V output
Output regulation	±0.1V	±0.1V	Maximum deviation of the output voltages from their nominal values
Steady current consumption from ±12V	500mA (max)	500mA (max)	Current to be consumed by the susceptometer and the magnetometer
Steady current consumption from 5V	200mA (max)	200mA (max)	Current to be consumed by the digital electronics
Inrush current per output	2A	2A	Peak current demanded to the PSU when the devices hanging from its outputs are powered on
ON/OFF feature	Yes	Yes	NEWTON instrument operation is enabled after +5V POWER ON of the Control Unit. Magnetometer operation is disabled by removing the +5V (switching OFF) of the PDU to the Control Unit
ISOLATION			
Isolation (Prim. – Sec.)	TBD	TBD	Different isolated and non-isolated topologies have been analyzed in order to evaluate the main advantages and drawbacks of them
Isolation	Isolation	Isolation	Two different grounds should be considered, referring the

(outputs)	required	required	+12V and the -12V outputs to an analogue ground, and the +5 output to a digital one (ground isolation)
EFFICIENCY			
Efficiency	≥ 90%	≥ 90%	Efficiency in a steady stage, calculated as the ratio between the total amount of power delivered and the input rms power
TEMPERATURE			
Operational Temperature	[3]	-40ºC to 85ºC	
ENVIRONMENTAL			
Vibration	[3]	NA	
Shock	[3]	NA	
Thermal Vacuum	[3]	NA	
Radiation	[3]	NA	
SIZE AND WEIGHT			
Area / Height	TBD	TBD	Including base plate (or other mechanical parts). The target is to achieve a reduced size.
Weight	TBD	TBD	Including base plate (or other mechanical parts). The target is to achieve a reduced weight.

FIGURE 3 shows the block diagram of the DC/DC converter. As it can be seen, the converter receives the primary power from the rover in the case of prototype 1 and 3, and from external batteries in the case of prototype 2, and provides three different output voltages with different power consumptions which interface with the sensor unit and the electronic control block respectively. As already mentioned in section 2, prototype 1 and 2 will be tested in field campaigns on different scientific demonstrations sites so external portable batteries will be used to emulate the primary power. In the case of prototype 3, which will be tested on the laboratory, commercial power sources will be used.

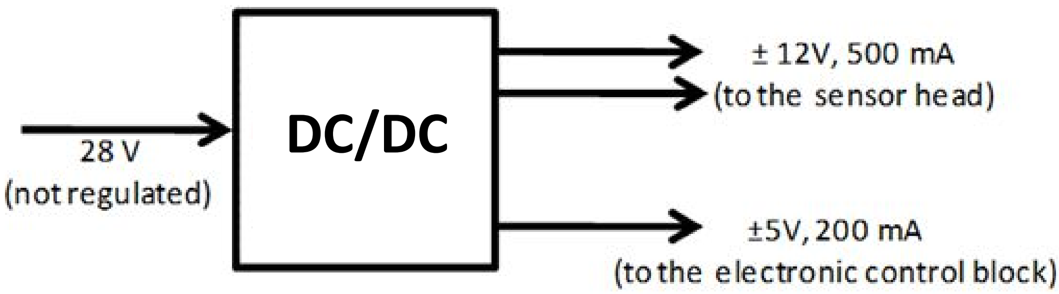


FIGURE 3. Block diagram of the DC/DC converter.

Although, there is no concrete requirements in terms of efficiency, the target is to achieve maximum efficiency (>90%) in order to save a maximum electrical power due to the scenarios of application of all prototypes are a limited energy scenario. Similarly, there is no concrete requirements with respect to size and weight. However, the target is also to reduce the size and weight of the conversor while the efficiency is maximized.

With the aim of finding the best approach for the specific design of the DC/DC converter considering the features of the three prototypes, different topologies of DC/DC sources (isolated and non-isolated) have been considered, analyzed and compared in terms of efficiency, power, design complexity, reliability and flexibility of the whole system. This analysis is shown in the following section.

3.1.2. Topologies comparison

Taking into account space environment conditions, the radiation effect as well as requirements for space applications, the converter design requires specific topologies and component selection with desirable characteristics. Moreover, as is usually demanded in the space applications, the switching converter core shall provide galvanic isolation between primary and secondary voltages. It is then necessary to select a switching converter that permits to fulfil power, efficiency and isolation.

Selection of components for the best performance can be difficult when the available space is reduced. The design requires low losses so the circuit must have a high efficiency. The design may also need certain components values that are difficult to attain due to board size requirements. One of the first problems is the output filter capacitor value constraints, due to no electronic capacitor can be used to avoid the risk of explosion. MKT and MKP capacitors have better performance than other ones, but they have a lower capacity density. Another important issue to take into account is the sense of the output voltage. With this regard, two possibilities can be considered: the use of an auxiliary winding or the use of an optocoupler. While the use of an auxiliary winding may be difficult in a multi output converter where the available space for power windings is already small, the use of an optocoupler can introduce problems in the output voltage regulation, due to their loss of linearity with aging. In addition to this, the leakage capacitance can become also a problem if lower values are required at the switching frequency due to the number of winding turns cannot be too high. To reduce the number of winding turns, a larger and heavier ferrite core is needed and this is difficult to achieve when the dimensions and weight are an important constrains [6].

While the aforementioned characteristics are key performance requirements, the ability of the power supply to meet the design life and to survive and operate through the radiation environments and space conditions without performance degradation is equally important. Selections of the circuit topology and components that are appropriate for the required electrical specifications as well as for the space environmental conditions are one of the major design considerations.

FIGURE 4 shows different non-isolated and isolated switch model power supply (SMPS). At this stage of the project, different solutions have been analyzed in order to find the most suitable solution for NEWTON instrument taking into account the requirements of the three prototypes which are being developed within the project.

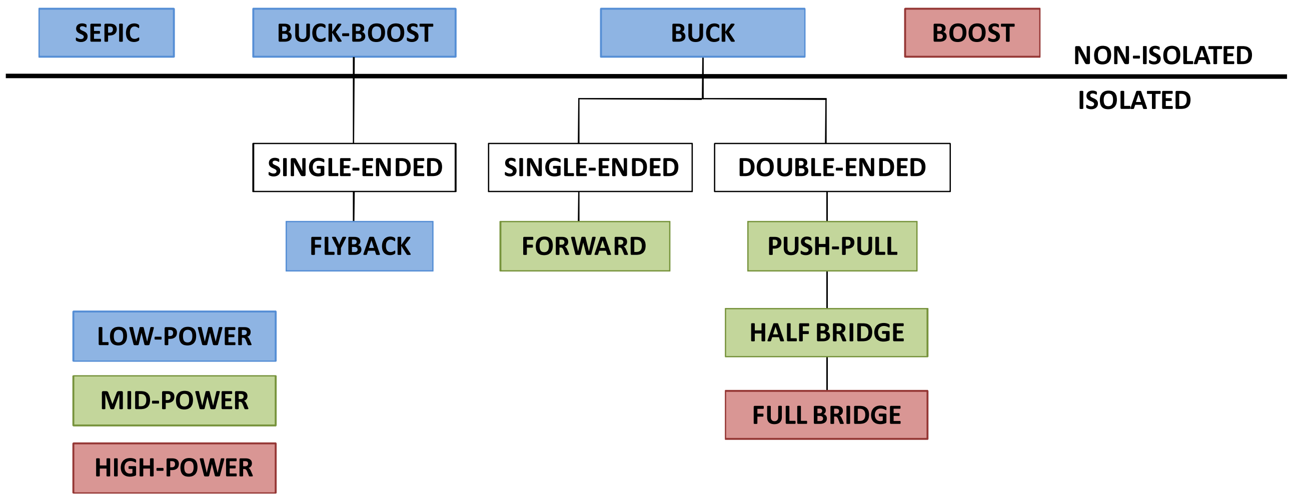


FIGURE 4. Converter topologies

Several aspects have to be considered when comparing power supplies topologies for certain application. The most popular rules of thumb are based simply on the output power rating to switch from one topology to another. However, this criteria for topology selection is, by itself, generally insufficient and grossly oversimplified, and apart from power level, other important and even critical specification parameters include input voltage and range, output voltage/current levels, load type and characteristics, efficiency, isolation criteria and magnetic volume utilization.

3.1.2.1. Isolated DC/DC converters comparison

With regard to the isolated power supplies topologies, the evaluation of a certain topology must take into account that:

- for a given power output rating, it makes a big difference to work with higher current and lower voltage or with lower current and higher voltage, as the voltage and current rating greatly influence the stresses and losses (and then the size and cost) of transformer and silicon devices,
- the way the transformer is reset and the number of windings has a big impact on transformer size and current rating capability,
- for any given topology, there can be different variants (e.g. diode rectification vs synchronous rectification, hard-switching vs soft-switching, etc), different combination of duty-cycle and transformer turns ratio, continuous conduction mode vs discontinuous mode, etc,
- a transformer can be designed in many different ways (magnetic core shape and material, windings allocation and interleaving, gapping, etc), this determining much different effects on size, losses and ringing,
- core temperature rise must be properly limited to avoid material operation in conditions of unpredictable temperature and losses levels,
- depending on the application, several multi-stage combinations of isolated and non-isolated, regulated and unregulated topologies can be adopted, with different bus voltage levels, enabling the achievement of better stresses distribution among the power devices and higher efficiency with respect to single-state architectures.

TABLE 2 presents a summary comparison of the different isolates topologies, i.e. Flyback, Forward, Half-Bridge, Push-Pull and Full-Bridge. Main advantages and disadvantages of the different topologies are included as well as different parameters as the MOSFET stress, typical power, and efficiency.

TABLE 2. Summary comparison of different isolated topologies.

Topology	Advantages	Disadvantages	MOSFET Stress	Duty Cycle	Typical Power	Typical Efficiency	Relative Cost
Flyback	No output filter inductors, voltage rating on secondary component is low	Poor transformer utilization, more EMI, more ripple, more output and input capacitance, higher losses	>Vin	<100%	Up to 100W	80-85%	Low-moderate
Forward	Better transformer utilization, filtered output, lower active device current.	Minimum load requirements, higher voltage demand for the MOSFET.	>Vin	<100%	Up to 200W	80-85%	Low
Push-Pull	Good transformer utilization, good at low input voltages,	Cross-conduction of switches possible, transformer design is	2.0 Vin	<50%	Up to 500W	80-85%	Moderate

	low output ripple	critical, high voltage required for switches					
Half-bridge	Good transformer utilization, magnetic cores are small, switches rated at input voltage, low output ripple	Poor transient response, cross-conduction of switches possible	Vin	<50%	Up to 500W	>90%	Moderate
Full-bridge	Good Transformer utilization, switches rated at input voltage, low output ripple	High parts count, cross-conduction of switches possible	Vin	<50%	Up to 2kW	>90%	High

- **SINGLE-ENDED CONVERTERS: FLYBACK VS FORWARD**

With regard to single-ended converters, the incomplete utilization of the magnetics, the maximum duty cycle limit and the high voltage stress of the switch, make the Forward converter feasible for the output power of an off-line low-cost power supply. While the efficiency is comparable to Flyback (maybe a bit lower in same conditions), it presents the disadvantage of having an extra inductor on the output. On the contrary, its non-pulsating output inductor makes them well for applications where the current exceeds 15A.

The duty cycle range which can be used is limited on both converters. On the Forward converter this limitation is due to the need to demagnetize the core of the transformer, therefore the maximum duty cycle achievable can be controlled by changing the relation between primary winding turns and demagnetizing winding turns. The voltage on the switch also limits the duty cycle. A high duty cycle results in a high voltage on the transistor. This degrades the efficiency because high voltage transistors have poor specifications.

On the Flyback converter the maximum switch voltage is directly related to the maximum duty cycle used, therefore higher duty cycles can only be achieved by using switches capable of blocking higher voltages. The Flyback converter would require the use of an output filter to keep the ripple voltage under the limits, due to capacitor ESR. The use of this filter increases the number of system poles, degrading the stability and increase the space needed on the PCB.

Regarding the efficiency, for any of the two converters the use of synchronous rectification allows a higher efficiency at the expenses of a higher cost and an added degree of complexity. In the Flyback converter a clamp circuit in parallel with the primary transistor is required, which can reduce efficiency.

TABLE 3 depicts in more detail the advantages and disadvantages of Flyback and Forward converters [7].Considering the advantages and disadvantages of both converters, Flyback topology has been selected as a possible solution to NEWTON.

TABLE 3. Comparative analysis between Flyback and Forward converters.

	PROS	CONS
FLYBACK	Low component count - reduced volume and cost. Simple coupled inductor design. Lower voltage requirements. Better tracking of output voltages with the input and load changes. Not minimum load requirements.	Difficult to control. Maximum duty cycle limited. Poor cross regulation. Higher ripple RMS current demanded to the output capacitor. Snubber needed.
FORWARD	Simple control. Output cross regulation. Better transformer utilization with lower peak currents which means lower copper losses. Output capacitor can be fairly small with a much lower ripple current rating. Lower active device peak current: due to much larger magnetizing inductance.	High component count - increased cost and volume. Maximum duty cycle limited. Minimum load requirements. Higher voltage requirement. Complex transformer.

- **DOUBLE-ENDED CONVERTERS (MEDIUM POWER): HALF-BRIDGE VS PUSH-PULL**

Though this kind of converters are thought to be used in medium-high power applications, we will consider them as a possible solution due to the better utilization of the transformer and its magnetic core, and hence their potentially better efficiency, even working at low load conditions.

In this case, the selection of the Half-Bridge over the Push-Pull is quite easy to argue. The main advantages of the Half-Bridge are a lower stress of the switch (half the voltage supported by the Push-Pull transistors) and the slightly better efficiency offered in the same load conditions. In addition, correction of the symmetry can be difficult to implement in Push Pull converters.

Due to simplicity, risks minimization and efficiency issues, the ***Half-Bridge*** topology will be the medium power double-ended converter selected as a promising isolated solution for developing the NEWTON DC/DC converter.

- **DOUBLE-ENDED CONVERTERS (HIGH POWER): FULL-BRIDGE**

Regarding a Full-Bridge based solution, and considering that the NEWTON DC/DC converters should deliver around 13W (maximum) in steady conditions, it’s difficult to find reasons for its selection over simplest solutions, as the previously commented Half-Bridge.

The Full-Bridge offers higher complexity, higher parts count, more risks due to the placement of four switches working in a synchronous mode. The efficiency is not better than a Half-Bridge or a Push-Pull at the loads required by the NEWTON DC/DC Converter.

Due to all these considerations, any of the double-ended isolated converters already presented are known to be a better option in the case under study.

3.1.2.1. Non-isolated DC/DC converters comparison

With regard to non-isolated topologies, although they do not provide isolation between primary and secondary stages they provide good performance in terms of efficiency so they can be a solution for NEWTON prototype 2 or even be used in a multi-stage combination of isolated and non-isolated topologies which can be adopted for NEWTON prototype 1 and 2.

With this regard, synchronous Buck converters improve efficiency while keeping the same degree of complexity as a Half-Bridge, by only placing a second switch, which minimizes the rectification losses, instead of a rectifier diode.

Due to this reasons, a synchronous Buck converter has been also considered at this stage of the project in order to validate its performance. This non-isolated converter could be a good alternative due to its relative low design complexity and good performance in terms of efficiency over a huge load conditions.

3.1.3. Detailed design

This section describes the detailed design of the different DC/DC converters implemented at this stage of the project. As already reported in section 3.1.2, different isolated and non-isolated topologies have been selected in order to find the most suitable solution for NEWTON requirements. The selected topologies are:

- Flyback Converter
- Half-Bridge Converter
- Synchronous Buck Converter.

As previously indicated, at this stage of the project, the mission requirements have been taken into account for the preliminary design, however commercial components have been used for the implementation. Within the next stage of the project, i.e. the final design, components with equivalent qualified for space mission will be identified. In the same way, components, materials or processes which results critical for a future flight model development will be identified during the final design stage and included in D3.6.

3.1.3.1. Flyback DC/DC converter

The Flyback topology is a transformer isolated converter based on the Buck-Boost topology where the transformer provides isolation and acts as a storage inductor, making possible to offer a single or multiple isolated output voltages with outputs that can be positive or negative and permits to adjust the output voltage by varying the turns ration. FIGURE 5 illustrates a schematic of the Flyback converter with a diode as an output switch [6].

The Flyback is the simplest and most common of the isolated topologies for low-power (5-150W) and low cost with possibly the lower component count. The output voltage isolation is guaranteed with two coupled inductances, a primary inductance, L_p, and a secondary inductance, L_s. On the input side there is only one winding, L_p, which means that only one power transistor is required. On the output side there is only the output capacitor, C_o, and one switch, which can be a power diode or a power transistor in the case of synchronous rectification. Therefore, there is no need to use an external inductor to filter the output voltage, which means less space required.

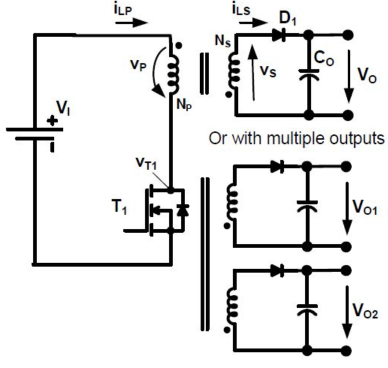


FIGURE 5. Flyback circuit configuration.

As it's shown in FIGURE 6, during t_{on} energy is stored in the transformer magnetic core through L_p inductance, while the output capacitor delivers energy to the load. During t_{off} the energy stored in the core is transferred to the output, resulting on a current in Ls inductance which forward-biases the output diode and delivers current to the load while charging the output capacitor as well. FIGURE 7 shows some waveforms present in the Flyback converter operation depending on the state of the switch.

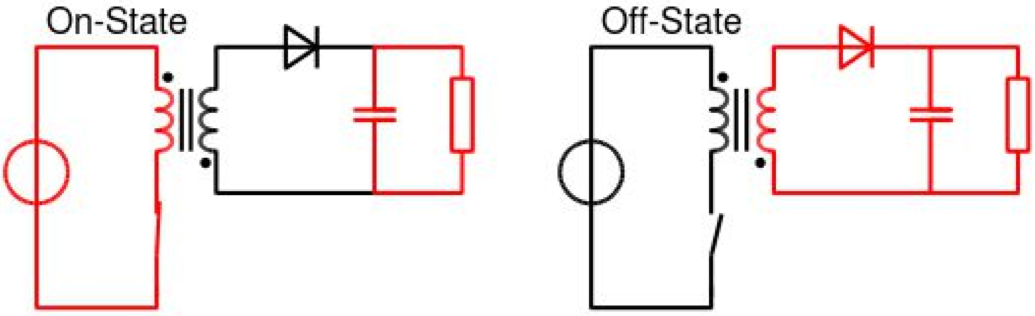


FIGURE 6. Flyback converter operation: On-state (switch closed) and Off-state (switch open).

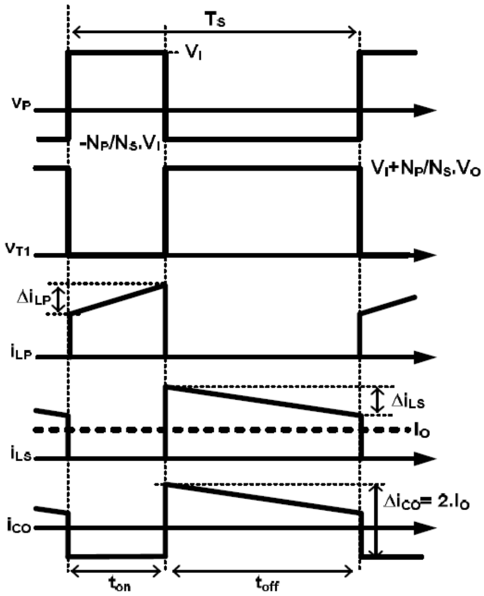


FIGURE 7. Flyback converter waveforms. From top to bottom

During the on-phase of the transistor, the drain-source-voltage, i.e. V_{ds}, will be zero. During the off-phase, the output voltage is back transformed to the primary side such that the drain-source voltage achieves the value [7]:

$$V_{ds} = V_{in\_\max} + V_O \cdot \frac{N_p}{N_S} \tag{3.1-1}$$

Moreover, it is necessary to consider that when the MOSFET is tuned off there is also a high voltage spike on the drain due to the transformer leakage inductance (L_l):

$$V_{ds\_max} = V_{in\_max} + V_o \cdot \frac{N_p}{N_S} + L_l \cdot \frac{dI_l}{dt} \qquad (3.1\text{-}2)$$

Taking this into account it is necessary to consider the maximum Vds when selected the MOSFET (adequate BVdss), otherwise an avalanche breakdown and eventually failure could occur. Nevertheless, an additional clamp circuits, are used to ameliorate the voltage spikes on power switched during commutation. Additionally, the high current ripple in Co, has the value of $2I_o$, and requires the use of a low ESR capacitor or a parallel of capacitors to provide the required output voltage ripple.

One advantage of the Flyback topology over the isolated topologies is that many of them require a separate output storage inductor (Flyback transformer acts a storage inductor), saving cost, volume and losses. Moreover, the rest of the circuit is simple, i.e. it does not require a freewheeling diode as forward, which makes the Flyback topology a cost effective and popular topology. Flyback topologies are well suited for high-output voltages. On contrary, their high peak currents limits their use to output current below 10-12A.

Flyback converters have two basic energy-transfer modes of operation: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM). In DCM, the Flyback period will continue till the output winding current drops to zero, so that all the stored energy in the Flyback transformer is transferred to the load. On the contrary, in the CCM, there is some residual energy stored in the transformer at the end of the ON and OFF periods. In general, DCM is recommended for high voltage and low current output applications while CCM is preferred for low voltage and high current applications. A comparison between CCM and DCM is presented in TABLE 4.

TABLE 4. Comparative analysis between CCM and DCM Flyback converters.

	PROS	**CONS**
CCM	Small ripple and rms current. Low core loss. Better cross-regulation. Lower MOSFET conduction loss. Lower primary MOSFET turn-off loss. Lower capacitor dissipation. Smaller EMI filter and output filter. Constant switching.	Slope compensation required at higher duty cycles (Peak CMC). Diode reverse-recovery loss. Higher voltage stress for secondary diodes. RHPZ (right half plane zero) - this leads to a phase decrease with increasing gain, which must be considered when defining control-loop compensation, otherwise, stabilization problems can arise. Synchronous-rectifier snubber loss. Low light-load efficiency.
DCM	No diode reverse recovery loss. No RHPZ problem. Lower inductance may allow smaller transformer size. Constant switching frequency.	Large ripple and peak current. Higher MOSFET conduction loss. Higher core loss. Higher primary MOSFET turn-off loss. Higher capacitor dissipation. Higher MOSFET voltage stress. Large EMI filter and output filter.

Taking into account the analysis presented above, a Flyback operating in CCM is selected for its implementation. FIGURE 8 illustrates the block diagram and the schematic of the Flyback DC/DC converter.

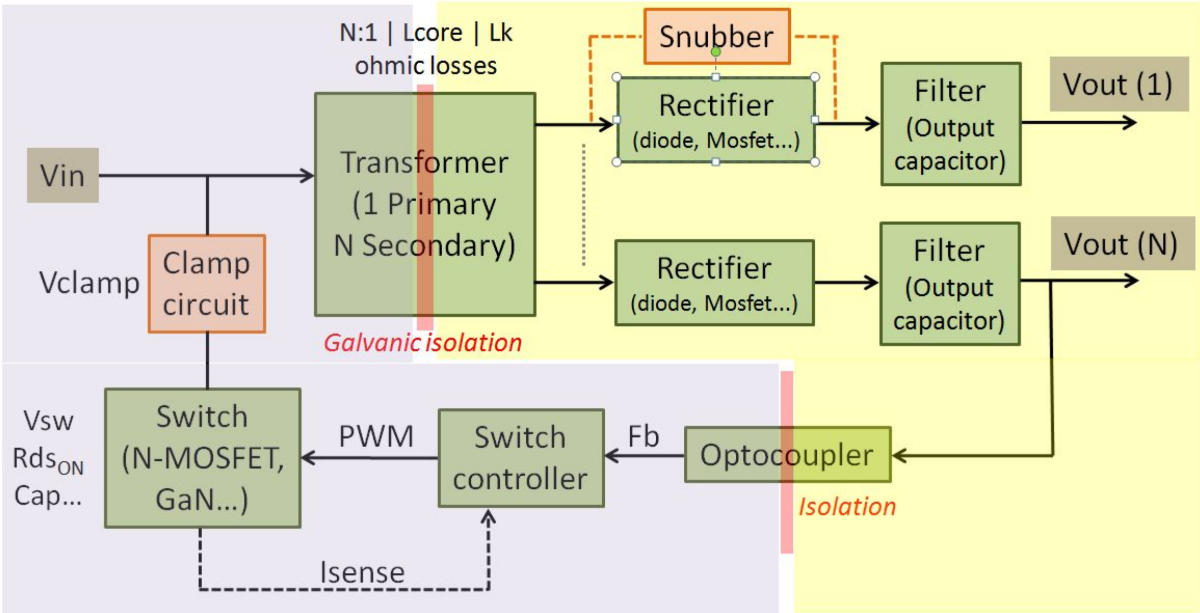


FIGURE 8. Block diagram of the Flyback converter.

1. **SWITCHING FREQUENCY:** The selection of the switching frequency affects to the efficiency and the size of the power supply. High switching frequency allow for lower primary inductance and smaller output capacitors reducing solution size when compared to a converter switching at lower frequency. However, higher switching frequency increases switching losses worsening the efficiency and thermal performance. The efficiency of a Flyback converter is particularly sensitive to switching frequency. Due to leakage inductance in the transformer, not all energy is transferred from the primary winding to the secondary winding. When the switch is turned off, a large voltage overshoot must be clamped below the drain to source the voltage rating of the internal MOSFET. The clamping circuit absorbs the leakage inductance energy during each switching period. Therefore, a higher switching frequency increases the power lost to the primary-side voltage clamp.

2. **TRANSFORMER - TURNS RATIO, DUTY CYCLE AND PRIMARY SIDE INDUCTANCE:** When designing a Flyback, one of the most important components is the transformer. Firstly, the maximum duty cycle is calculated (D_{max}) by means of estimating the maximum primary to secondary turns ratio (N_p/N_s). After that, average current (I_{avg}) is calculated and then the primary side inductance (L_m) considering an excursion of 50%.

3. **MOSFET:** Different parameters should be taken into account in order to select the most appropriate MOSFTET. With this regard, appreciable current carrying capability, high reverse blocking voltage, very low ON resistance and fast switching capabilities make a MOSFET and ideal choice as a switching element in SMPS topologies. In addition to this, a MOSFET with low RON and low gate charge is required in order to reduce the switching and gate charge loss.

4. **CLAMP/SNUBBER CIRCCUIT:** As already mentioned a primary switch clamp/snubber is needed to limit the voltage and absorb the energy stored in leakage inductance of the transformer. Various topologies for the clamping circuit can be found, but a resistor-capacitor-diode (RDC) scheme is selected in this case. First, the capacitor has been selected to limit the voltage ripple, and the resistance is calculated to set the voltage clamp level. Finally, a diode with short forward recovery time is selected with the

aim of activating the clamping circuit as soon as possible. FIGURE 9 shows the circuits and Vds waveform.

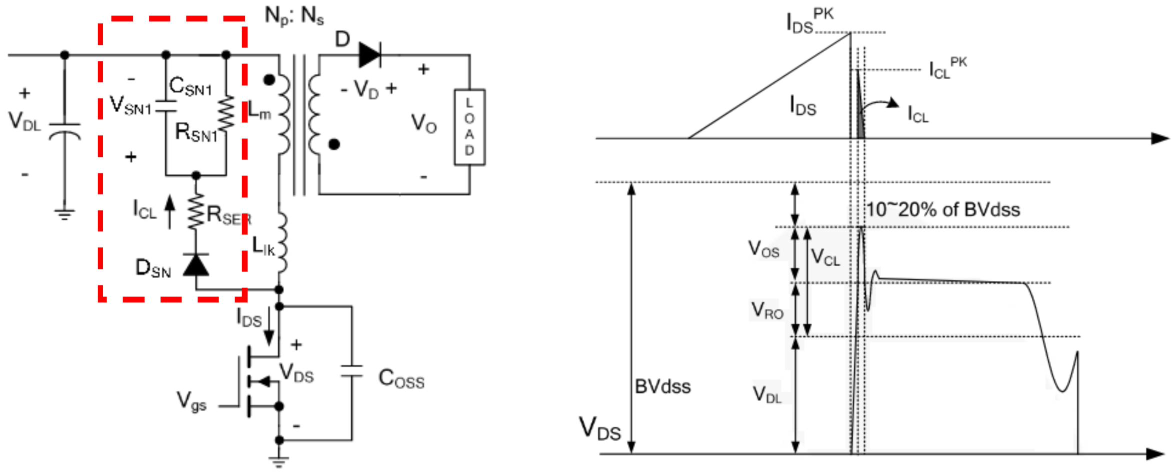


FIGURE 9. Flyback clamp circuit (Primary side)

In some occasions, and depending of the transformer manufacture, the leakage inductance could be placed in the secondary side, affecting the voltage over the rectifier. Due to the parasitic of the output diode (commonly a capacitance in parallel) and that undesired and not-coupled induction an oscillation or transient could happen in Vd. As shown in FIGURE 10 this effect can be minimized by placing a RC circuit to snub that overvoltage oscillation.

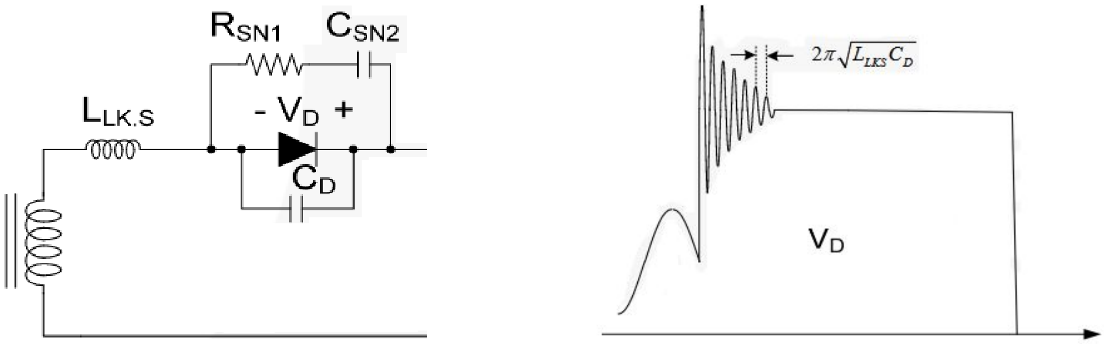


FIGURE 10. Flyback snubber circuit (Secondary side)

5. **OUTPUT RECTIFICATION:** An output rectification is required at the secondary side to conduct the current in the secondary winging of the transformer. As it was previously explained this rectification can be obtained by using a passive or active mode. An active rectification implies the use of a switch (i.e. an additional MOSFET or GaN transistor) working in a synchronous way respect to the input switching, adding complexity while reducing the rectification losses and improving the efficiency a little bit at low output voltages. Both, diode or transistor option, shall be capable of withstanding the reverse voltage and required rms current at the output. In case of selecting a rectifier diode, it should present low forward voltage and low maximum reverse recovery time in order to minimize the diode losses.

6. **OUTPUT CAPACITOR (C_o):** There are three primary considerations for selecting the value of the output capacitor. The output capacitor determines the modulator pole, the output voltage ripple and how the

supply responds to a large change in the load current. The capacitor must supply the output current when the internal MOSFET is turned on and current is flowing in the primary winding. It must also supply increased load current until the regulator responds to a load step.

7. **PWM - CURRENT MODE CONTROL:** The output voltage is function of the input voltage, duty cycle and load current, as well as converter circuit components values. The output voltage should be constant (within a certain limit) with independence of input voltage, load current or converter circuit parameter values. This is achieved with negative feedback and setting the duty cycle to a single value. In order to achieve this, a current mode control technique has been designed which schematic is shown in FIGURE 11. Two control parameters are used in this mode: the output voltage at the load end and the output inductor/primary switch current. In case of the NEWTON DC/DC converter, the output current is not expected to suffer great variations from the nominal steady current originally set, no having devices with current consumption fluctuations, so the current mode control is not going to be implemented.

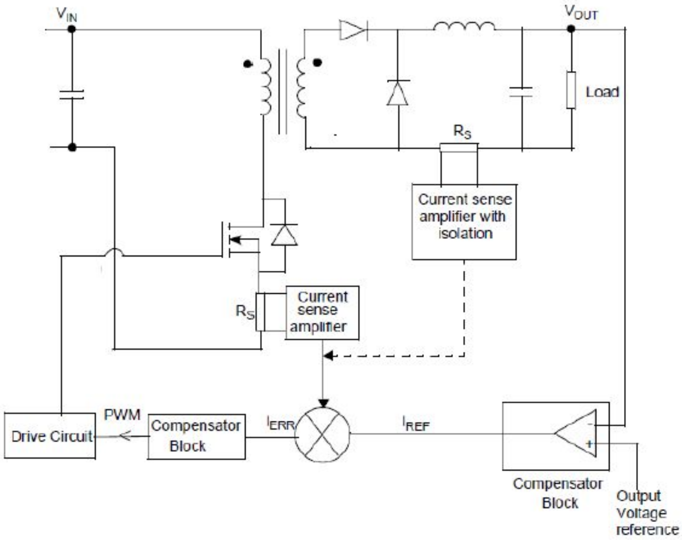


FIGURE 11. Schematic of the current control block.

8. **OUTPUT VOLTAGE REGULATION:** In order to achieve the maximum output voltage accuracy, a feed-back loop based on an optocoupler has been designed as can be seen in FIGURE 12.

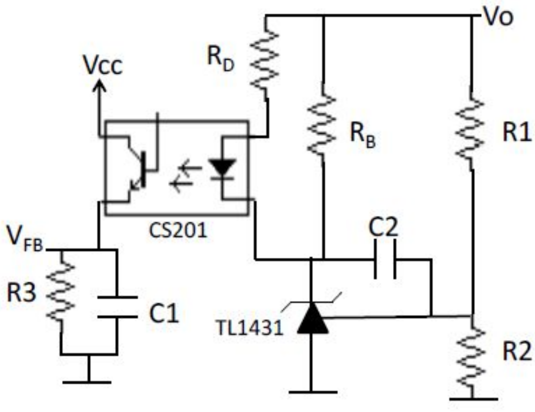


FIGURE 12. Opto-coupler and feedback circuitry.

The evaluation of the Flyback converter has been carried out using PSPICE simulator. FIGURE 13 shows the schematic used in the simulations. Simulations have been done with non-ideal components excluding feedback.

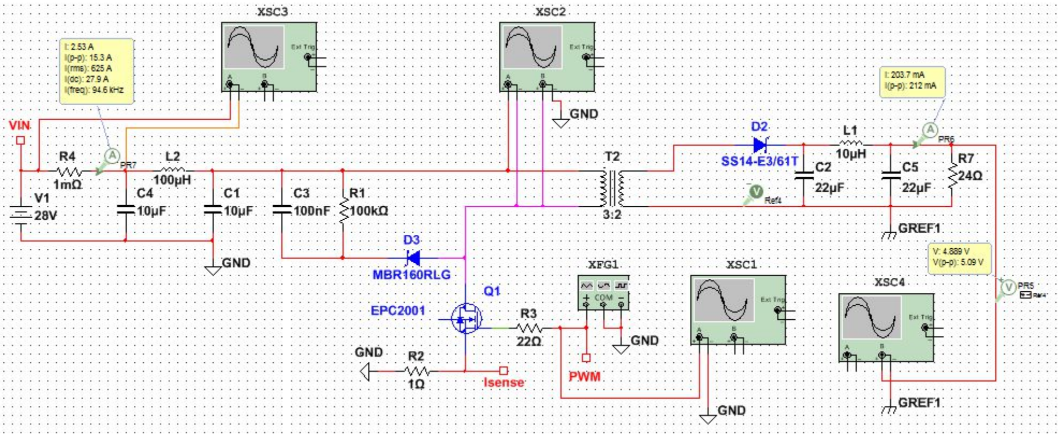
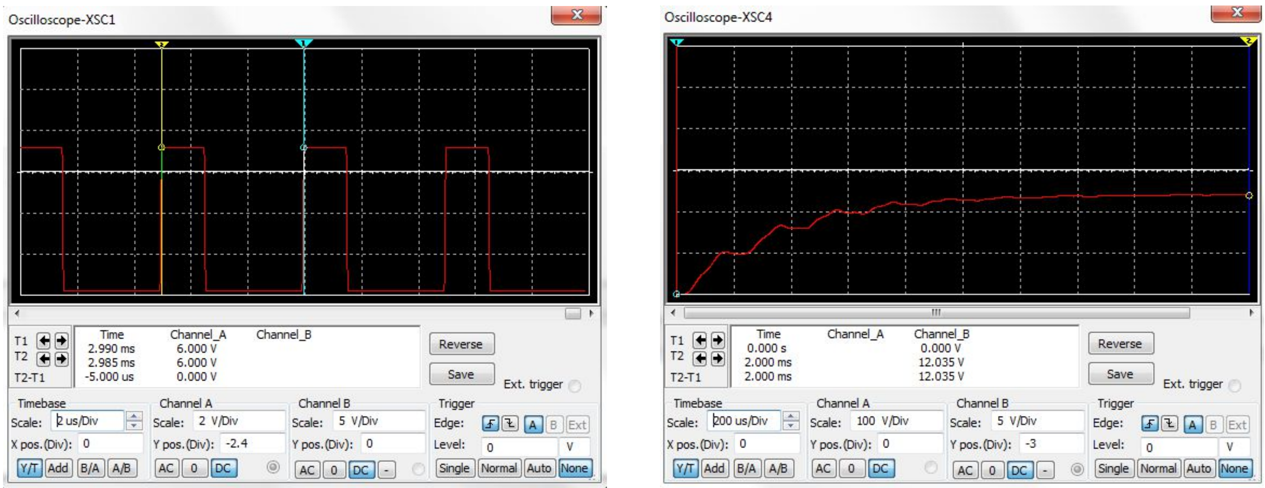


FIGURE 13. Schematic of the Flyback converter (open loop simulation).

The simulation results obtained for the design of the Flyback converter described above are shown in FIGURE 14. A prototype of the Flyback converter has been manufactured in order to validate the concept and analyse the main advantages and limitations of this source. FIGURE 15 shows the layout of the PCB, while section 4.1.1 reports the results obtained from the measurement of this prototype.



(A) (B)

FIGURE 14. Simulation results obtained for the Flyback converter: (A) PWM control signal (B) Output voltage.

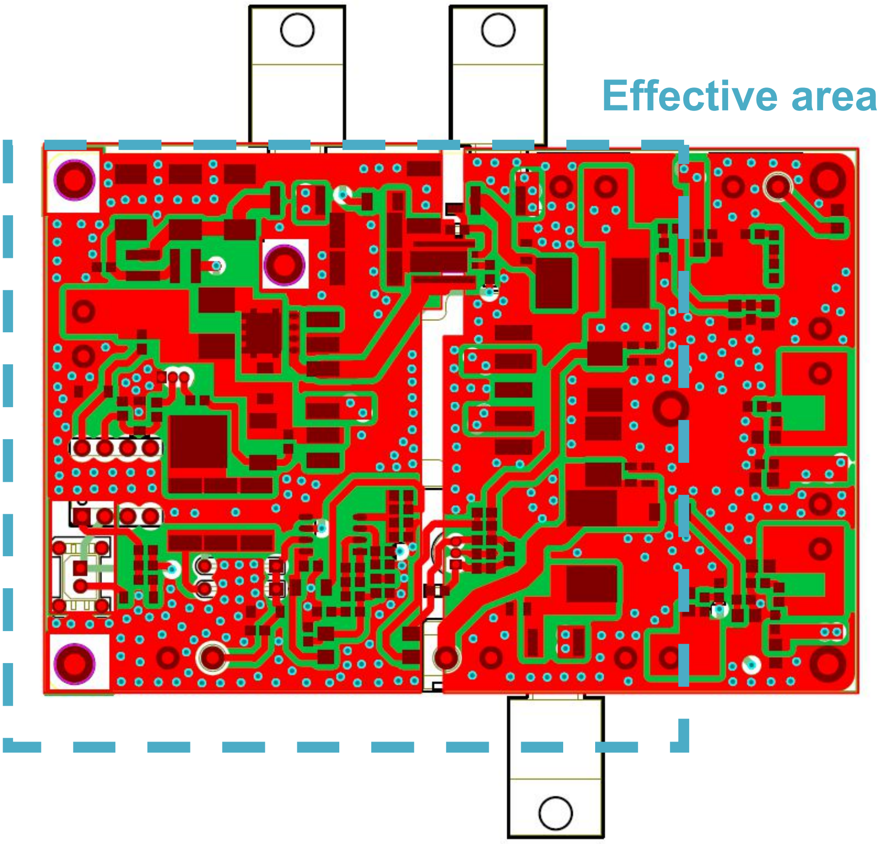


FIGURE 15. Layout of the PCB manufactured for the validation of the Flyback Converter.

3.1.3.2. Half-Bridge DC/DC converter

The Half-bridge converter is a transformer-isolated converter based on the basic forward topology. FIGURE 16 and FIGURE 17 show respectively the basic schematic and switching waveforms of the Half-bridge converter. The switched Q_1 and Q_2 form one leg of the bridge, with the remaining half being formed by the capacitors C_3 and C_4.

The switches Q_1 and Q_2 create pulsating AC voltage at the transformer primary. The transformer is used to step down the pulsating primary voltage, and to provide isolation between the input voltage source VIN and the output voltage. In the steady state of operation, capacitor C_3 and C_4 are charged to equal voltage, with results in the junction of C_3 and C_4 being charged to half the potential of the input voltage [8].

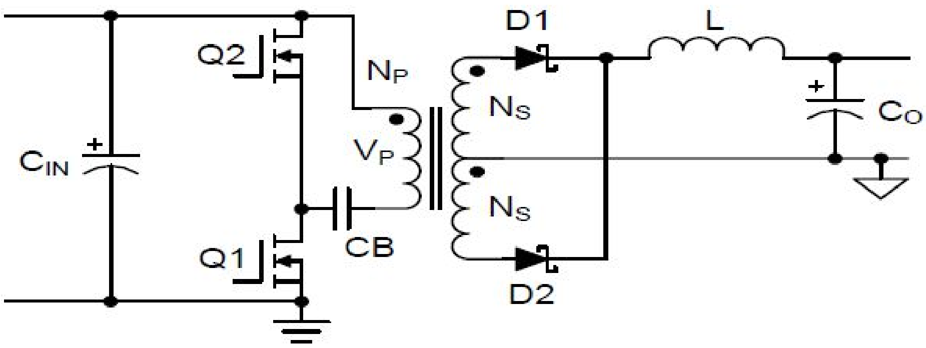


FIGURE 16. Basic schematic of the Half-bridge converter.

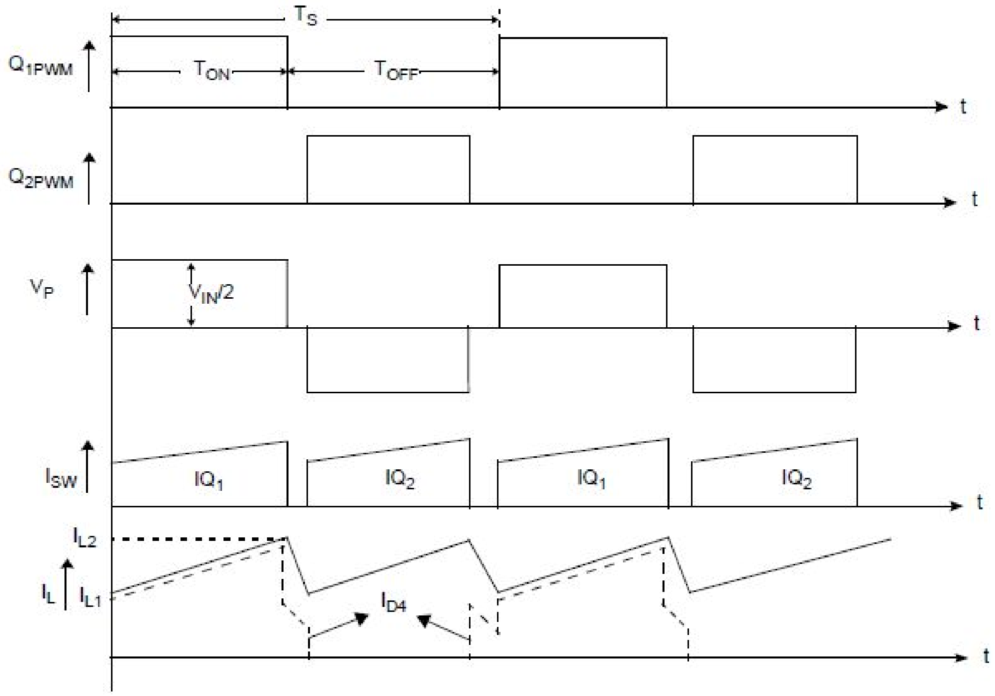


FIGURE 17. Half-bridge converter switching curves. From top to bottom: gate pulse waveform of Q_1 and Q_2, voltage across transformer primary, current through the switch Q_1 and Q_2 and output inductor and diode D_4 current.

A preliminary evaluation of the suitability of a Half-bridge converter for NEWTON PDU has been performed. FIGURE 18 shows the simulation schematic of the Half-bridge converter designed at this stage of the project. PSPICE simulators have been used to perform the simulation of the power source. Nonlinear models and parasitic have been included for the most critical components of the design, i.e. GaN FETs, rectifiers and transformers. FETs based on GaN technology have been used due to this technology is considered as the state-of-the-art in switching technology for DC/DC converters. FIGURE 19 shows the main curves of the simulations, such as PWM used, the control voltages for each of the switches, the resultant voltage stress on them and the output voltage and current.

As in the of the Flyback converter, the PWM frequency affects to the size of the transformer, and this to the size of the overall transformer, and also to the efficiency. In principle, higher switching frequencies allow the reduction of the size at the expense of reducing the efficiency. FIGURE 20 shows the PCB designed for the validation of the concept of the Half-bridge transformer.

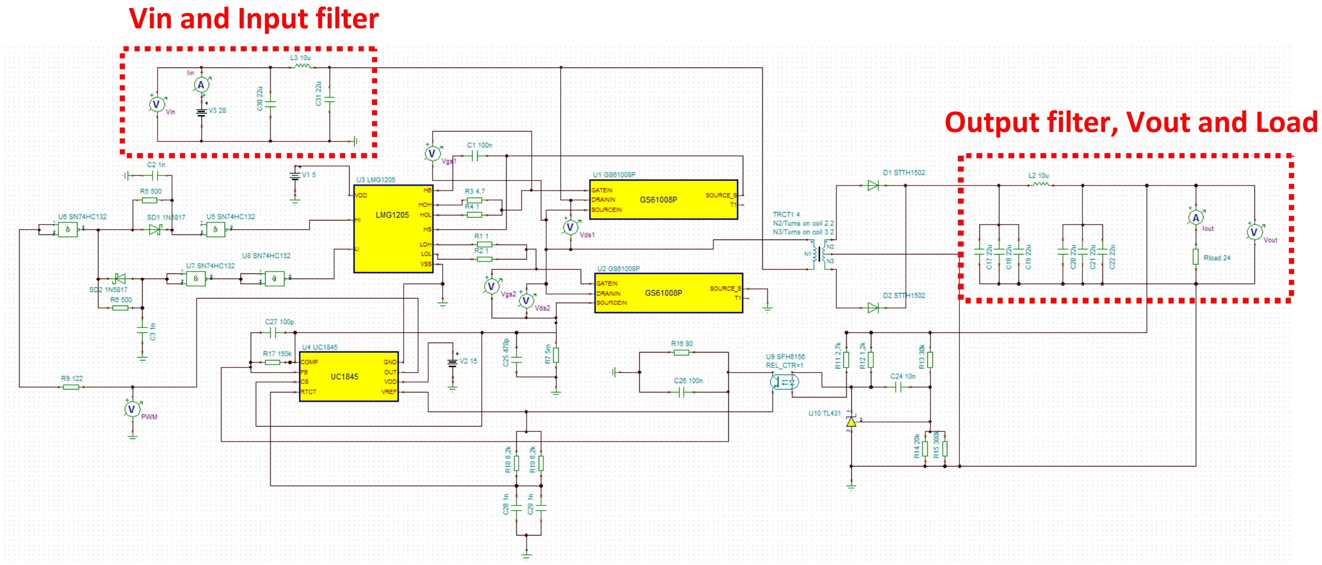


FIGURE 18. Simulation schematic of the Half-bridge converter.

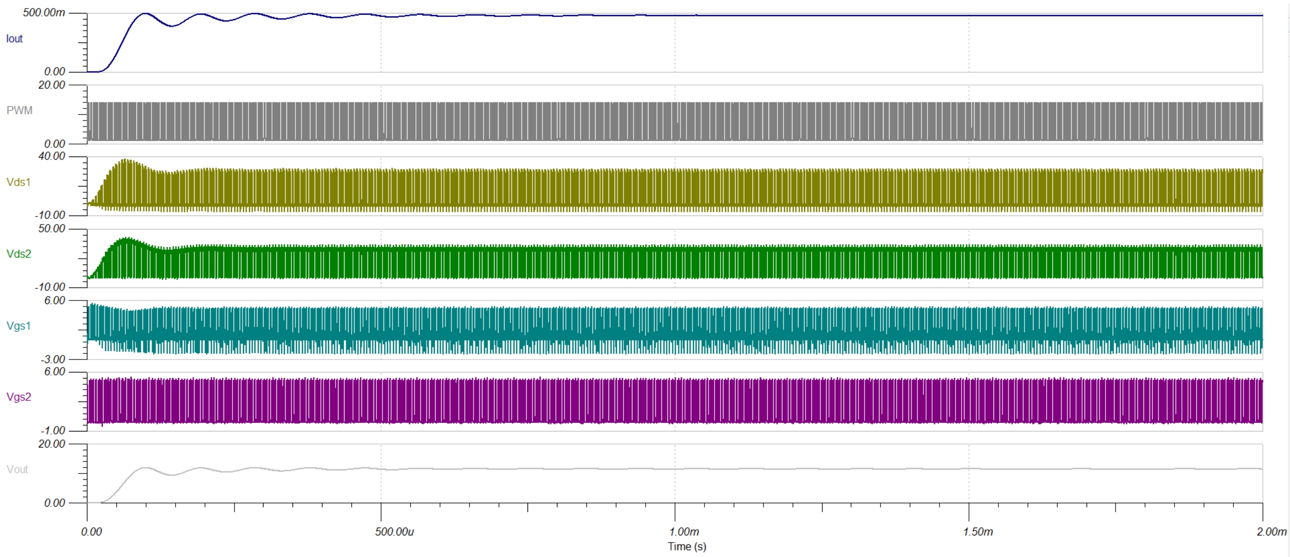


FIGURE 19. Simulation results for the Hal-bridge converter

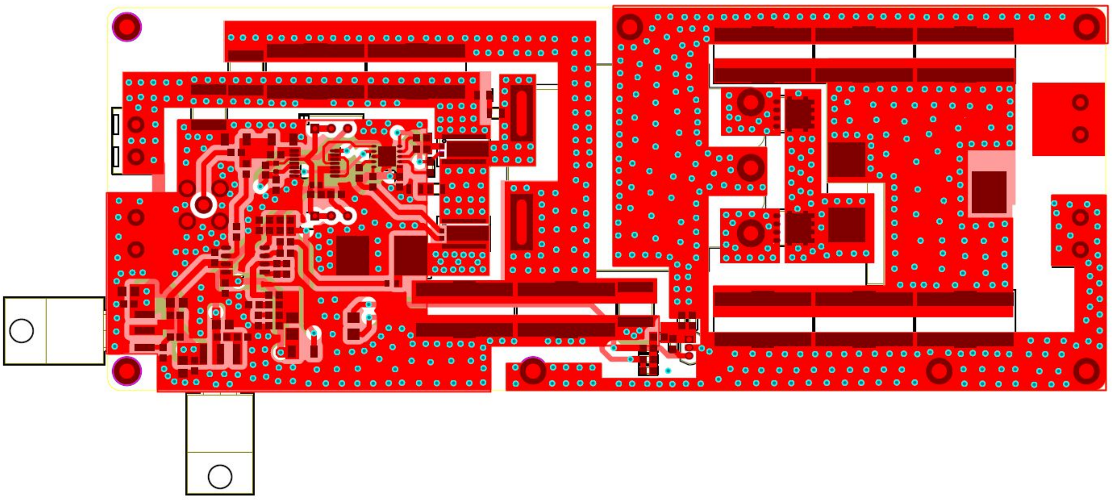


FIGURE 20. Layout of the PCB implemented for the proof-of-concept of the Half-bridge converter.

3.1.3.3. Buck DC/DC converter

Buck converters are one of the most commonly used topologies due to its reduced design complexity and cost. It is widely used in different applications to convert a higher input voltage into a lower output voltage. The buck converter (voltage step-down converter) is a non-isolated converter, hence galvanic isolation between input and output is not give. This topology can provide high efficiency levels, and also high power levels, especially with poly-phase topologies. The main disadvantage of this configuration is that the input current is always discontinuous, resulting in higher EMI. However, this EMI issues can be addressed with filter components [9].

FIGURE 21 illustrates the basic circuit configuration of a buck converter while FIGURE 22 shows the operation and FIGURE 23 shows the switching waveforms [8]. A switch (Q1) is places in series with the input voltage source V_{IN}. The input source V_{IN} feeds the output through the switch and a low-pass filter, implemented with an inductor and a capacitor.

In a steady state of operation, when the switch is ON for a period of T_{ON}, the input provides energy to the output as well as to the inductor (L). During the T_{ON} period, the inductor current flows through the switch and the difference of voltage between V_{IN} and V_{OUT} is applied to the inductor in the forward direction. Therefore, the inductor current IL rises linearly from its present value I_{L1} to I_{L2}.

During the T_{OFF} period, when the switch is OFF, the inductor current continues to flow in the same direction, as the stored energy within the inductor continues to supply the load current. The diode D1 completes the inductor current path during the Q1 OFF period. During this T_{OFF} period, the output voltage V_{OUT} is applied across the inductor in the reverse direction. Therefore, the inductor current decreases from its present value I_{L2} to I_{L1}.

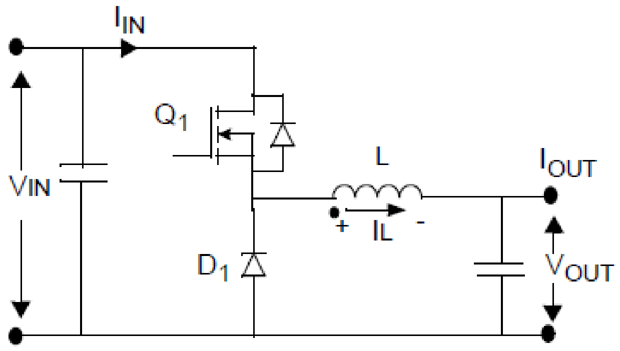


FIGURE 21. Basic circuit configuration of a buck converter.

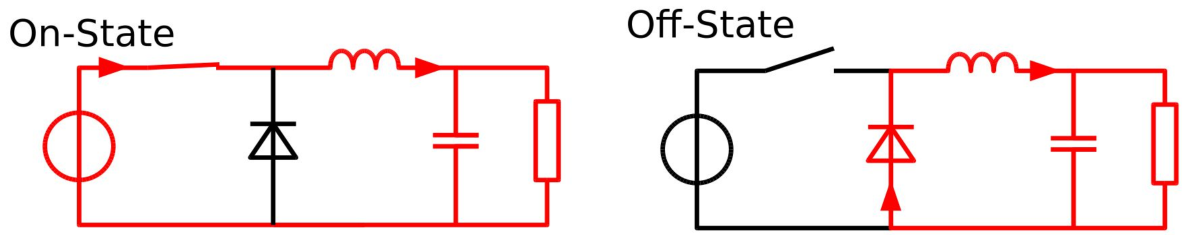


FIGURE 22. Buck converter operation: On-state (switch closed) and Off-state (switch open).

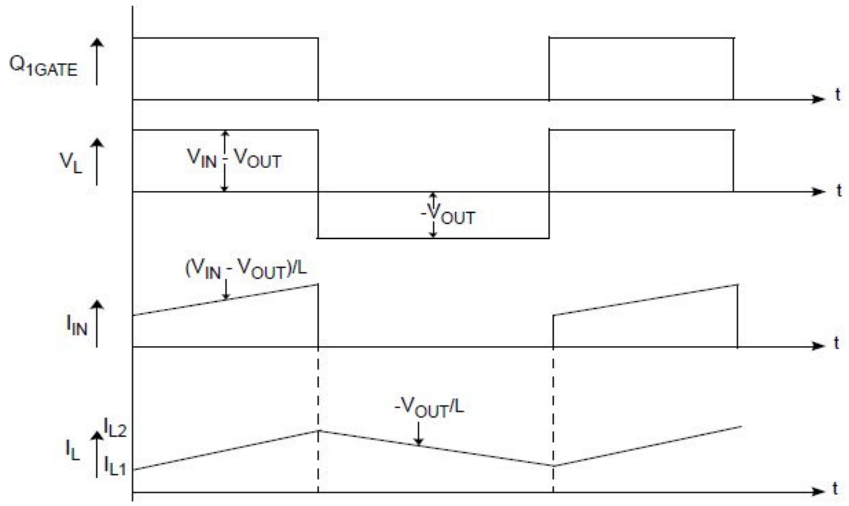


FIGURE 23. Switching waveforms in the buck converter. Gate pulse of the MOSFET Q1 (top), voltage across the inductor L (middle-up), Input current I_{IN} (middle-down) and load current (bottom).

At this point, a synchronous buck converter operating in continuous conduction mode is considered. The inductor current is continuous and never reaches zero during one switching period (Ts), the relation between output and input voltage is given by:

$$V_{OUT} = D \cdot V_{IN} \tag{3.1-3}$$

where D is the duty cycle defined as:

$$D = \frac{T_{ON}}{T_S} \quad (3.1\text{-}4)$$

where T_{ON} is the ON period.

FIGURE 24 shows the basic schematic of a synchronous buck converter. As can be seen, it is composed by two MOSFET, and output inductor and output capacitors.Q1, is connected directly to the input voltage circuit. When Q1 turns on, IUPPER is supplied to the load through Q1. During this time, the current through the inductor increases and Q2 is off. When Q1 turns off, Q2 turns on and ILOWER is supplied to the load through Q2. During this time, the inductor current decreases [10],[11].

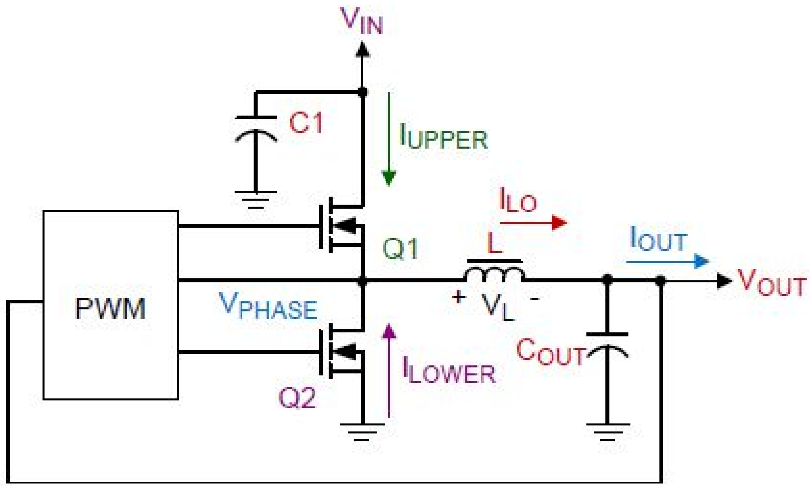


FIGURE 24. Basics of s synchronous Buck converter.

At this stage of the project, a commercial solution based on GaN technology has been used to validate the concept and to analyzed experimentally the advantages and disadvantages of the buck converter. This solution is based on GaN-on silicon E-HEMT transistor (GS61008P). The properties of GaN allow for high current, high voltage breakdown and high switching frequency which combine to provide very high efficiency power switching. The validation of the concept has been carried out by means of using a demo board of a synchronous buck DC/DC converter provided by GaN Systems [12]. This demo board comprises a universal GaN half bridge with open loop control and on-board PWM dead time generation which is used to implement a 48-12V synchronous buck DC/DC conversor. The circuit schematic of the evaluation board is shown in FIGURE 25.

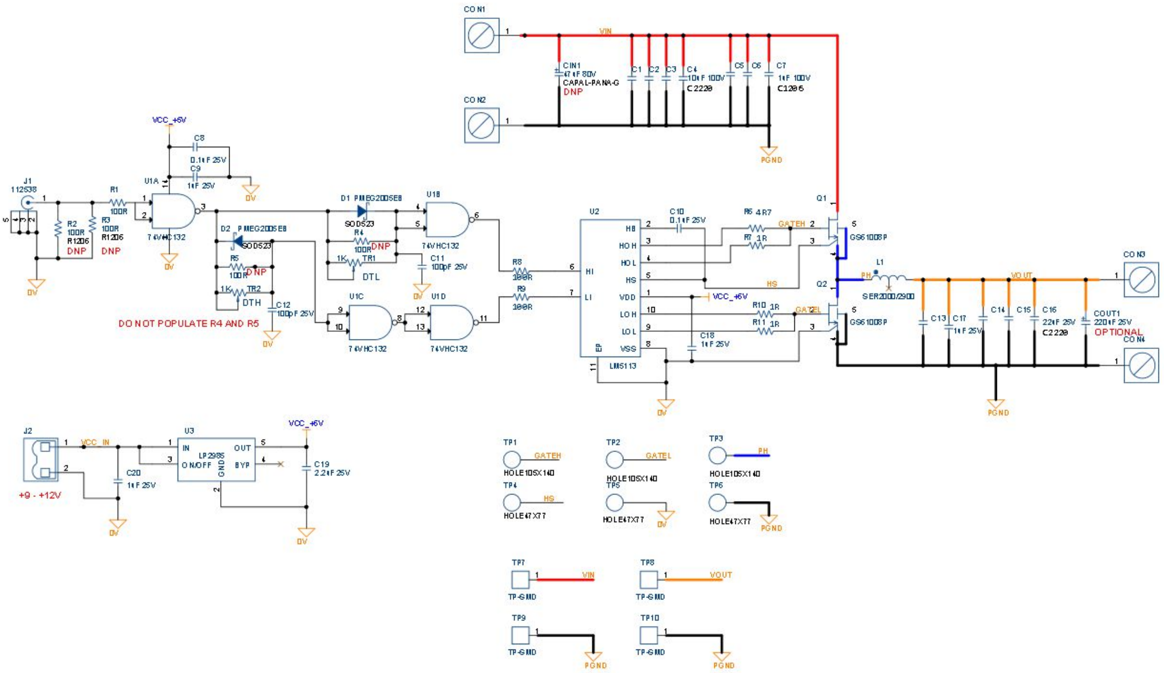


FIGURE 25. Circuit schematic of the 48V synchronous buck DC/DC demo board.

The demo board has been configured in order to provide the requirements of NEWTON. By doing so, an input voltage of 28 V has been used as the input voltage while the output voltage has been fixed to 12V. Then the performance of the demo board in terms of efficiency has been measured as will be shown in 4.1.3.

3.1.3.4. Inrush Current Limiter and Input Filter

The PDU has to work satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances. Electromagnetic Interference (EMI) is the major adverse effect caused by the application of switch-mode power supplies (SMPS). In them, EMI noise is unavoidable due to the switching actions of the semiconductor devices and resulting large discontinuous currents. Voltage ripple generated by discontinuous currents can be conducted to other systems via physical contact of the conductors. Without control, excessive input and/or output voltage ripple can compromise operation of the source, load or adjacent system. Whereas the voltage ripple at the output side is usually well filtered by the output filter of the converter the input ripple control is one of the more difficult challenges in SMPS design.

In order to reduce the influence of the NEWTON PDU over the main power supply of the rover (or similar) and assure the EMC/EMIC, and input filter is included at the input of the DC/DC converter. The DC/DC converter input filter shall reduce the amplitude of the high frequency input current harmonics (conducted emissions) injected back into the main power bus, thus preventing the electromagnetic interference (EMI) from reaching the bus and affecting other equipment. Moreover, it also shall prevent high frequency voltage on the primary power source from passing through the secondary power supply. The input filter has been designed as part of the DC/DC conversor and the presented designs of the Flyback and Half-bridge converters already include this stage. The evaluation board of the Buck converter also includes the filter stage.

In addition to the input filter, it might be necessary to include also an inrush current limiter in order to limit the peak currents that can occur when the instrument turns on, as FIGURE 26 illustrates. Inrush current is the current drawn by a power system when power is applied or it is turned on. The different stages in a typical switching system will contain several capacitors. Each of these capacitors requires current to charge them from their initial or zero state to their final steady state voltage. This current can have a high peak magnitude depending on the input voltage rise time and source impedance, and is referred to as the inrush current. Due to the characteristics of the loads at the output of the DC/DC converter, it is not necessary to include an inrush current limiter.

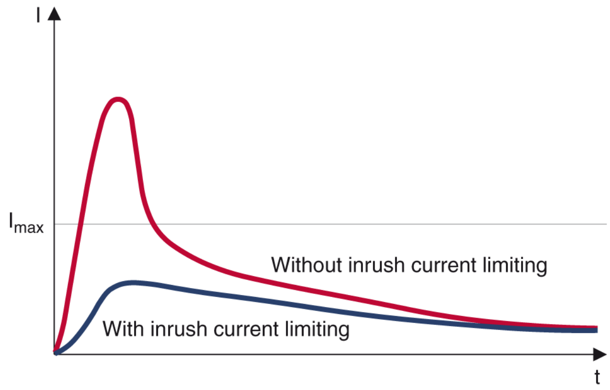


FIGURE 26. Effect of the inrush current limiter.

3.1.3.5. ON/OFF Feature

The ON/OFF feature of the DC/DC converter can be used to save energy during the standby period of the instrument. Due to this reason, the ON/OFF feature will be included in the final design of the DC/DC converter (it has not been included in the preliminary design stage). NEWTON instrument operation will be enabled after +5V POWER ON of the Control Unit. Sensor Unit operation will be disabled by removing the +5V (switching OFF) of the PDU to the Control Unit.

There are mainly three mechanisms to switch off the DC/DC converter. The first one could be developed by enabling or not the +28V input voltage. A switch (high power transistor) should be implemented al the input, controlling its ON and OFF states by acting on the gate voltage. The mentioned gate voltage could be directly driven by the Control Unit in terms of a TTL signal (+5V to switch it OFF, 0V to switch it ON). The main disadvantage of this method is the lost efficiency of the converter due to the power dissipated by the Switch, even chosen a low saturation Vds device.

A second mechanism to include this feature could be applied to the output in the same way that the previous one. The way it would be developed is analogue to the input case, but the disadvantage offered by this method in terms of efficiency of the whole converter is clear.

A third mechanism is based on acting directly on the Driver that generates the PWM signal. The circuit responsible of generating the proper PWM signal to control the switching of the converter is relatively easy to modify to include the ON/OFF feature. In all the DC/DC converters exposed, a feed-back loop is necessary to regulate the output with an adaptive PWM signal. That PWM will modify its duty cycle in order to dynamically increase or decrease the output voltage trying to reach a steady stage that, with independence of the loads, keeps the output voltage fixed. Due to this reason, if we could include a Switch inside that feedback loop, we would be able to modify the behaviour of the converter in terms of output voltage. Thanks to the fact that the converter doesn't give any output without the presence of a PWM signal, we would be able to activate or deactivate de feedback loop that control the generation or not of a PWM. The main advantage of this method is that acting on the loop, the efficiency of the DC/DC converter would be the same, as there is no extra element placed on the input or the output, but only a switch opening or closing the path of the optocoupled output voltage sample that will provide or not a PWM signal, enabling or disabling the DC/DC converter.

3.1.3.6. Interfaces

At this stage of the project, the preliminary interfaces defined in TABLE 5 have been defined.

TABLE 5. Interfaces of the DC/DC converter.

Signal	From	To	Interface / Connector
Input DC Voltage	Rover (or similar)	PDU	MDM 15 pins
+5V, 200 mA	PDU	Electronic control block	MDM 15 pins
+12V, 500 mA	PDU	Sensor head	MDM 15 pins
-12V, 500 mA	PDU	Sensor head	MDM 15 pins
ON/OFF (+5V/0V)	Electronic control block	PDU	MDM 15 pins

3.2. AC CURRENT POWER SOURCE (Prototype 3)

3.2.1. Introduction

As already indicated in section 2, the PDU of the NEWTON instrument is composed of the DC/DC conversor and the AC current source. The AC current source drives the primary winding of the sensor unit. In the case of prototype 1 and 2, it is not required to implement an individual AC current source, therefore the generation of the AC current will be implemented as part of the Electronic Control Unit by means of using a frequency generator and an external amplifier placed in the Sensor Unit. In the case of prototype 3, the demand of the AC current needs and ad hoc development, which is based on a Full-Bridge switching as described in this section. In this preliminary stage, the design of this source has been developed.

Before starting with the design of this power supply, it is necessary to select the adequate technologic options which are described in the following points:

1. LEVEL 1 - INTELLIGENT POWER INTEGRATION (ON/OFF CONTROL): At Level 1, electronic intelligence augments a standard analog-based design. The intelligence provides limited on/off control functions such as start-up sequencing, automatic shutdown and watchdog fault detection functions.

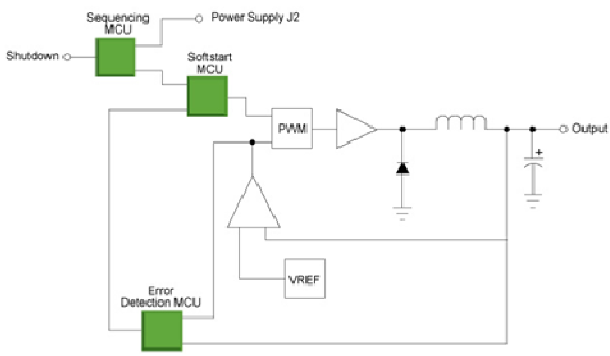


FIGURE 27. Level 1 - Basic elements.

Intelligence can be added to an existing power supply design with minimal modifications. Level 1 integration typically involves monitoring and basic control functions, so microcontrollers which integrate voltage comparators and ADCs are good choices. Additionally, communications peripherals may be required. Many microcontrollers, as Microchip's PIC10F and PIC12F 8-bit low pin count and small package microcontrollers with built-in peripherals, such as ADC, PWM and GPIOs, can make the existing analog power supplies intelligent by controlling the output sequencing and monitoring of input/output voltage, current and temperature.

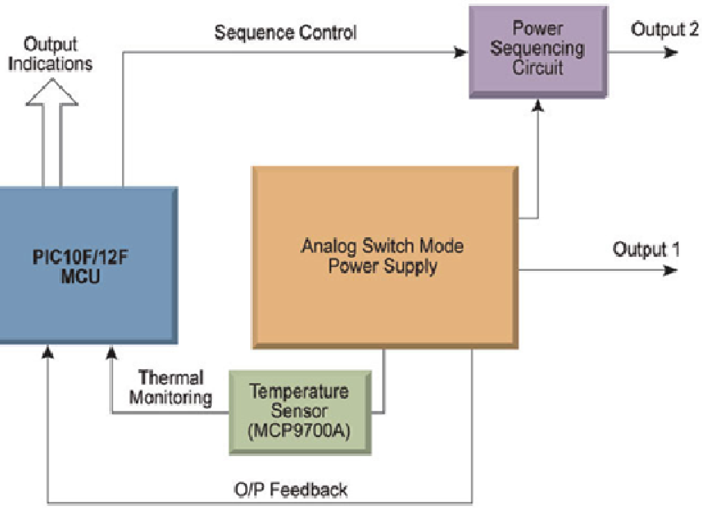


FIGURE 28. Level 1 - Integration example.

2. LEVEL 2 - INTELLIGENT POWER INTEGRATION (PROPORTIONAL CONTROL): This integration level adds additional digital control to the standard analog design and Level 1 basic control features to actively adjust the output voltage, voltage limits, current limits and thermal limits. At this level, most of the operating parameters of the analog power supply can be digitally controlled and monitored. For instance, the output voltage can be fine-tuned to provide coordination between multiple power supplies in a system. Depending on the system I/O requirements, 8-bit solutions, like in the PIC12, PIC16 or PIC18 device families, can provide good performance, while larger systems may require the flexibility of a 16 bit microcontroller, as the included in PIC24 family.

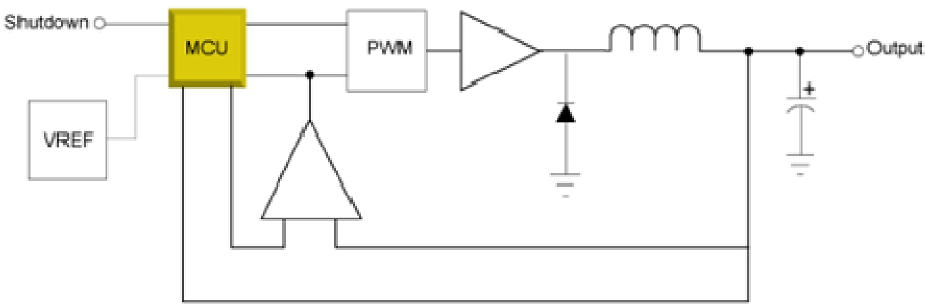


FIGURE 29. Level 2 - Basic elements.

A Level 2 control system has much greater integration with the power supply and allows better power supply environment monitoring. Integrated comparators can also be used to ensure fast response to system events or faults. A PWM peripheral is used to provide direct control of the analog PWM circuitry of the power unit, and can control the power-up conditions to provide soft-start. The MCU can monitor the power supply input current during the soft-start to ensure that components are not over-stressed. Serial communication peripherals allow coordination from a host device, control and monitoring of cooling fans and temperature sensors.

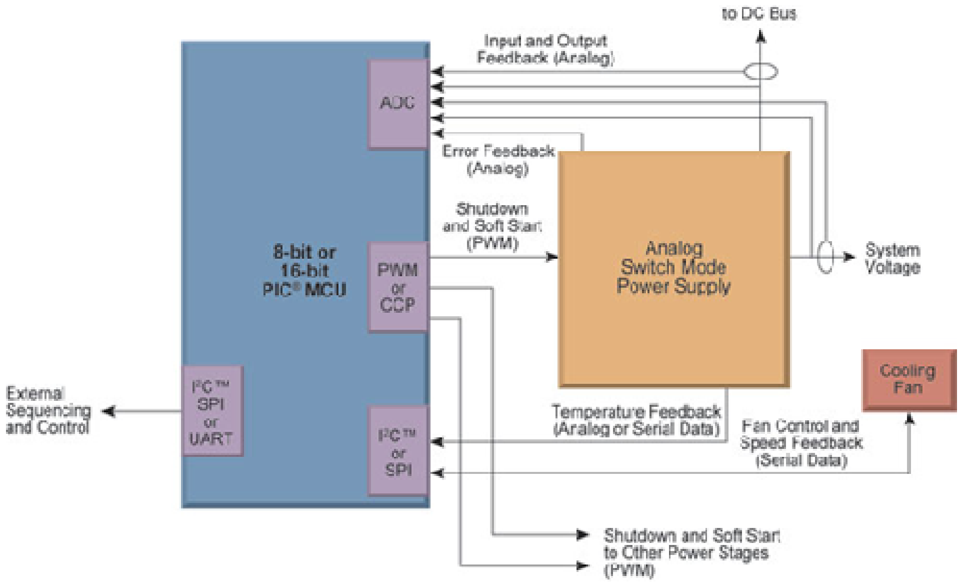


FIGURE 30. Level 2 - Integration example.

3. LEVEL 3 - INTELLIGENT POWER INTEGRATION (TOPOLOGY CONTROL): In addition to Level 1 and Level 2 features, this level permits the standard analog design to be reconfigured, including changing the analog loop configuration and alternating between two different analog control loop filters. For example, a power supply can change from a PWM control loop to a hysteretic control loop at light loads, thereby increasing system efficiency. Switching frequency adjustment can also be used to minimize losses. Microchip's entire range of PIC® MCUs and dsPIC® DSCs can assist in Level 3 control applications.

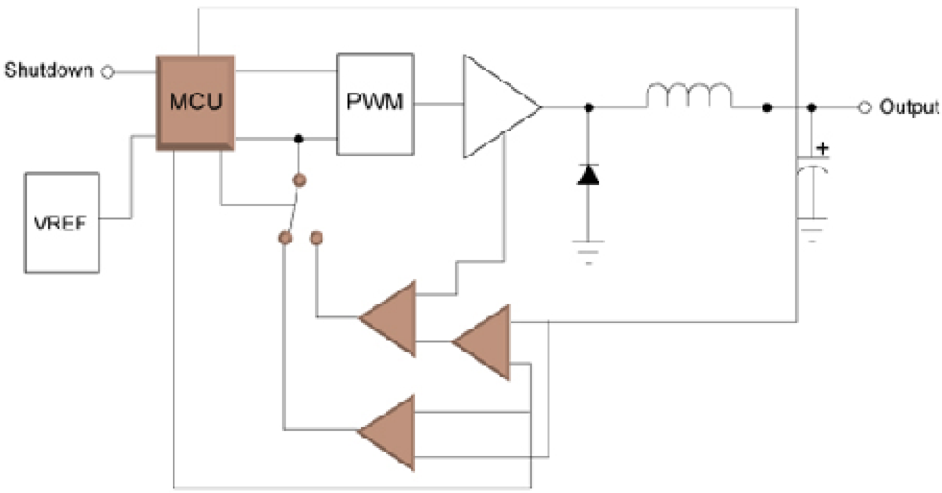


FIGURE 31. Level 3 - Basic elements.

For instance, Microchip's family of Digitally-Enhanced Power Solution offer a Programmable, Hybrid Power Controller combining a mid-voltage analog power stage (including analog control loop, MOSFET drivers, and sensing) with a microcontroller, enabling a user-configurable power converter. So, as an example, the PIC16F785 can be used in a Level 3 application due to the on-chip analog peripherals. The device has two analog PWM modules that can control power stages. Two error amplifiers and two high-speed comparators can be connected to the PWM modules in many ways through digital configuration. All pins associated with the error amplifiers and comparators are available externally so any type of analog control loop can be created. Twelve ADC inputs are available to monitor power supply operating parameters.

Mixed-signal solutions such as the PIC16F785 integrate an MCU with analog peripherals and are well-suited for topology control. In addition, the MCP1630 and MCP1631 PWM controllers are designed for PIC MCU power controller applications. PFC with Advanced Digital Control

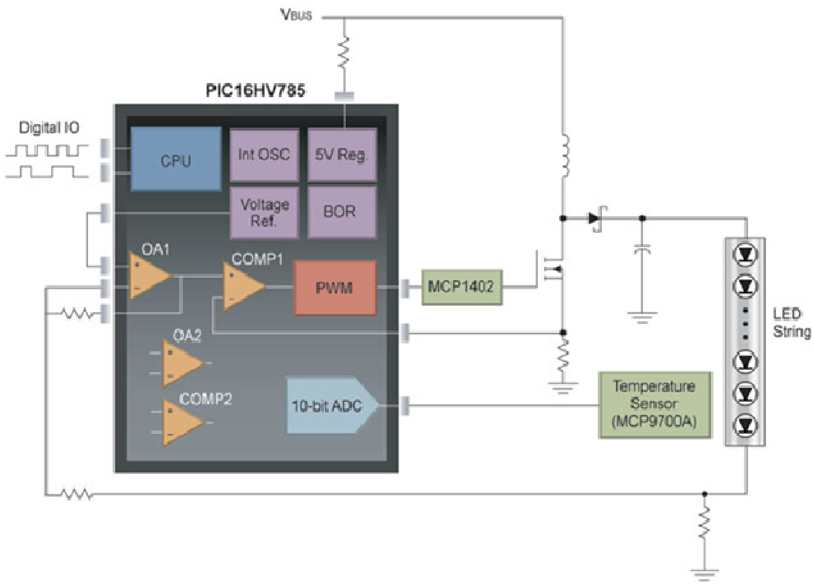


FIGURE 32. Level 3 - Integration example.

4. LEVEL 4 - FULL DC/DC CONVERSION: Full digital control replaces the standard analog design and also provides the power management functions of Levels 1-3 integration. The power supply regulation function is directly controlled by the digital circuits on the processor and the software running on the processor. The full digital solution allows the designer to employ techniques that are not possible with the analog solution, including proprietary digital compensation algorithms and non-linear control techniques. The full digital solution enables a customized response to power input change or load change events, which can lower system cost and increase system efficiency. Microchip's 16-bit dsPIC DSCs enable the Level 4 solution. Feedback from the power supply is obtained using high-speed ADCs. The power supply is controlled using specialized high-speed PWM peripherals. The PWM module can directly drive all popular power supply topologies and the CPU core allows digital compensation algorithms to be executed quickly. dsPIC DSCs can be used for various power conversion and power control applications, and they offer higher power density, lower system cost, improved reliability, and lower manufacturing and maintenance cost.

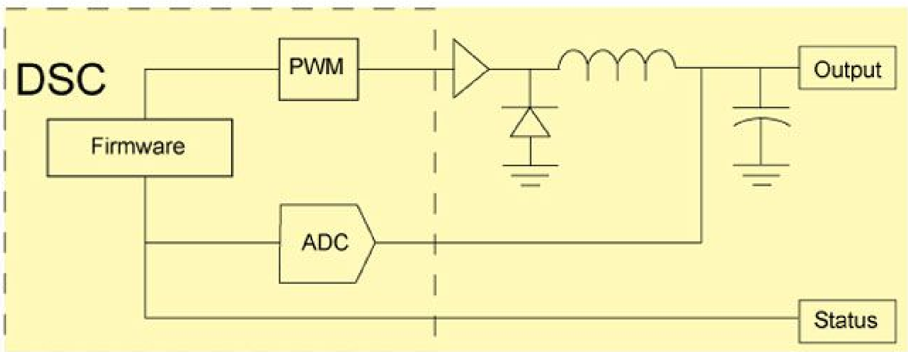


FIGURE 33. Level 3 - Basic elements.

Examples of the integration of the level 4 are shown below:

- **PFC with Advanced Digital Control:** Power Factor Correction (PFC) is essential in higher wattage power supplies to reduce harmonic contents, system losses and radiated emissions. In this example, the dsPIC DSC simplifies implementing Boost-PFC algorithms with the Average Current Mode Control technique. The current signal is calculated digitally by computing the product of the rectified input voltage, the output of voltage error compensator and output of voltage feed-forward compensator. Implementing the digital PFC function uses little of the DSC resources, leaving plenty of additional capability to perform the rest of the primary side control.

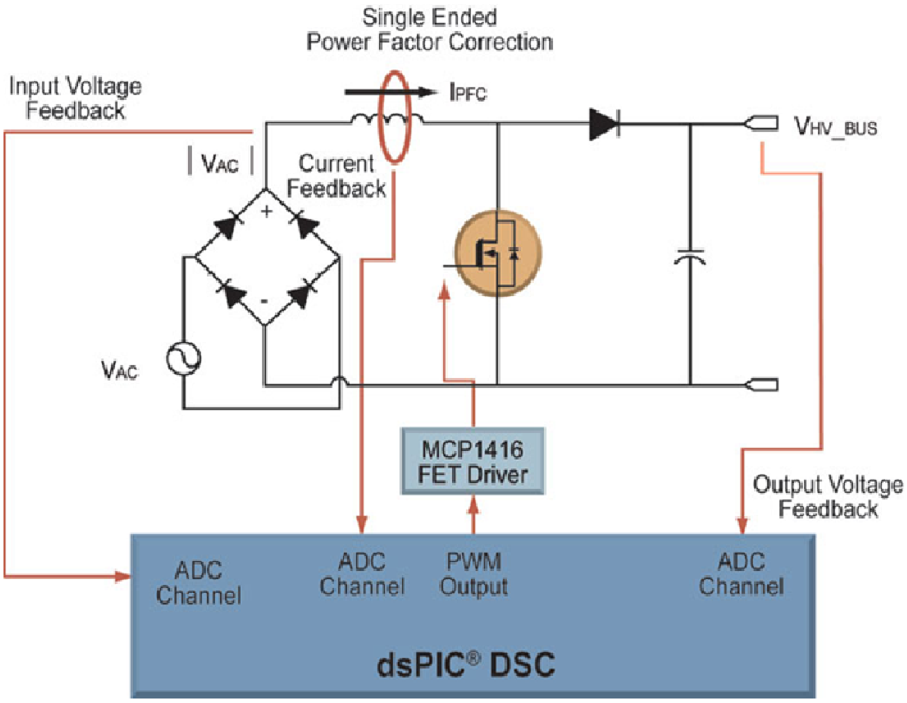


FIGURE 34. PFC with Advanced Digital Control.

- **AC-DC Conversion with Completed Digital Control:** To design an efficient, reliable, cost effective AC-DC power supply with advanced features, the family of dsPIC DSCs can help optimize design cycles effectively. The high-speed PWM module with multiple advanced operating modes helps implement various advanced conversion stages such as PFC, phase shift, zero voltage, transition converter with full-bridge conversion and synchronous rectification and multi-phase buck converters. The microcontroller´s high-speed ADC can be triggered on an edge of the PWM to sample the various voltages and currents for high speed processing. The high-performance CPU helps in implementing advanced PID digital control loops and compensators in software.

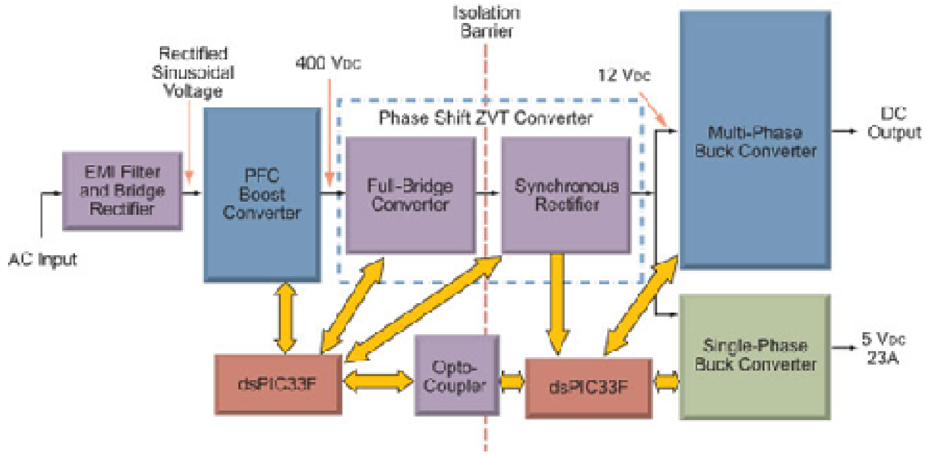


FIGURE 35. AC-DC Conversion with complete digital control.

- **Full Digital DC/DC conversion:** The dsPIC33FJXXGS dsPIC DSC in power efficient and highly integrated DC/DC converters dynamically controls different power stages. High-speed ADC, PWM and comparators work together without using much CPU bandwidth. Faster digital control loops and compensators can be executed using a high-performance DSP engine. Advanced features such as dynamic load response, protections, sequencing, remote control and communications can also be implemented.

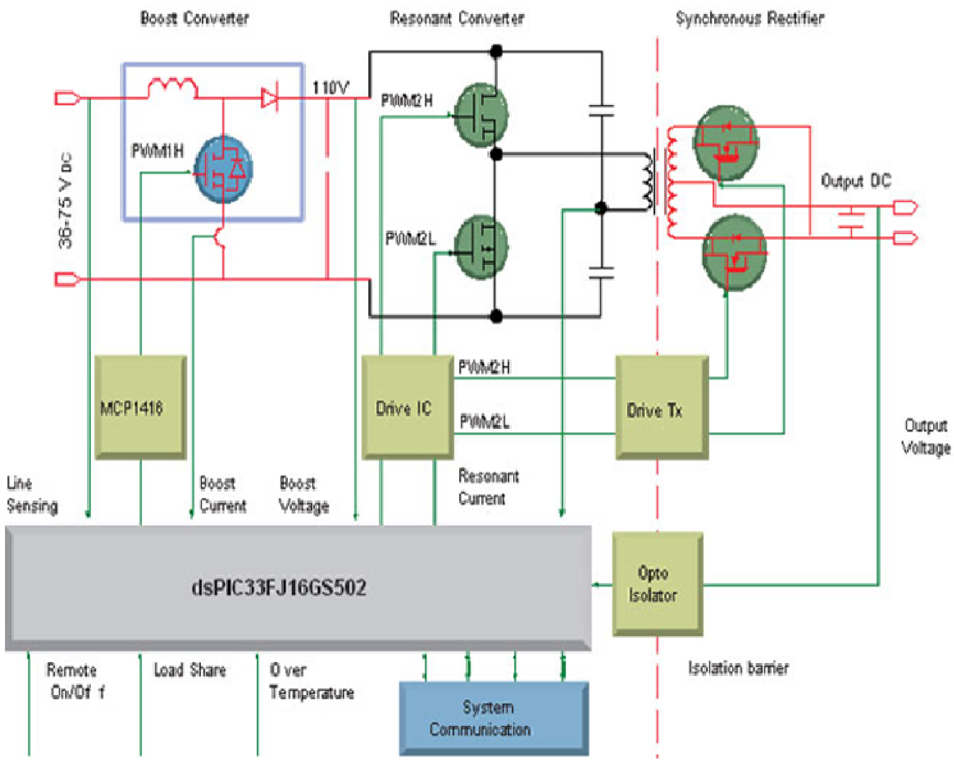


FIGURE 36. Full digital DC/DC conversion.

This last approach would be the better for NEWTON design, but as a previous stage, it is necessary to develop a solution with a more modest 8 bit microprocessor, to test the validly of the system as ilt is shown in next point.

3.2.2. Conversor Design

3.2.2.1. Electronic Design

The system basically must obtain two symmetrical outputs of +-40V and a very high current, to excite the solenoid that generates the heavy magnetic field, used to drive the detection head.

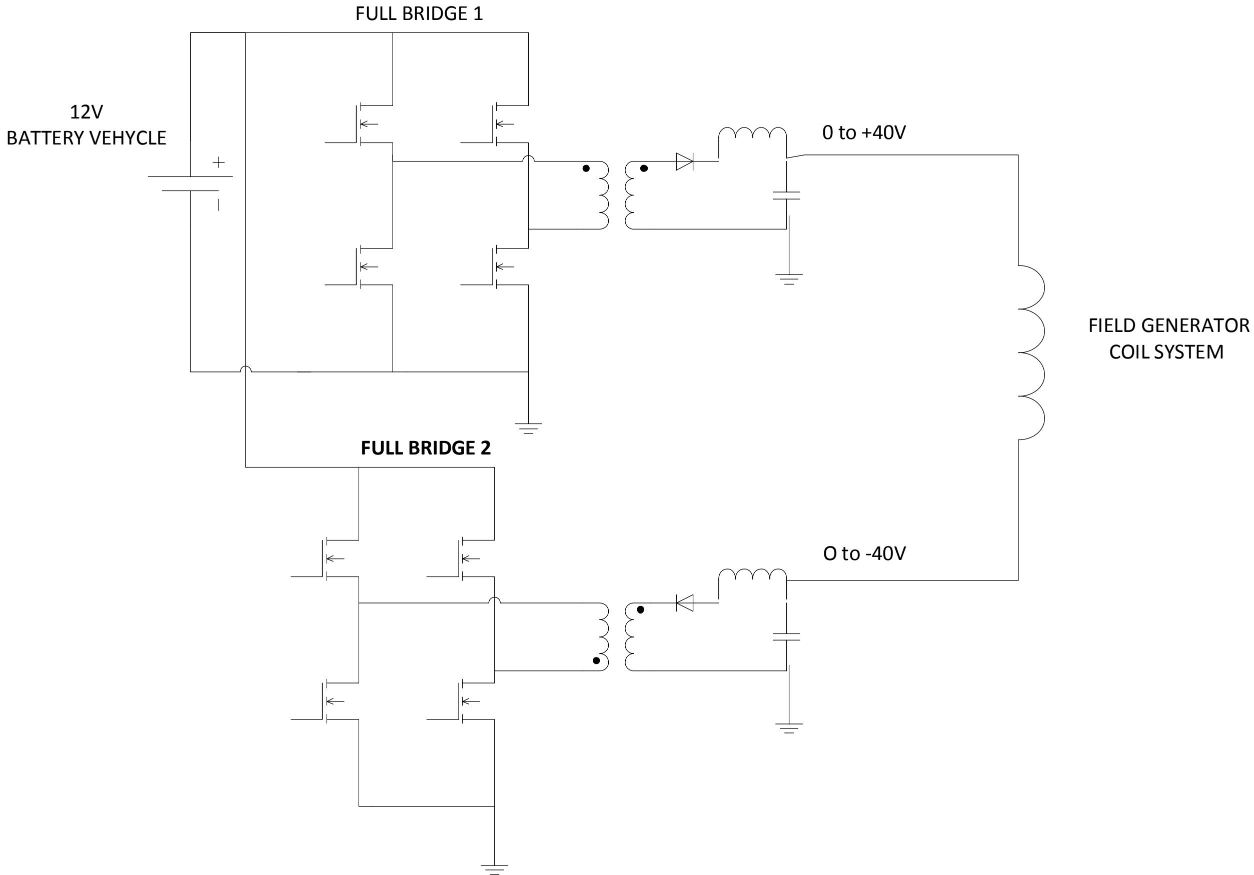


FIGURE 37. Schematic of the conversor developed for the prototype 3.

FIGURE 37 shows the schematic of the conversor developed for the prototype 3. The elements use in the design are: two full bridges sources, to obtain the maximal efficiency, and two transformers. Of course, all controls signals will be produced on a microcontroller system, as shwon in FIGURE 38.

In this case, a preliminary solution with two half bridges and the same two transformers, that will be exposed later, have been developed.

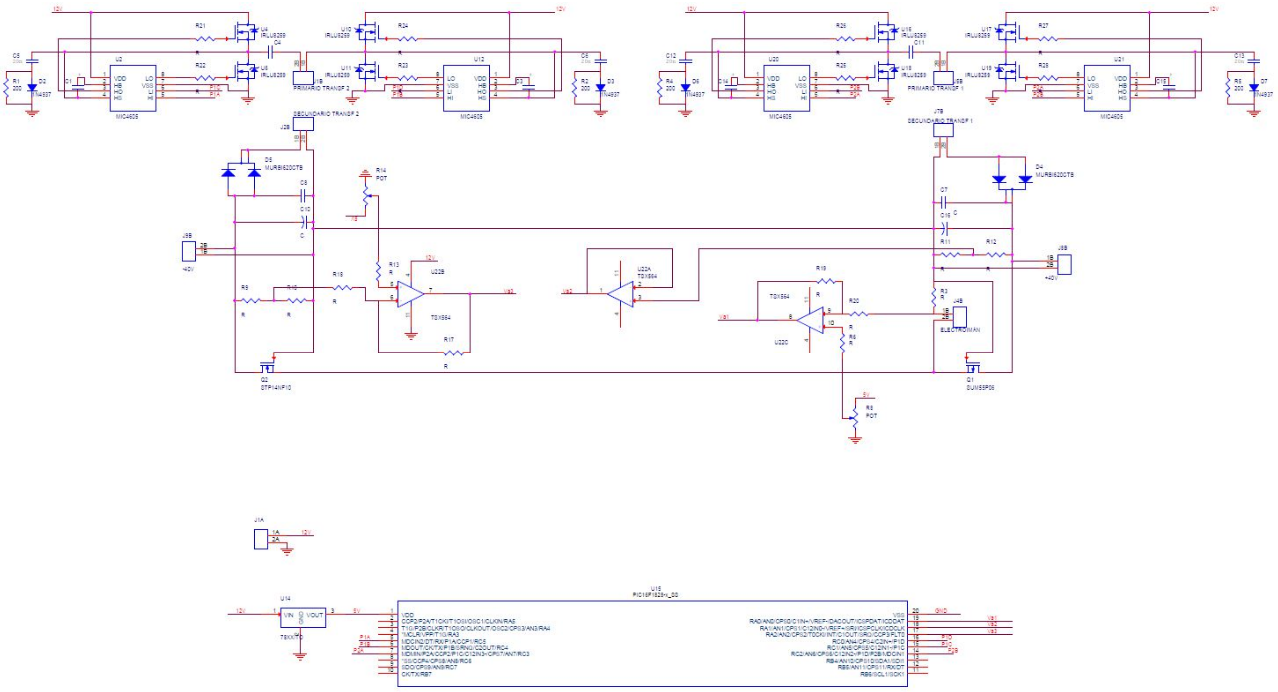


FIGURE 38. Design of the conversor including control.

The source has two different modes of operation:

- **Mode 1:** In this mode the source must generate a voltage that can be varied continuously from +40 V up to -40 with a maximum current of 10 A to power the electromagnet.
- **Mode 2:**In this mode the source must generate two adjustable voltages: one from 0 V up to 40 and the other from 0 up to -40, with a maximum current of 5 A. These voltages are used to power a class D amplifier capable of giving an AC excitation of +/- 40 V 5 A, in the 20Hz- 200Kz range, to power the solenoid.

Both working modes will not work simultaneously. The solution which has been developed is to make two independent sources that give from 0 to 40 V and from 0 to -40 V.

When the sources power the electromagnet, only the source of + 40 works if it has to give positive currents and the -40 if it has to give negative currents. The control of the magnetic field produced by the electromagnet, e is made through the measurement of the intensity in the resistor R3 of the circuit. Current control is carried out with the PWMs of the PIC16F1828 (U15) through the measurement of the voltage at its analogue input AN1, Ra1, Va2 must be between 0 and 5V the OP TSX564 U22A is responsible for adequately conditioning the signal.

When the sources are used to power the power amplifier both sources operate simultaneously and give adequate voltage to minimize power dissipated. The control of both voltages is done through the measurement of the voltage in the voltage dividers formed by the resistors R9, R10 in the negative branch and R11 and R12 in the positive one. The control is performed with the PIC16F1828 (U15) PWM by measuring the voltage at its analog inputs AN0, Ra0, Va1 and AN2 Ra2 Va3 the voltages must be between 0 and 5V the TSX564 U22C and U22B OPs condition the signals

For the sources, a bridge configuration with four mosfet has been chosen in order to give enough intensity to meet the requirements, they are driven by two drivers, they wereselected because they can be provided by different sellers and therefore easy to find for the realization of the first prototype. For the final design, a surface mount mosfet can be used. In series with the primary, a condenser has been placed to avoid the displacement of magnetic flux and two snubbers to reduce the energy dissipation in the mosfet. As the drivers give an output for a maximum capacity of 100pF and the capacity of the mosfet is higher, a resistance has been included on the doors so that the peak of current does not pull down the drivers.

3.2.2.2. Transformer Design

This section describes how the size of the transformer is estimated:

The current in the primary I_{in} will be:

$$Iin = \left(\frac{Vout}{Vin}\right).Iout \tag{3.2-5}$$

So, $\left(\frac{40}{12}\right).10$= 33 A will pass through primary wires

The dissipated power W in the transformer is $W = J.E.\left(\frac{1}{2}\right).Vol$, where E is the electric field, J the current density which we estimate on the order of 4 A / (mm * mm) and Vol the bobbin volume. If could be calculated in terms of the conductivity (σ) and the resistivity (ρ). With some assumptions, as 10% losses in winding, the resulting volume is 4000mm^3.

And, so we selectedthe transformer (with core former), which is shown in FIGURE 39.

Calculating the flow for a winding of Np turns we estimate self-induction and wind resistance by turn.

If we make the calculation for a 6 turns in the primary, with a switching frequency of 120 KHz, if in the secondary we have 10 A, on the primary the current is of 33.3 A.

Taking into account the skin effect, the largest permissible diameter is 0.5 mm. With this, the resistance is 0.032 Ohm, and the dissipated power is 35 Watts. If we put sixteen parallel wires, the power in the primary is then 2.2 Watts, what is an acceptable quantity. With this set-up, at secondary we would need a number of 20 turns and5parallel cables. With implies a total dissipated power at the core of 6 Watts.

With less turns in primary (3), the power in the primary now would be 1.2 Watts, and at the secondary, we will need 10 turns of five parallel cables, to obtain a total dissipated power at the core of3.5 W. So 2Watts at the coils and 3.5 at the core, which is quite compensated.

The section occupied by the coils is 37 mm^2 and the section available on the coil is197.2 mm^2, so there is plenty of room to reel. Therefore, it would be preferable to make the transformer with 6 coils and would increase the number of conductors in parallel to the coil and reduce the resistance

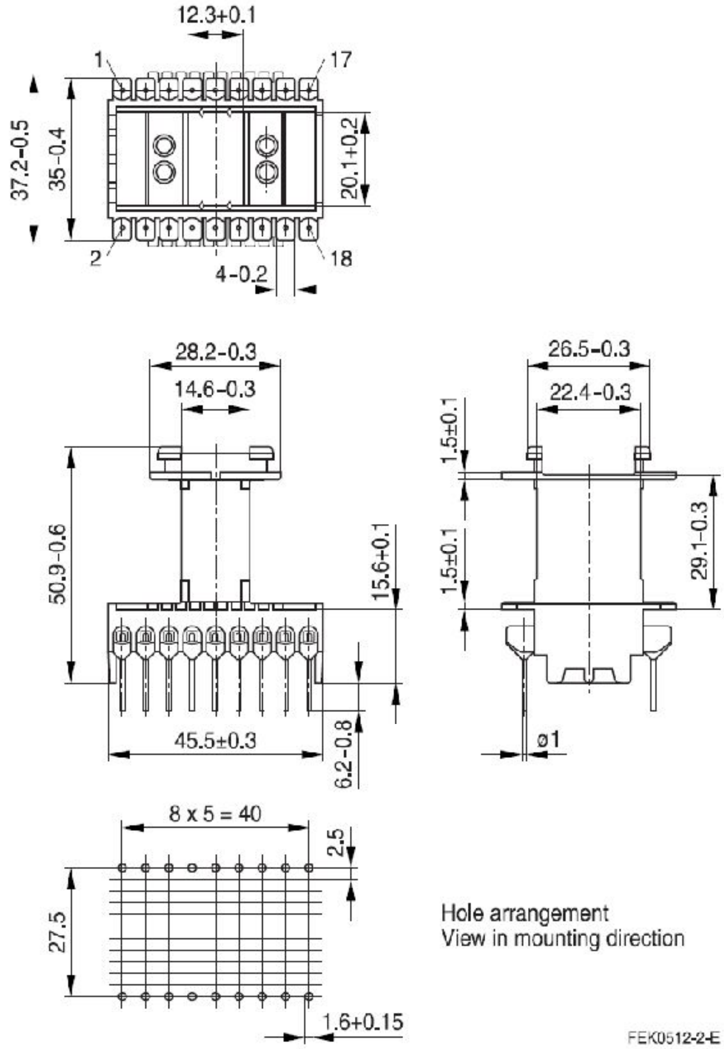


FIGURE 39. Selected transformer.

3.2.2.3. Board Design

FIGURE 40 shows the PCB designed for the current source of NEWTON instrument prototype 3. This board is under manufacturing, therefore it has not been possible to validate the performance of this part of the design. This taks will be developed during the next stage of the project.

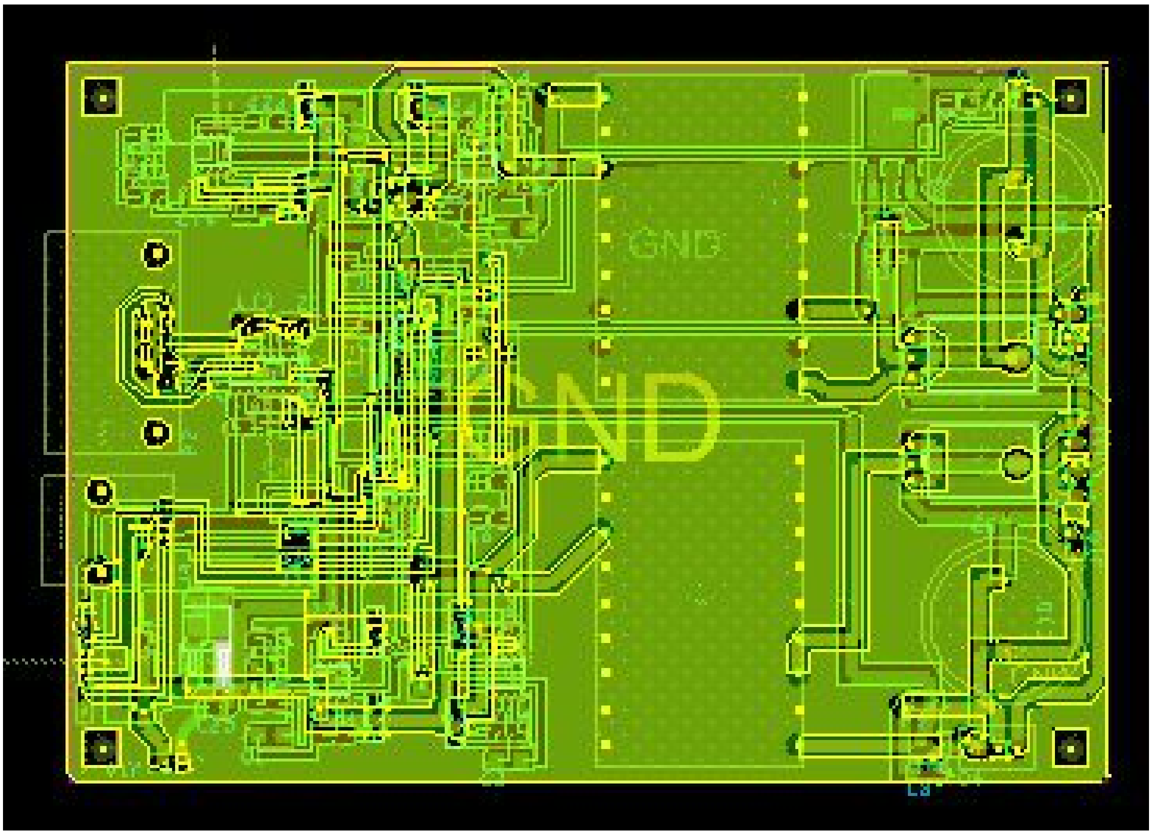


FIGURE 40. Picture of the board designed for the source of the prototype 3.

4. PROOF-OF-CONCEPT AND VALIDATION

4.1. DC/DC CONVERTER (Prototype 1, 2 and 3)

4.1.1. Flyback DC/DC converter

FIGURE 41 shows the prototype manufactured for the validation of the Flyback converter. The performance of this prototype has been evaluated in the laboratory for an output voltage of 12V. The results obtained from the validation of this PCB are shown in TABLE 6 while FIGURE 42 represents the main parameters obtained from the validation of the Flyback converter.

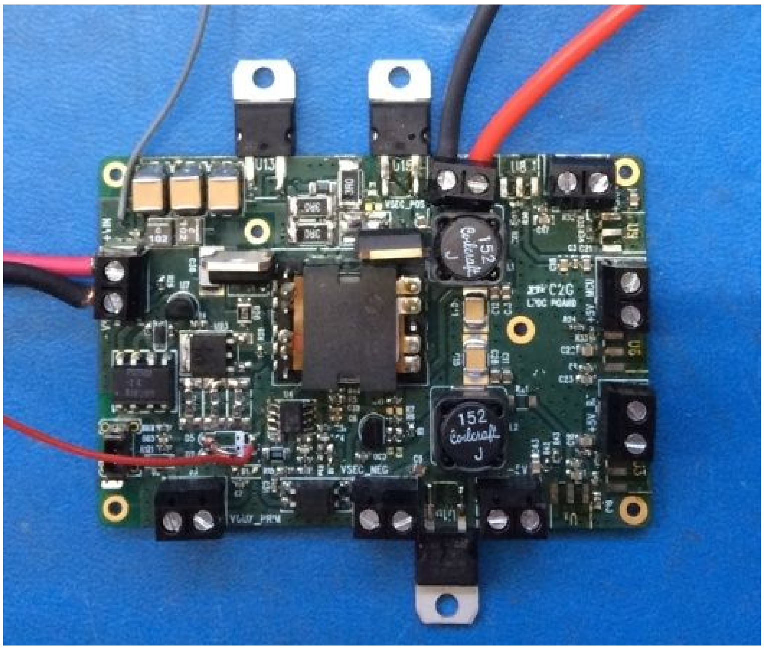


FIGURE 41. Prototype manufactured for the validation of the Flyback converter.

TABLE 6. Results obtained from the validation of the Flyback converter.

V_{in}(V)	I_{in}(A)	P_{in}(W)	V_{out}(V)	I_{out}(A)	P_{out}(W)	Efficiency(%)	P_{diss} (W)
28.00	0.14	3.92	12.13	0.20	2.43	61.89	1.49
28.00	0.22	6.16	12.11	0.30	3.63	58.98	2.53
28.00	0.28	7.84	12.07	0.40	4.83	61.58	3.01
28.00	0.34	9.52	12.05	0.50	6.03	63.29	3.50
28.00	0.42	11.76	12.04	0.60	7.22	61.43	4.54
28.00	0.49	13.72	11.95	0.70	8.37	60.97	5.36
28.00	0.51	14.28	11.35	0.80	9.08	63.59	5.20

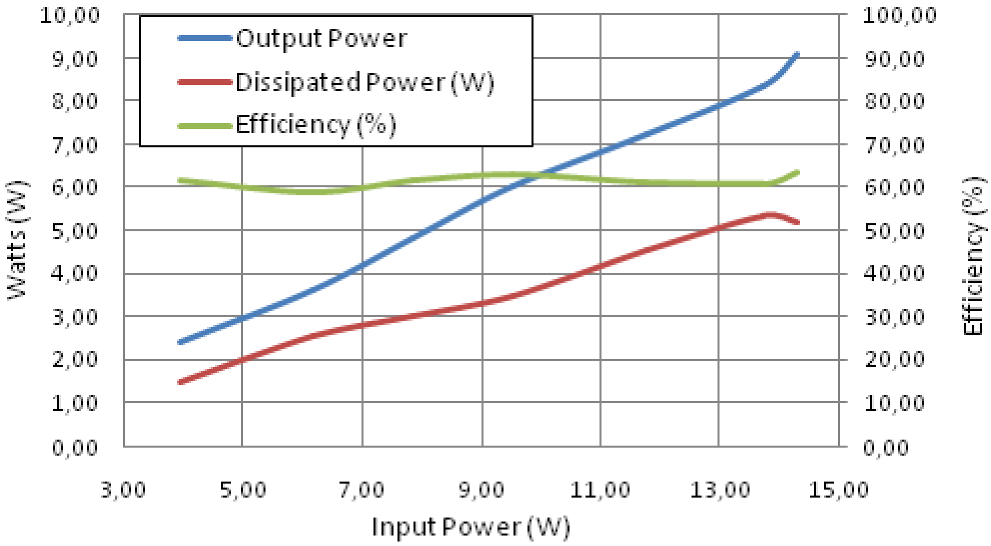


FIGURE 42. Results obtained from the validation of the Flyback converter.

The results obtained from the measurements of the Flyback converter asses the performance observed during the design period. Though this kind of DC/DC converters are suitable for medium power applications, the fact of having only one switch doesn't provide good efficiency at very low loads, due to the intrinsic losses of this architecture.

4.1.2. Half-Bridge DC/DC converter

FIGURE 43 shows the prototype manufactured for the validation of the Half-Bridge converter. TABLE 7 and FIGURE 44 represent the results obtained from the measurement of the converter in the laboratory.

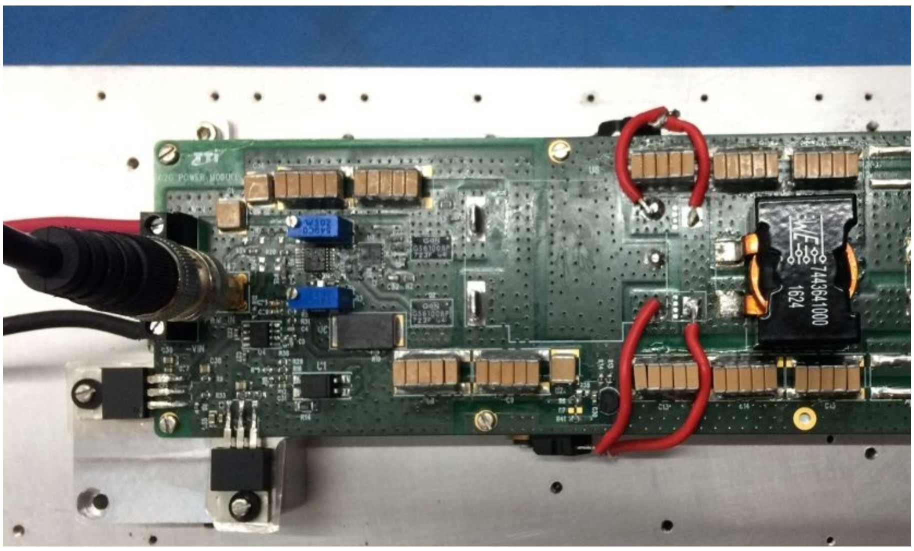


FIGURE 43. Prototype manufactured for the validation of the Half-Bridge converter.

TABLE 7. Results obtained from the validation of the Half-Bridge converter.

V_{in}(V)	I_{in}(A)	P_{in}(W)	V_{out}(V)	I_{out}(A)	P_{out}(W)	Efficiency(%)	P_{diss} (W)
28.00	0.19	5.32	12.00	0.30	3.60	67.67	1.72
28.00	0.24	6.72	12.00	0.40	4.80	71.43	1.92
28.00	0.29	8.12	12.00	0.52	6.22	76.55	1.90
28.00	0.33	9.24	12.00	0.60	7.20	77.92	2.04
28.00	0.38	10.64	12.00	0.70	8.40	78.95	2.24
28.00	0.43	12.04	12.00	0.80	9.60	79.73	2.44
28.00	0.48	13.44	12.00	0.90	10.80	80.36	2.64
28.00	0.53	14.84	12.00	1.00	12.00	80.86	2.84
28.00	0.78	21.84	12.00	1.50	18.00	82.42	3.84
28.00	1.04	29.12	12.00	2.00	24.00	82.42	5.12

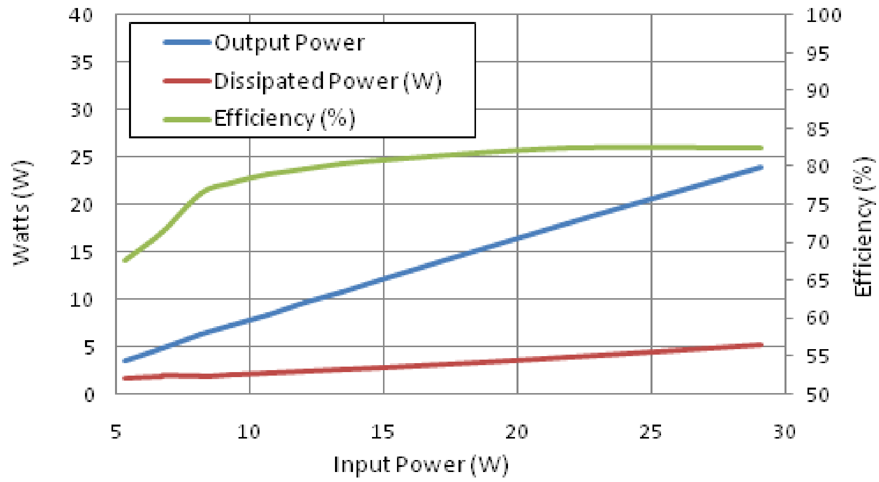


FIGURE 44. Results obtained from the validation of the Half-Bridge converter.

As it can be seen in the obtained results, the efficiency for an output current of 500mA (maximum required) is around 76%, almost 15 points better than the efficiency obtained from the Flyback converter. This is due to a better optimization of the magnetic core usage thanks to the two primary switches, but still low for the desired NEWTON DC/DC Converter performance.

There are some possible improvements to be consider for a future stage, such as selecting a more suitable transformer which allows the use of a better duty cycle, closer to 40-45% in order to stress both switches and rectifier diodes in a more symmetrical way, or study each individual component requirements trying not to oversize each element in excess. Some derating must be considered when we are designing the converter, even more knowing the critical application in which it's going to be placed, but a trade-off must be carefully carried out during the final design and selection of components process.

Even taking all these considerations into account, it would be hard to reach efficiency values over the 80% at 6W output load conditions. Some possible topologies could be based on generating 13W output power (all the output voltages and currents hanging by the same Half-bridge converter), but the efficiency would always be below a value of 85% in a very optimistic case.

4.1.3. Buck DC/DC converter

FIGURE 45 shows a picture of the demo board used for the validation of the buck converter topology.

FIGURE 45. Demo Board for the proof-of-concept of the buck converter.

The buck converter has been validated in the laboratory with the measurement setup shown in FIGURE 46. As can be seen, PWS signal (0-5V) shown in FIGURE 47 is applied by means of using an external signal generator set to Hi-Z output mode. The frequency is set to 300 kHz while the duty cycle is 44%.

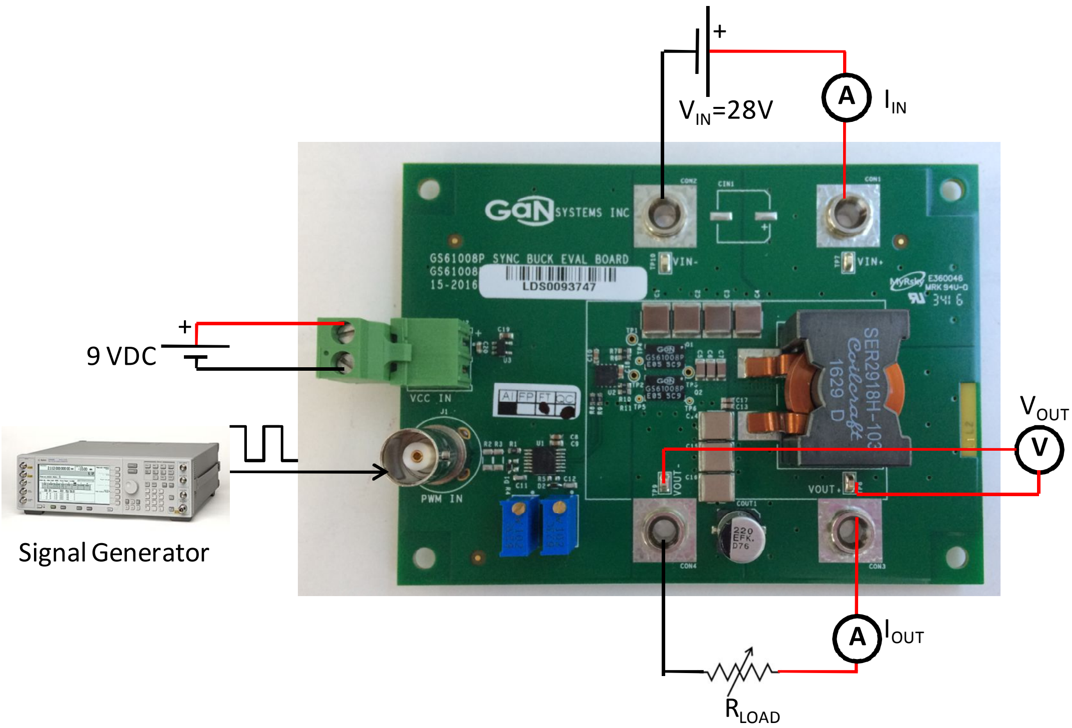


FIGURE 46. Measurement setup for the validation of the Buck converter.

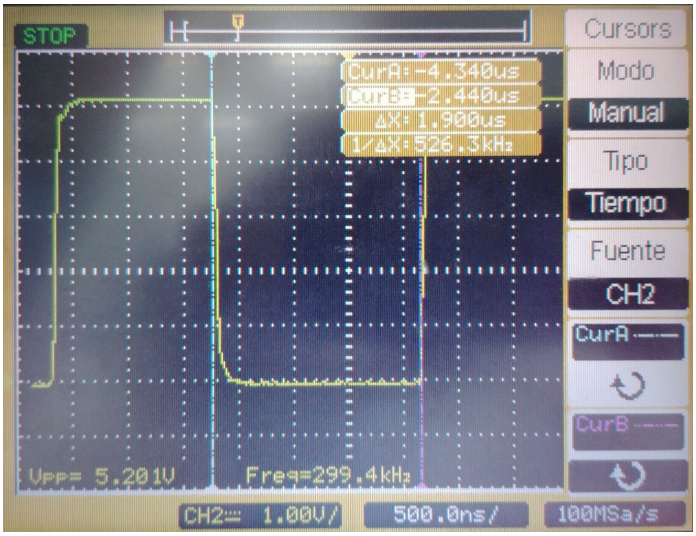


FIGURE 47. Buck converter main PWM signal.

TABLE 8 and FIGURE 48 shows the results obtained from validation of Buck converter.

TABLE 8. Results obtained from the validation of the Buck converter.

V_{in}(V)	I_{in}(A)	P_{in}(W)	V_{out}(V)	I_{out}(A)	P_{out}(W)	Efficiency(%)	P_{diss} (W)
28.00	0.09	2.60	12.00	0.20	2.40	92.17	0.20
28.00	0.14	3.81	12.00	0.30	3.60	94.54	0.21
28.00	0.18	5.04	12.00	0.40	4.80	95.24	0.24
28.00	0.22	6.24	12.00	0.50	6.00	96.09	0.24
28.00	0.27	7.48	12.00	0.60	7.20	96.31	0.28
28.00	0.31	8.71	12.00	0.70	8.40	96.46	0.31
28.00	0.36	9.94	12.00	0.80	9.60	96.58	0.34
28.00	0.40	11.17	12.00	0.90	10.80	96.67	0.37
28.00	0.44	12.40	12.00	1.00	12.00	96.74	0.40
28.00	0.67	18.70	12.00	1.50	18.00	96.24	0.70
28.00	0.89	25.00	12.00	2.00	24.00	95.98	1.00

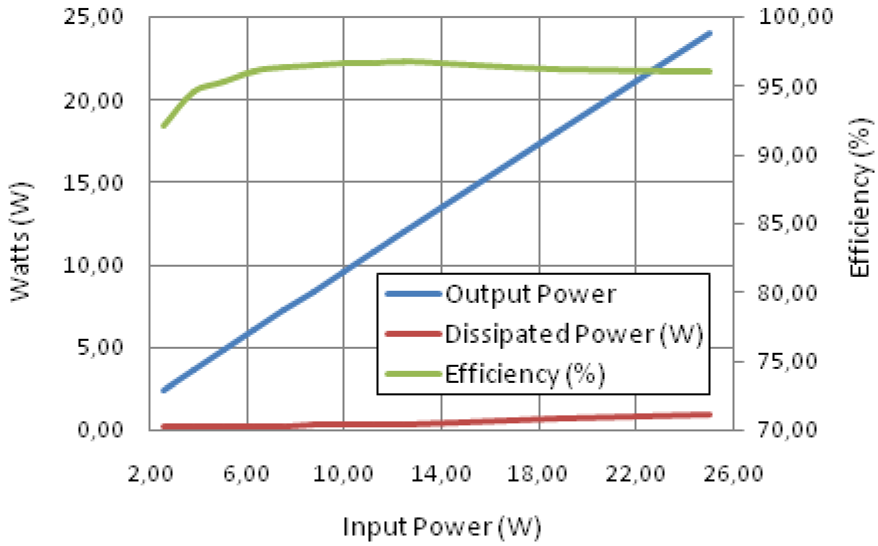


FIGURE 48. Measurement results obtained from the validation of Buck converter.

The results obtained from the synchronous Buck converter have been quite good. It offers great efficiency values from low to high loads while having a reduced size and components cost. Due to the simplicity of the design and the proven performance, this topology was found as the most promising one from a not isolated point of view.

The only disadvantage of this architecture is the need of placing one of them for each required output voltage, while multiple outputs could be obtained from a simple isolated converter. The total size can be easily reduced by adjusting the maximum rating of each component to the requirements of the NEWTON DC/DC converter, so the disadvantage of placing a synchronous Buck per output wouldn't be critic.

5. ANALYSIS OF RESULTS AND FUTURE WORK

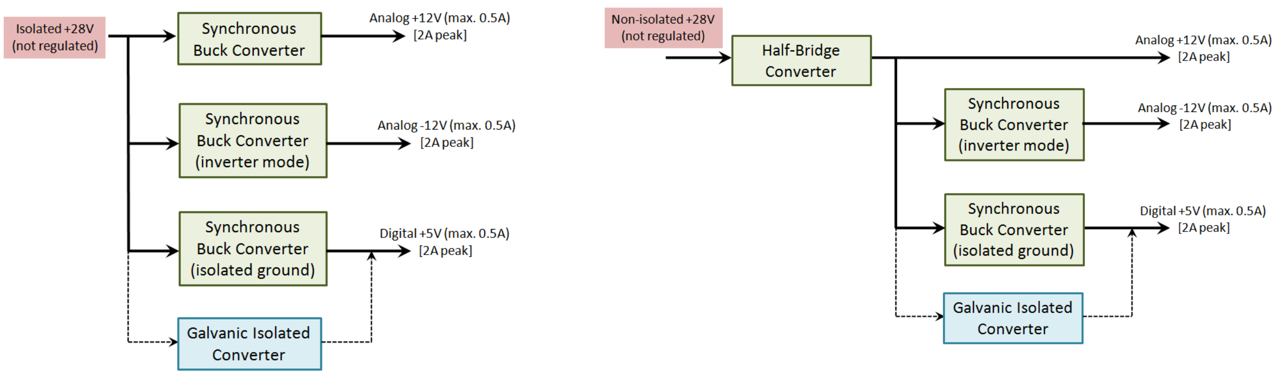
During this stage of the project the preliminary design of the power distribution unit has been developed. With this regard, different topologies for the DC/DC conversor have been analyzed with the aim of selecting the most adequate and efficient solution for the NEWTON PDU. Three different solutions have been designed and implemented, i.e. Flyback, Half-Bridge and Buck converter.

Preliminary validation results show that synchronous Buck converter provides really high values of efficiency, i.e. around 96%, while it has a reduced size and mass. In the case of isolated topologies, Flyback converter has been discharged due to the low efficiency obtained at the required loads. In the case of Half-bridge, although preliminary results show an efficiency close to the 80%, which is considered a good value, it is far from the efficiency provided by the synchronous Buck converter.

Considering these results, two different lines of work can be distinguished depending on the way in which the power supply isolation is obtained. If we consider that the not-regulated +28V that supply the NEWTON DC/DC converter already offers huge isolation from the main supply of the system, a synchronous Buck based architecture can be deployed, obtaining a very good efficiency-volume-cost ratio. In the other hand, if the +28V input doesn't guarantee isolation from a main supply, galvanic isolation should be implemented, and an architecture based on a main Half-Bridge converter and some synchronous Bucks hanging from a main output line could be a good option. These two lines of work are still open as the Consortium is working on the implications at rover level that an non-isolated power supply is used.

Regarding the isolation required between the analogue and digital outputs, another two different lines can be adopted. This fact is independent from the necessity of having galvanic isolation between the input and the outputs, and is only related to the nature of the outputs and the devices they are going to be supplied. As the design of the instrument is still on-going, the need of isolation between analogue and digital outputs is still open. If digital requirements allow a simple ground isolation (i.e. to avoid ground noise feedbacks and analogue ground interferences) a non-isolated converter would be selected to generate the +5V output. If that isolation is not considered enough from a digital point of view due to potential fluctuations of the current demanded by the analogue side, an isolated converter should be implemented.

FIGURE 49 shows two possible DC supply architectures in case of requiring or not isolation from the +28V input, with some modifications depending on the isolation type offered between outputs.



(A) Example of not isolated DC/DC PSU (B) Example of isolated DC/DC PSU

FIGURE 49. Different DC PSU depending on the input-output and output-output isolation required.

During the next stage of the project and in the framework of WP3, T3.3, the final design of the DC/DC converter will be developed. The first step will be to analyze these points in detail and select the final architecture of the PDU. With regard to the AC current source, it has not been possible to achieve preliminary validation results during this stage of the project. The PCB is under manufacturing, therefore, the validation, as well as the final design, will be carried out in the following stage of NEWTON project.

6. SUMMARY AND CONCLUSIONS

This document reports the preliminary design of the power distribution unit for the three prototypes of NEWTON instrument. As described in section 2, the three prototypes share the same architecture and the same key building blocks, i.e. the Power Distribution Unit (PDU), the Electronic Control Unit (CU) and the Sensor Unit (SU). The PDU is composed by a DC/DC conversor and the AC current source.

With regard to the DC/DC conversor, it generates the secondary voltage lines that supply the CU and the SU. First step of the preliminary design has been to define the design requirements. These requirements have been determined taking into account the scenarios of application of NEWTON as well as the design requirements defined for the blocks which interface with the DC/DC converter, i.e. the sensor unit and the electronic unit. Prototype 1 and prototype 3 share the same requirements. With regard to the prototype 2, the difference is that NEWTON prototype 2 will operate on Earth in the field of civil engineering application, therefore the space operation requirements applicable to prototype 1 and 3 are not required in prototype 2. Therefore, the same design is adopted for the three prototypes with the peculiarity that the design of prototype 2 is not necessary to be adapted for space applications.

One of the main and more challenging requirements of the DC/DC converter is its efficiency, especially in space applications. With this regard, although, there is no concrete requirements in terms of efficiency, the target is to achieve maximum efficiency (>90%) in order to save a maximum electrical power. Similarly, there are no concrete requirements with respect to size and weight. However, the target is also to reduce the size and weight of the conversor while the efficiency is maximized.

With the aim of finding the best approach for the specific design of the DC/DC converter considering the features of the three prototypes, different isolated and non-isolated topologies of DC/DC sources have been analyzed and compared in terms of efficiency, power, design complexity, reliability and flexibility of the whole system. In particular, a Flyback converter, a Half-Bridge conversor and a Synchronous Buck conversor have been designed and experimentally validated in order to study the advantages and drawbacks of them. Preliminary validation results show that Buck converter provides really high values of efficiency, i.e. around 96%. In the case of isolated topologies, Flyback converter has been discharged while Half-Bridge converter can be a possible isolated solution due to preliminary results provide an efficiency close to 80%.

After analyzing these preliminary results, two different lines of work can be distinguished depending on the way in which the power supply isolation is obtained. If we consider that the not-regulated +28V that supply the NEWTON DC/DC converter already offers huge isolation from the main supply of the system, a synchronous Buck based architecture can be deployed, obtaining a very good efficiency-volume-cost ratio. In the other hand, if the +28V input doesn't guarantee isolation from a main supply, galvanic isolation should be implemented, and an architecture based on a main Half-Bridge converter and some synchronous Bucks hanging from a main output line could be a good option. These two lines of work are still open as the Consortium is working on the implications at rover level if an non-isolated power supply is used.

With regard to the AC current source, the requirement of the AC current needs to implement and ad hoc development in the case of prototype 3. (In the case of prototype 1 and 2, it is not required to implement an individual AC current source, therefore the generation of the AC current will be implemented as part of the Electronic Control Unit and the Sensor Unit). This ad hoc design is based on a Full-Bridge switching conversor. A PCB has been designed and it is under manufacturing process. Therefore, the AC current source cannot be validated during this stage of the project and these activities will be developed in the next phase of NEWTON and the final design of the AC current source will be also carried out.

It is important to highlight that, the design developed at this stage of the project is a preliminary design, therefore the environmental requirements for space applications have been considered, but COTS have been used. For the final design of the PDU, it will be identified/used components with equivalents that are space qualified, in such a way that the final PDU to be developed for prototypes 1 and 3 will make use of components suitable for an EM, but assuring that there is available a space qualified version, that can allow a quick transition to a FM PDU. The final design of the PDU will be reported in the next D3.6 which is planned to be submitted in April 2018.

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