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COMMISSIONING OF IMPERIX B-BOARD PRO CONTROLLER

TURKU AMK
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BACHELOR'S THESIS | ABSTRACT

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Turku University of Applied Sciences' New Energy Research Center is tasked with producing a power electronics study module for the degree programme of Energy and Environmental Technology. Additionally, they also do Research, Development, and Innovation work in the field of power electronics. Some of the tools used for this are a BoomBox controller, manufactured by a Swiss company called Imperix, and components compatible with it, such as sensors and DC-to-DC converter modules. Currently there are devices for only one system. To increase capacity newer B-Board PRO controllers have been acquired from Imperix and they need to be commissioned to be useful. The purpose of the commissioning is to have controllers that can be used in the same way as the already existing controller system.

The B-Board PRO is made as an embeddable controller, which meant that it could not be used out-of-the-box. In order to commission them an assessment into what additional components are required alongside the controller was made, so it could interface with the research group's pre-existing power electronics equipment. Technologies used in the interfacing were assessed and it was noticed that adapters were required to connect sensors to the controller in addition to optoelectronics couplers for using the DC-to-DC converter modules. The new controller also functions with a different MATLAB based software development kit to the pre-existing Imperix controller. This development kit will simultaneously be taken into use with the B-Board PRO.

To test the functionalities of the B-Board controller and the software development kit components required for a laboratory exercise were specified. This laboratory exercise will be implemented using Imperix's components and development kit. For the laboratory exercise a DC-to-DC converter capable of charging and discharging a battery was selected, because this went together with ongoing projects at the New Energy Research Center. The DC-to-DC converter control software was implemented using the new software development kit, and requirements for the battery system were written.

Due to a strict time limit the laboratory exercise was not physically implemented, because the necessary adapters, optoelectronic couplers, and battery system were not acquired or realised. To test the converter and battery they were implemented as a model in Simulink and simulated. So that the exercise could be constructed in the future, the necessary steps were planned and future work in the form of possible improvements were devised.

KEYWORDS:

Converters, Electricity, Electronics, Simulation

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IMPERIX B-BOARD PRO -OHJAIMEN KÄYTTÖÖNOTTO

Turun ammattikorkeakoulun Uuden energian tutkimusryhmän vastuulla on järjestää tehoelektroniikan opintomoduuli energia- ja ympäristötekniikan koulutusohjelmaan. Lisäksi he tekevät tutkimus-, kehitys- ja innovaatiotoimintaa tehoelektroniikkaan liittyen. Näissä tehtävissä käytetään Sveitsiläisen Imperix-nimisen yrityksen valmistamaa BoomBox-ohjainta ja sen kanssa yhteensopivia komponentteja, kuten sensoreita ja DC/DC-muunninmoduuleita. Näitä järjestelmiä on kuitenkin vain yksi, ja kapasiteetin lisäämiseksi on hankittu saman valmistajan uudempia B-Board PRO –ohjaimia. Niiden hyödyntämiseksi ne täytyy ottaa käyttöön. Käyttöönoton tarkoituksena oli saada ohjaimia, joita voidaan käyttää samalla tavalla kuin jo olemassa olevaa järjestelmää.

B-Board-ohjain on sulautettavaa elektroniikka, mikä tarkoitti, että sitä ei voitu ottaa suoraan käyttöön. Käyttöönottamiseksi tehtiin selvitys mitä ohjaimen rinnalle tarvittaisiin, jotta se voitaisiin yhdistää tutkimusryhmän käytössä oleviin tehoelektroniikan opetus- ja tutkimuskomponentteihin. Selvityksessä tutkittiin liittämiseen käytettyjä tekniikoita, ja yhteensopivuuden huomattiin vaativan sekä adaptereita, joilla olemassa olevat sensorit saataisiin kiinni ohjaimeen, että optoelektronisia muuntimia DC/DC-muunninmoduulien käyttämiseksi. Uusi ohjain vaatii myös toimiakseen uuden MATLAB-pohjaisen ohjelmistokehityspaketin, joka otettiin ohjaimen kanssa samaan aikaan käyttöön.

B-Board-ohjaimen ja ohjelmistokehityspaketin toimivuuden testaamiseksi määriteltiin vaadittavat komponentit laboratoriotyötä varten, joka tultaisiin toteuttamaan Imperixin komponenteilla ja ohjelmistokehityspaketilla. Laboratoriotyöksi valittiin akun purkamiseen ja lataamiseen kykenevä DC/DC-muunnin, sillä tämä sopi hyvin yhteen tutkimusryhmän käynnissä olevien projektien kanssa. DC/DC-muunnin suunniteltiin uuden ohjelmistokehityspaketin avulla, ja sen kanssa käytettävälle akkujärjestelmälle kirjoitettiin vaatimukset.

Aikarajan vuoksi laboratoriotyötä ei toteutettu fyysisesti, sillä adaptereita, optoelektronisia muuntimia ja akkujärjestelmää ei ehditty hankkia tai toteuttaa. Laboratoriotyön testaamiseksi ennen näiden puuttuvien osien hankkimista DC/DC-muunnin ja akusto mallinnettiin ja simuloitiin Simulink-ohjelmalla. Jotta laboratoriotyö voidaan joskus toteuttaa, suunniteltiin loppuun viemiseen vaadittavat toimenpiteet, ja pohdittiin mahdollisia parannuksia.

ASIASANAT:

Elektroniikka, Muuntimet, Simulaatio, Sähkö

CONTENT

LIST OF ABBREVIATIONS

ASIC	Application Specific Integrated Circuit
BMS	Battery Management System
CC	Constant Current
CPU	Central Processing Unit
FET	Field Effect Transistor
FPGA	Field Programmable Gate Array
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NERC	New Energy Research Center
PI	Proportional Integral
PWM	Pulse Width Modulation
SoC	System on a Chip
V2G	Vehicle to Grid

LIST OF FIGURES

1 INTRODUCTION

Turku University of Applied Sciences' New Energy Research Center (NERC) is tasked with producing courses for the Environmental, Energy and Chemical Engineering degree programme and this includes a Power Electronics Systems study module [1]. For teaching purposes, they have acquired half-bridge and full-bridge modules from a Swiss company Imperix. The modules are building blocks used in building various power electronics circuits and they are controlled by an external controller, BoomBox, also by Imperix. Currently there is only one of these controllers and it is not an optimal solution for an environment where multiple student groups are doing power electronics laboratory exercises since it can only control one circuit at a time. Additionally, the controller is now deprecated.

To increase the number of students doing exercises simultaneously, 5 additional controllers have been purchased from Imperix. Since the BoomBox is now deprecated the controllers are from their new B-Board PRO embeddable controller line. Because the controllers are embeddable in nature and not usable out-of-the-box they need to be commissioned. Suitable adapters to make interfacing between the B-Board and existing Imperix sensors will also need to be specified. In this thesis a small student exercise for the Power Electronics study module will be designed and implemented on the new Imperix hardware to commission them. In the exercise the students will implement control logic for a DC-to-DC converter and perform measurements while charging and discharging a battery with DC-to-DC converter. The design process of this exercise consists of selecting a suitable battery, battery management system for the battery and design of the DC-to-DC converter used in the exercise.

In addition to producing courses for the degree programme of Environmental, Energy and Chemical Engineering it also does research in the same field. One of the research project NERC is involved in requires the use of a bidirectional DC-to-DC converter for a Vehicle-to-Grid application and if the research group is to develop its own converter, the work done in this thesis would be a valuable introduction into developing and implementing such a converter with the group's existing Imperix hardware.

Structurally this thesis is divided into 6 main chapters. In this first chapter the premise and goal of this thesis is shortly introduced, and in chapter 2 the main technologies important to this thesis are shortly explained. Chapter 3 is devoted to developing

requirements, based on which the work done in thesis will be carried out and Chapter 4 describes this process of implementing simulation models based on the requirements. Chapter 5 shows the process of running the simulation done in the previous chapter and testing the software used for development during this thesis. Finally in chapter 6 conclusions about the work are presented and work to be done in the future is planned.

2 TECHNOLOGIES OVERVIEW

In this chapter the technologies found within the devices used in this thesis are introduced. The introductions begin with a short overview of Battery Management Systems and Field Programmable Gate Arrays. The focus is on DC-to-DC conversion and basic technologies used in the conversion as it is fundamentally related to the product being commissioned and its usage within the research group.

2.1 Battery Management System

Battery Management System (BMS) is an individual device with its own hardware and software [2] that can measure key parameters of the battery and its operation. BMS devices are essential in ensuring safe and optimal operation of a battery or a battery pack. In conjunction with the battery charger, they prevent battery health threatening conditions such as over discharging and over charging.

The core functionalities of a Battery Management System are to measure battery cell voltages, measure current going to and coming from the battery and, if multiple cells are used, balance the voltage between the battery cells. In **Figure 1** a simple BMS device that implements low side current measurement, voltage measurements and balancing for 4 battery cells is depicted. The balancing is done passively by turning the excess charge of the selected cells into heat in the balancing resistors, occupying the left side of the pictured BMS. All functionality on the depicted BMS is handled by the controller located in the lower left corner in the picture.

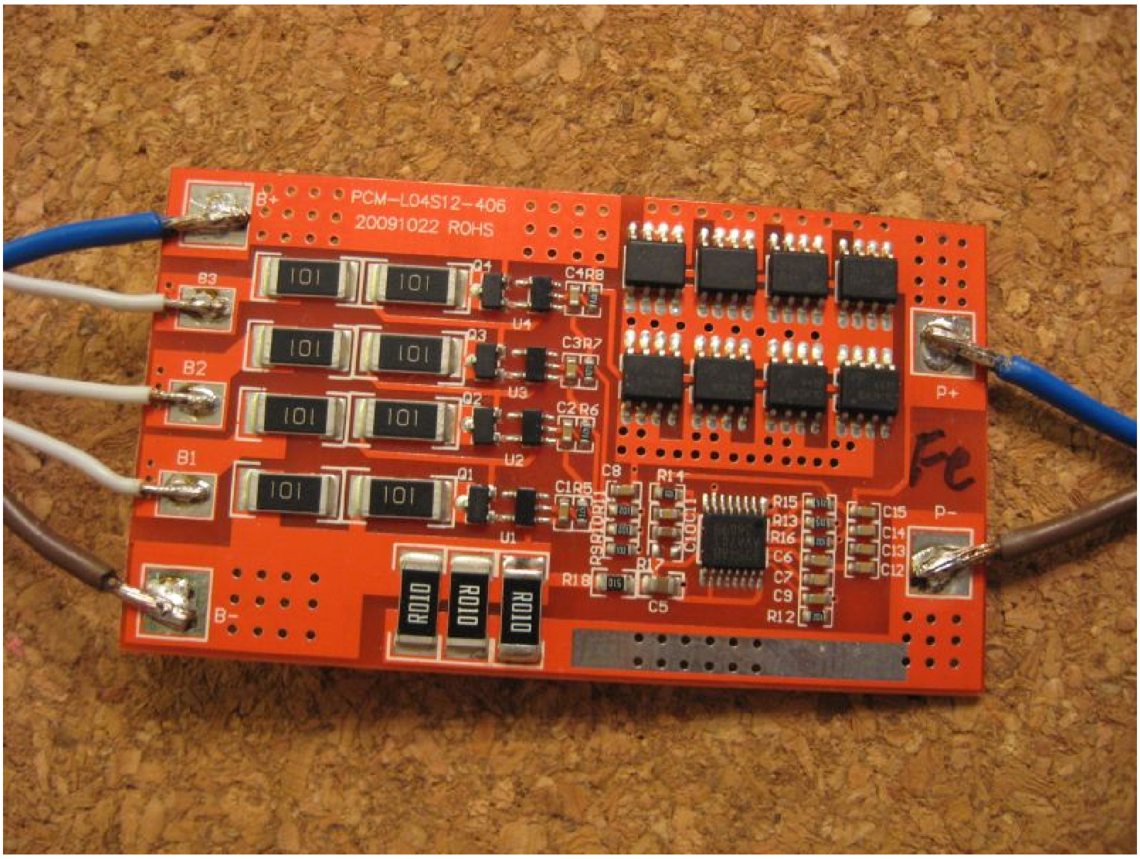

Figure 1. A simple Battery Management System with passive cell balancing (Picture by Hadhuey - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=25132721)

2.2 Field Programmable Gate Array

Field Programmable Gate Arrays (FPGA) are a family of integrated circuits where the functionality of the device is configurable by the user. Internally FPGAs comprise of input-output blocks that handle communications to the outside of the FPGA, and logic blocks that together with programmable interconnects are configured to execute the user's desired application logic. Programming of these internal blocks is done with hardware description languages, the two most popular ones being VHDL and Verilog [3]. Invented by Xilinx co-founder Ross Freeman in the 1980s [4], FPGAs offer certain advantages over traditional processors and their use cases are for example high performance computing, Application Specific Integrated Circuit (ASIC) prototyping and wireless communications equipment [5]. The common factors between the use cases are

flexibility and high performance and these are also the two big advantages offered by FPGAs [6].

In **Figure 2** 2 FPGAs can be seen, and their appearance is very similar to other integrated circuits packaged in black epoxy but usually larger in size due to a large number of internal components. The FPGA is not a stand-alone device and needs supporting components like power supplies to function and that can be seen in **Figure 2**.

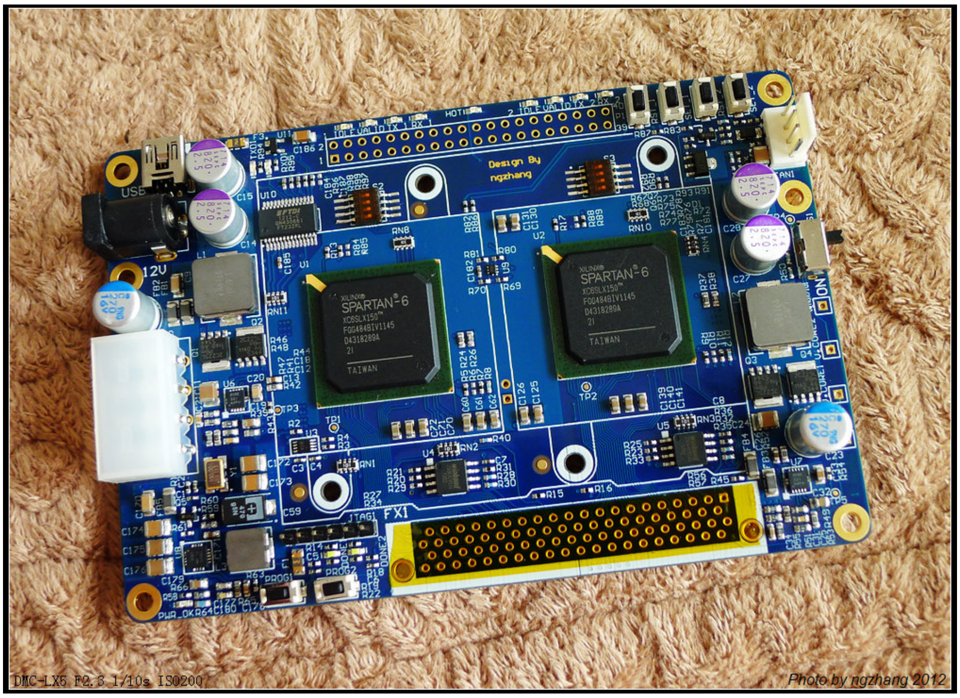

Figure 2. 2 FPGAs mounted on a printed circuit board with supporting components (Picture from commons.wikimedia.org, CC0)

Many modern FPGAs, including the one used in the B-Board PRO, have a so-called System-on-a-Chip (SoC) structure. They contain most processors and controllers needed by the system internally. The SoC used in the B-Board PRO contains the FPGA and additionally 2 central processing unit (CPU) cores. In **Figure 3** the internal structure of the SoC used is depicted split into the two parts. On the top are the CPU cores and on the bottom is the FPGA side and the functionalities handled by it.

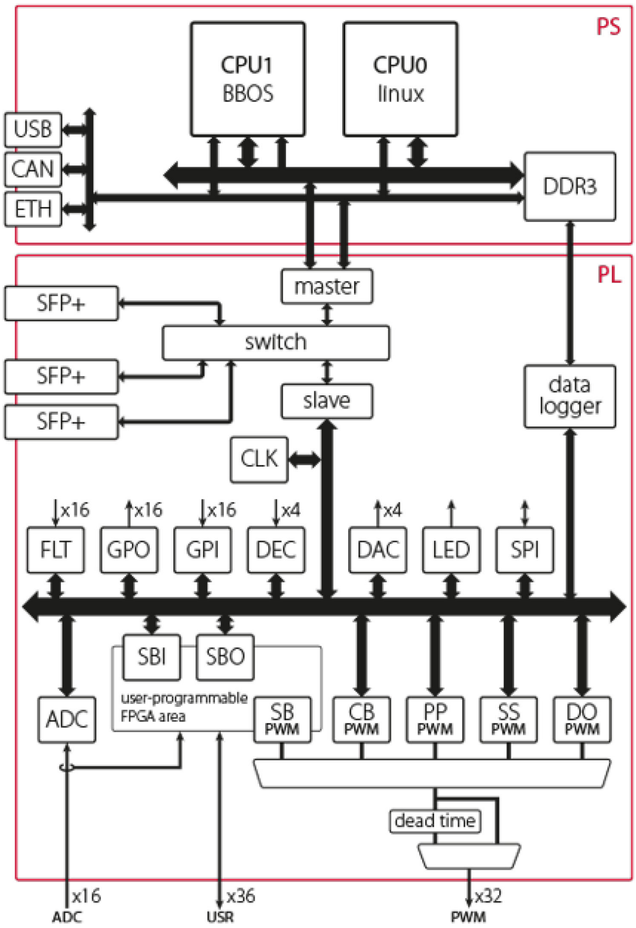

Figure 3. Internals of a Xilinx ZYNQ SoC containing an FPGA and 2 CPU cores (Picture from imperix.com)

2.3 DC-to-DC converter

The purpose of a DC-to-DC converter is to convert the voltage at the input to another voltage at the output. The voltage at the output can be made lower, called stepping down or bucking the voltage, or higher, called stepping up or boosting. Other variations to the conversion include inverting the polarity of the voltage or allowing the current to flow in either direction creating a bidirectional converter. The different operation modes that the converter can operate in can be given in quadrants on the cartesian system of coordinates. These quadrants are shown in **Figure 4**.

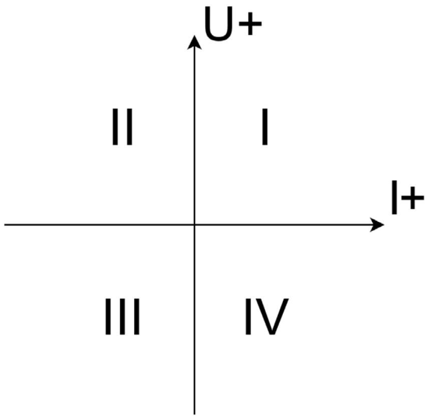

Figure 4. Current-Voltage coordinates with the operating quadrants numbered I-IV

A converter which only allows current to flow from source to load and does not invert the output voltage would only operate in quadrant **I** as shown in **Figure 4**. There are various methods of achieving DC-to-DC conversion, two of which will be discussed in further detail in this thesis.

2.3.1 Linear Regulation

Linear regulation is a very simple form of regulation that is cost effective and suitable for powering low power devices, for example a microcontroller with a 3.3V operating voltage from a 5V source. A typical linear regulator can only operate in quadrant **I** from **Figure 4**, and it can only step down the voltage. The resistors R_1 and R_2 seen in **Figure 5** are chosen so, that at the desired output voltage the voltage at the non-inverting terminal of

the error amplifier is the same as the reference voltage U_{ref} [7]. Because of this the output voltage is fixed, but the regulator does smooth fluctuations in the input voltage.

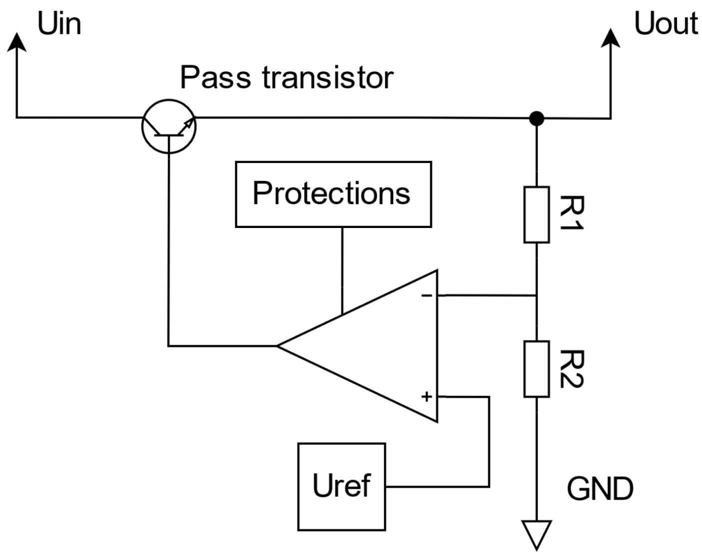

Figure 5. Simplified block diagram of a linear regulator with closed loop control

The regulating element in a linear regulator is the pass transistor [7], it limits the current flow from input to output and any additional power is turned into heat, mostly in the pass transistor. Because of this the efficiency of a linear regulator is poor and dependeds on the input voltage. The equation:

$$\eta = \frac{U_{out} \times I_{out}}{U_{in}(I_{out} + I_Q)} \tag{1}$$

gives the efficiency η of the linear regulator. I_Q is the quiescent current, or the self consumption, of the regulator at idle. For a typical use case of converting 12V to 5V with an output current of 1A and a quiescent current of 5mA, equation 1 gives an efficiency of 41.5%. The efficiency can be improved by lowering the input voltage, but the equation for defining minimum input voltage

$$U_{in} \geq U_{out} + U_{dropout} \tag{2}$$

says that it needs to be atleast $U_{dropout}$ higher than output voltage. A typical minimum value for $U_{dropout}$ is 2 Volts [7]. In this best-case scenario of converting the minimum amount of voltage the efficiency would be 71.1%.

2.3.2 Switch Mode Regulation

In switch mode regulators, instead of dissipating excess power as heat, only the required amount of energy is transferred from the source to the load. This is achieved with inductors or capacitors, that can temporarily store energy in their magnetic field or electric field, and switches to let the energy flow into the storage.

In **Figure 6** a simplified block diagram of a switching regulator is given with generic block names. In practice the switch is some variant of a transistor, typically an Insulated Gate Bipolar Transistor (IGBT) or some form of a Field Effect Transistor (FET). The energy storage can be a capacitor, inductor or even the transformer windings in the case of some isolated designs. The *Switch Controller* opens and closes the *Switch*, and the most common form of switching signal is some sort of a Pulse Width Modulated (PWM) signal [7].

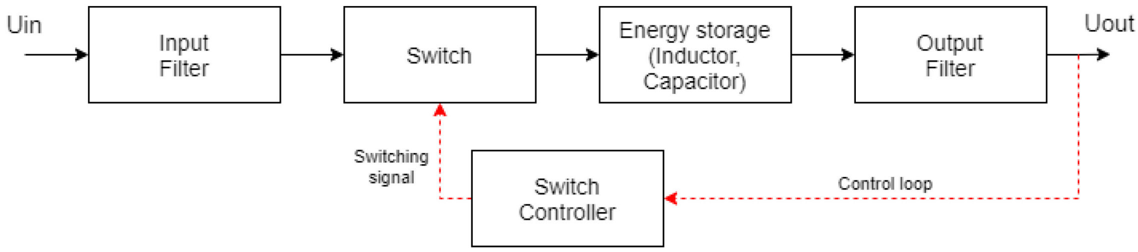

Figure 6. Block diagram of a switching regulator

A PWM signal is seen in **Figure 7** where T is the period of the signal and t_{on} is the time that the signal is on. T can be calculated from the frequency f of the signal with

$$T = \frac{1}{f}. \tag{3}$$

In a PWM signal t_{on} can be changed creating a different duty cycle. Duty cycle d can be calculated with the formula

$$d = \frac{t_{on}}{T} \tag{4}$$

The output voltage of a switching regulator is directly affected by the duty cycle of the switching signal and allows the output voltage to be variable, unlike in the linear regulator.

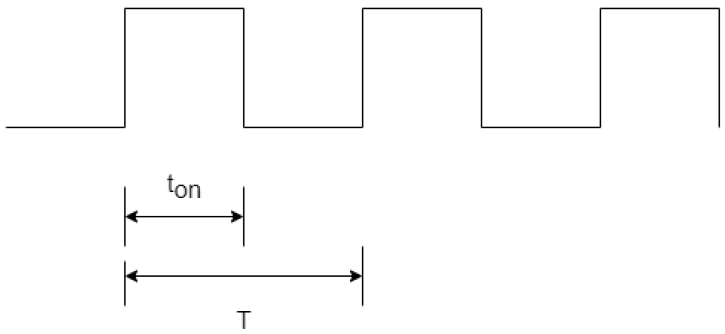

Figure 7. Pulse width modulated signal

The relationship between the energy storage element and switching signal's frequency is the same whether the storage is capacitive or inductive. The size of the storage can be decreased if the frequency is increased [7].

$$P(L) = \frac{I^2 \times L \times f}{2} \tag{5}$$

$$P(C) = \frac{V^2 \times C \times f}{2} \tag{6}$$

For both inductive and capacitive energy stores the power stored in them is affected by the frequency. In practice smaller inductors and capacitors both in value and physical size are easier and cheaper to get, but the switching frequency cannot be raised indefinitely. The switching transistors are limited in the speed of their switching, Metal-Oxide-Semiconductor FETs (MOSFET) being capable of the fastest switching from commonly used switching transistors. Another effect of higher switching frequencies and smaller components is that the device will be harder to make electromagnetically compliant with standards [7]. In common designs the switching frequency is limited to hundreds of kilohertz.

Efficiency of a switching regulator can be much higher than in a linear regulator. Instead of continuously dissipating the extra energy as heat, energy is only taken when the switch is closed, and the switch has lower losses than the pass transistor that limits current in the linear regulator. Most of the losses in the switch occur during the short periods of transitioning when the PWM signal either turns on or off, otherwise the switch is either

fully on or fully off, where it is at its most efficient. A switching regulator can have an efficiency over 97% [7].

2.3.3 Isolated and Non-Isolated

Depending on the requirements of the converter design, a galvanic connection between the input and output might not be permitted. Two common reasons for using an isolated converter design are safety and high conversion ratios. By changing the ratio of the primary and secondary windings in the isolating transformer the bucking or boosting effect of the converter can be improved over non-isolated designs. **Figure 8** shows that the input and output are isolated because of the transformer *T*.

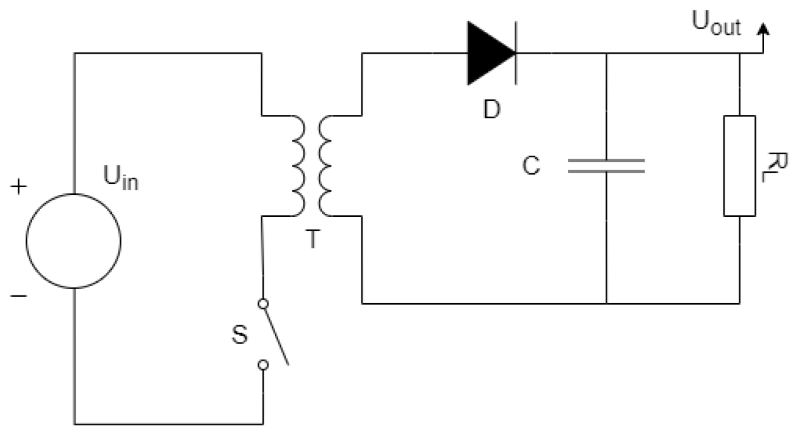

Figure 8. Schematic of an isolated converter

2.3.4 Buck Converter

The Buck, or step-down, converter is a simple switching converter topology which easily demonstrates the principle behind switching converters and has many real uses.

The buck converter pictured in **Figure 9** coverts an input voltage *Uin* into a lower voltage *Uout* at the output. When the switch *S1* is closed current flows from the input into the capacitor *Coutput* through the inductor *L1* and the voltage at output rises. The inductor is the energy storing element in this circuit and when *S1* is opened, the stored energy discharges through the load and diode *D1* causing voltage at the output to decrease. The switch is toggled opened and closed repeatedly with a PWM signal, to create a desired output voltage on average across the load. Output filtering is needed because of the voltage being correct only on average, called ripple, needs to be filtered out as much as possible

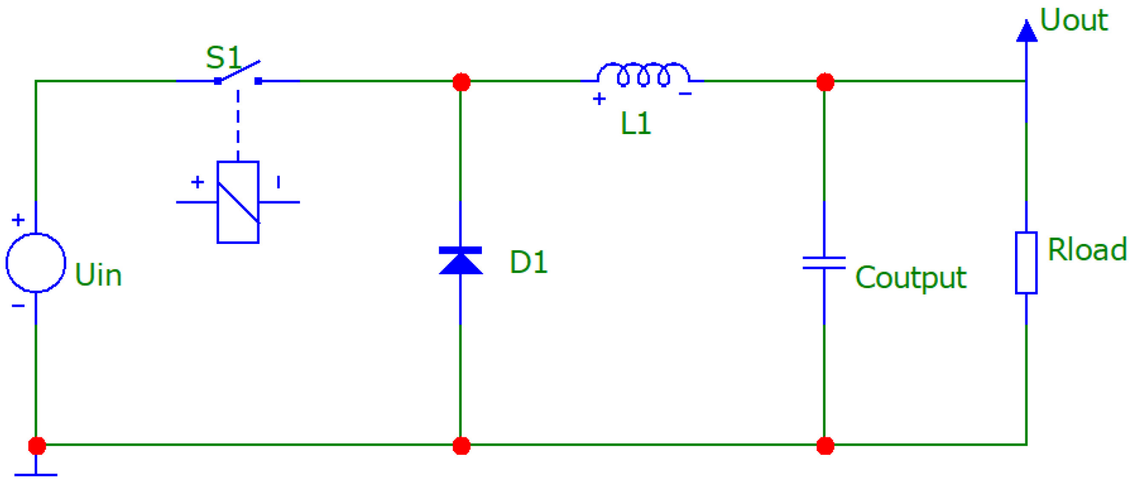

Figure 9. Schematic of an asynchronous buck converter. Switching transistor represented by a voltage-controlled switch *S1*

Waveforms shown in **Figure 10** are simulation results from the buck converter shown in Figure 6. The simulation results show that when the switch is closed energy is stored in the inductor *L1*, and when the switch is opened diode *D1* starts conducting and energy is released from storage.

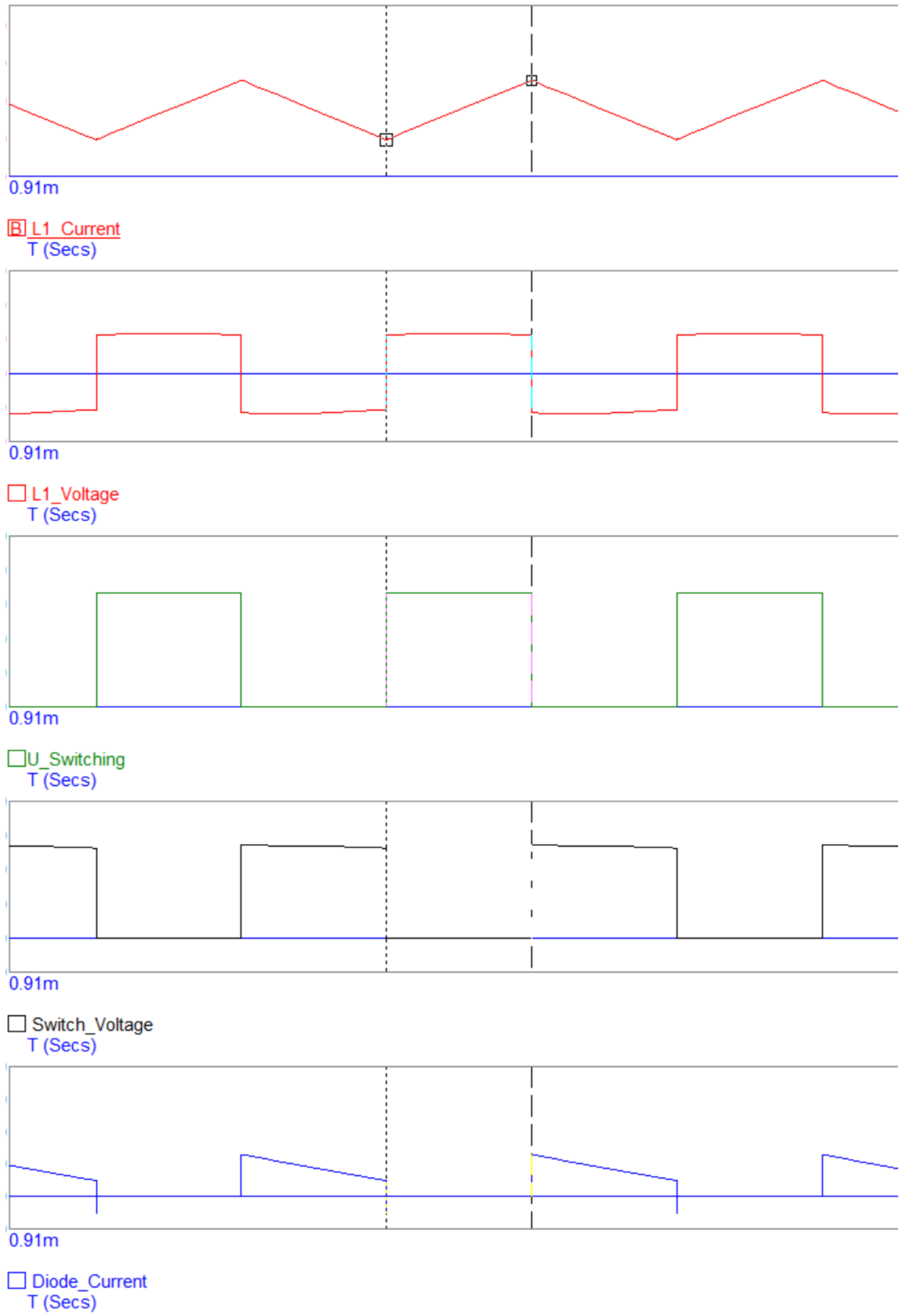

Figure 10. Voltage and current waveforms from a buck regulator's key components

In a buck converter the output voltage and duty cycle of the switching PWM signal are directly related [7]. The equation

$$U_{output} = d \times U_{input} \quad (5)$$

where *d* is the duty cycle, can be used to calculate the output voltage from the input voltage and it is valid when $U_{input} > U_{output}$. The simulation results in **Figure 10** and **Figure 11** were achieved with a duty cycle of 50%. Calculating the output voltage with an input voltage of 12V and a duty cycle of 50%, $U_{output} = 0.5 \times 12V$, gives a result of 6V.

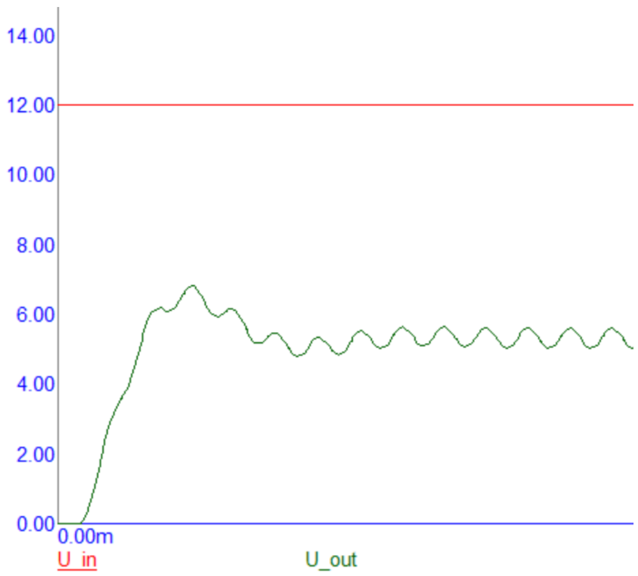

Figure 11. Input and output voltage of a buck regulator with 50% duty cycle

The components used in the simulation are not ideal components, so some inefficiencies are modelled, but the simulated output voltage with an input voltage of 12V is close to the calculated value of 6V. The ripple is shown clearly in the waveform *U_in*, being approximately 1V peak-to-peak. In a commercially available buck regulator, the output filtering would be better resulting in less ripple, and the output voltage would be monitored by the controller and regulation adjusted so voltage would meet the desired value.

2.3.5 Boost Converter

A simple boost converter consists of the same basic elements as the buck converter but arranged differently and can alternatively be called a step-up converter. The boost converter seen in **Figure 12** consists of the same elements as the buck converter in **Figure 9**, but the inductor is located on the input side and the switching element grounds the other end of the inductor *L1* instead of connecting it into the voltage source. A lower voltage at the voltage source *Uin* is converted into a higher voltage at *Uout*. When the conversion process starts, the output voltage will be the diode *D1's* forward voltage below the input, this can be seen at the beginning of the graph shown in **Figure 13**. When the switch *S1* is closed current flows through the inductor and energy is stored in it. When *S1* is closed, the voltage across the inductor reverses in polarity and rises rapidly over the input voltage at the anode of *D1*. This allows current to flow though the diode *D1* and voltage at *Uin* rises. When done rapidly enough a higher than input DC voltage is reached at output.

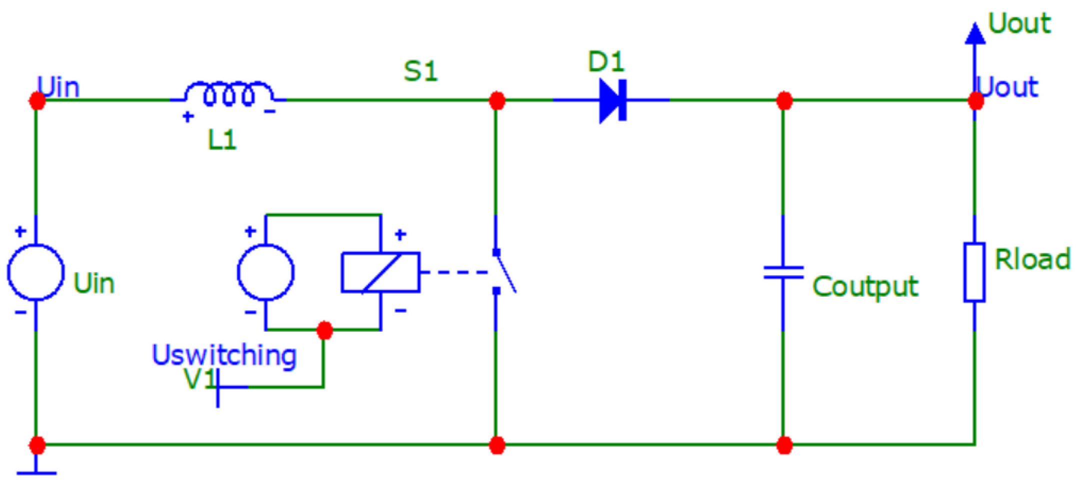

Figure 12. Schematic of an asynchronous boost converter. Switching transistor represented by a voltage-controlled switch *S1*

Like in the buck converter, the relationship between the duty cycle of the switching signal and the output voltage is linear [7]. The equation

$$U_{output} = \frac{1}{1-d} \times U_{input} \qquad (6)$$

is like the one used to calculate a buck converters output voltage, and a higher duty cycle results in a higher output voltage. In **Figure 13** simulation results with a duty cycle of 50% are shown. The output voltage at 50% duty cycle and an input voltage of 12V, calculated with equation 6 would be, $\frac{1}{1-0.5} \times 12V$ = 24 Volts. This result is roughly mirrored by the simulation, although the unideal components and high output voltage ripple change the simulation results slightly.

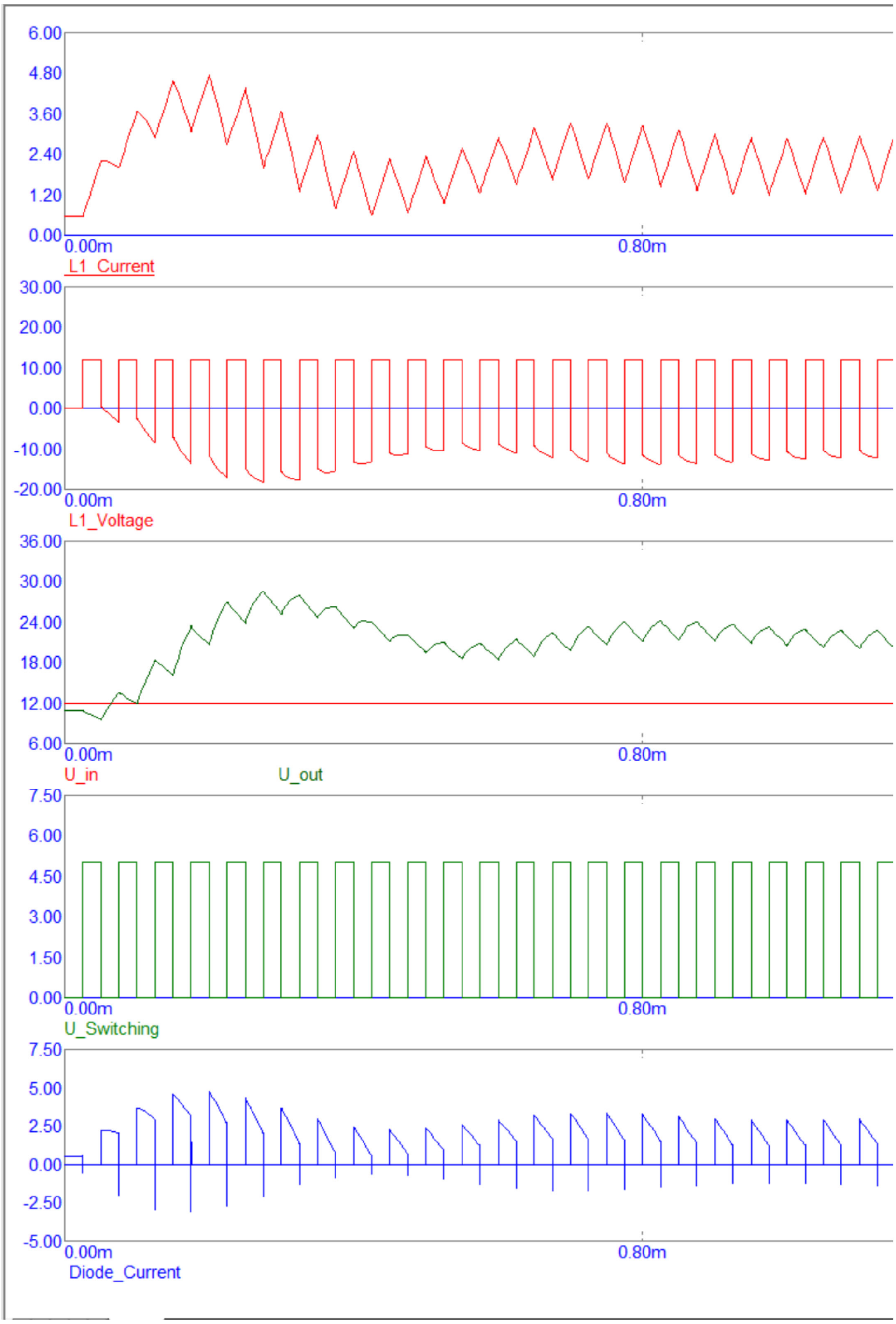

Figure 13. Simulation results from a boost converter

2.4 Imperix B-Board PRO

Imperix Power Electronics provides rapid prototyping solutions for power electronics consisting of accessories, converter modules, software, and controllers for the converters. As mentioned in the introduction to DC-to-DC converters the controller is an integral part in the operation, so Imperix offers controllers that are plug-and-play with their own converter modules. The rack mountable B-Box RCP is a full-size solution maximizing ease of use, and the B-Board PRO used in this commissioning is what is found inside the B-Box, but it is also available as a separate unit for embedding into solutions that do not need the flexibility of a rack mounted unit. Due to this relationship control programmes are fully compatible between B-Box and B-Board.

The B-Board is based on a Xilinx Zynq System-on-a-Chip, containing 2 ARM CPU cores and an FPGA. Since controlling power electronics can be hardware intensive, for example creating accurate PWM signals with minimal jitter for toggling the semiconductor switches used in the converter modules cannot be done in software on the ARM CPUs. Imperix has among other features implemented their PWM generators on the FPGA so that it meets the speed demands. The FPGA also has a user programmable section programmable with a hardware description language if the user's implementation requires more speed than the ARM CPU can offer. Majority of the control software can run on the ARM CPU cores and can be written in C++ or generated from MATLAB models available from Imperix. In this thesis the MATLAB models will be used because it allows for fast creation of control implementation from ready-made blocks seen in **Figure 14**, and simulation of the control scheme.

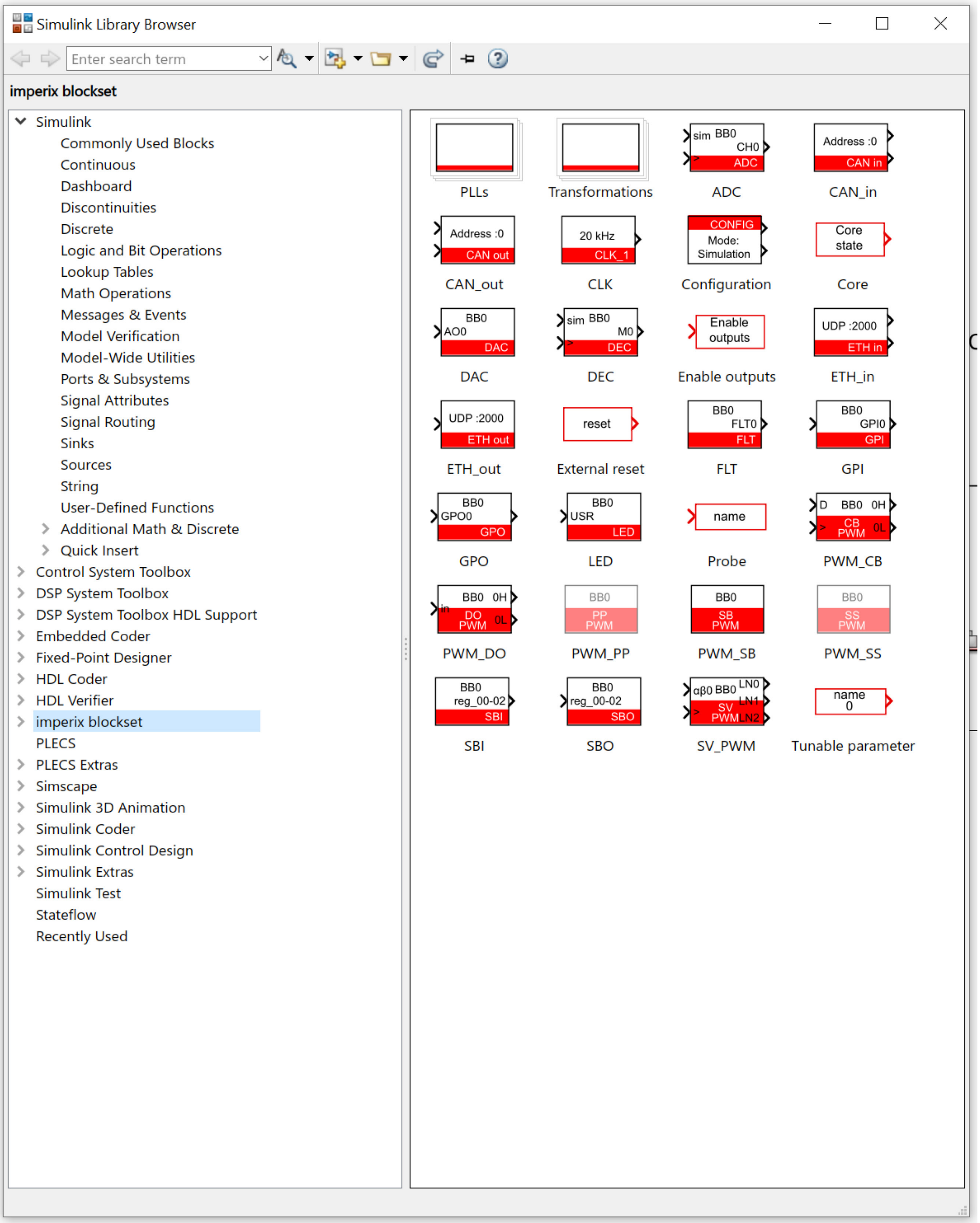

Figure 14. MATLAB blockset provided by Imperix

Because the B-Board controller is embeddable its inputs and outputs are exposed only on connectors on the bottom side of the board. For usage, a custom board where the B-Board can be plugged in needs to be made or Imperix's own breakout board, where the B-Board can be seen mounted in **Figure 15**, can be easily used for exposing the inputs and outputs into simple to use screw terminals. The converter modules purchased by NERC have their electrical connectors terminated into rj-45 jacks and have optical connections for toggling the semiconductor switches. Optical transmitters and screw terminal to rj-45 adapters will need to be made or procured to allow connection between the converter modules and the controller.

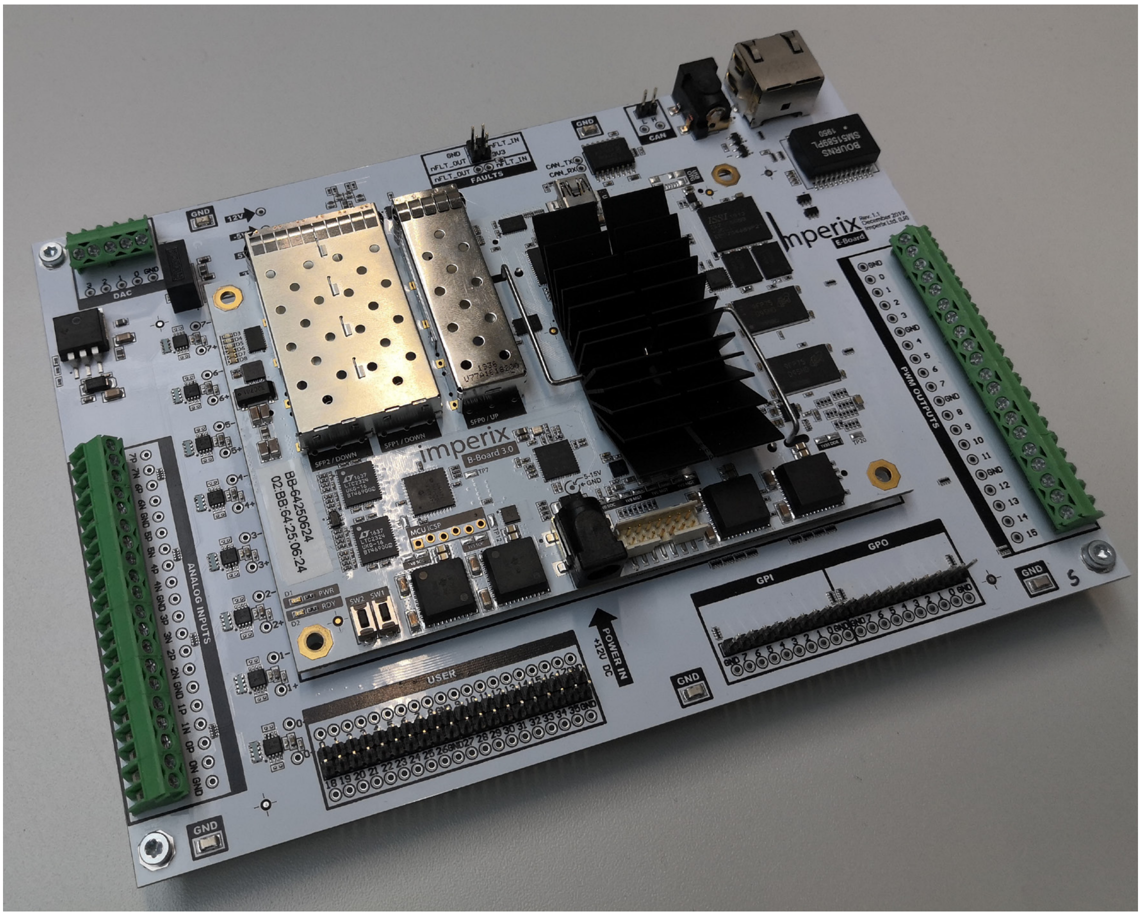

Figure 15. B-Board PRO mounted on a breakout board to route its connections to screw terminals

Since the B-Board functions as the controller, its capabilities define specifications for the controller design. Since the controller that will be designed for the commissioning will be simple in design, the capabilities of the B-Board will not be a limiting factor, but for example the maximum switching signal frequency it is capable of needs to be considered when choosing the inductor size used in the converter.

Table 1. Specifications of the Imperix B-Board important to the commissioning

System on Chip	Xilinx Zynq XC7Z030-3FBG676E
FPGA	Kintex 7 125K
Communication ports	USB OTG USB 2.0 Console 1Gbps Ethernet
Power Supply (Digital circuitry)	4.5V – 17V
Power Supply (Analogue circuitry)	≤ 5.2V
Analog Inputs	8
PWM Outputs	32
General Purpose Outputs	16
General Purpose Inputs	16

3 REQUIREMENTS

In this chapter the requirements for the DC-to-DC converter system, battery system and the possible laboratory exercise are developed and summarized. The summary is divided into categories of Must Have, Should Have, Could Have, Will Not Have. **Table 2** containing the summary is located at the end of this introduction.

Because the systems developed in this thesis can possibly be used in teaching, they all share a common requirement of safety. Other requirements common to the development process of all 3 mentioned systems are simplicity and utilisation of available equipment as much as possible.

Table 2. Requirements for the commissioning categorized into Must have, Should have, Could have and Won't have categories.

Battery System	
Must have	Voltage under 24 Volts Battery Management System Fuses
Should have	BMS with communication capability
Could have	Pre-made construction Self-made construction
Won't have	Voltage higher than 24 volts
Converter System	
Must have	2-Quadrant operation Current control
Should have	User input for current control
Could have	Capability to be expanded
Won't have	Connection to power grid Voltage Control
Laboratory Exercise	
Must have	Over current limit Over voltage limit Under voltage limit Power sourcing and sinking Operation within Constant Current mode
Should have	Quick setup time of exercise
Could have	Control of power supply equipment from MATLAB
Won't have	Operation outside Constant Current mode

3.1 Requirements for Battery System

To stay within voltages that are safe to work with, the battery system voltage should be specified to be 12 volts to 24 volts. Batteries in this voltage range are readily available or alternatively can be constructed for example from 18650 form factor $LiFePo_4$ battery cells that are already in teaching use by the research group, because they have been deemed safe enough. The battery needs to have a BMS to ensure safe operation when charging and discharging. If a ready-made battery is obtained it needs to have a BMS available or if the battery is self-constructed, generic BMS modules for multiple battery cells need to be used. Short circuit situations can be dangerous, so fuses are required to deal with them.

3.2 Requirements for Converter System

The converter must function in quadrants I and II seen in **Figure 4**. The current must be able to flow in either direction so that the battery can be both charged and discharged, and the voltage must always remain the same polarity in either direction of current flow because the battery nor the power supply should be subjected to reverse polarity. Additionally, the converter will function between two DC voltages so that connections to the power grid do not need to be designed.

The Imperix converter modules contain either a half bridge, sometimes referred to as a converter leg, or a full bridge, sometimes called a H-bridge. Simple diagrams of these structures can be seen in **Figure 16**. There are only a few modules available for use at the laboratory and because the design needs to be simple a minimal amount of these converter modules should be required to build the converter in the lab. The component values of the passives such as capacitors and inductors cannot be chosen arbitrarily but instead values already available at the lab must be used and their limits considered.

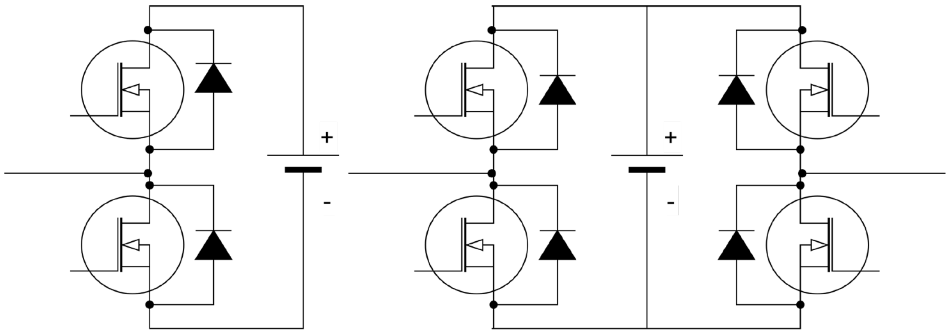

Figure 16. Half bridge (left) and full bridge (right) structures modelled with MOSFETs

The physical components of the DC-to-DC converter system do not contribute the safety of the system apart from built in protections of the Imperix converter modules. The safety in the DC-to-DC converter system come from the controller, the B-Board PRO, and the control scheme built in MATLAB.

The control system needs to have current control and it would benefit from user input for the current control, and safety limits for the user inputs. To simplify the design process Imperix provided MATLAB blocks and stock MATLAB blocks can be used to build the control and safety elements.

3.3 Requirements for Laboratory Exercise

For the purpose of the laboratory exercise use the B-Board PRO controllers should be mounted into plastic enclosures to make them easier to use and ensure their safety. Either a bidirectional power supply that can both source and sink power can be used or alternatively a separate power supply in conjunction with an electronic load. Both options are available to the research group, but the separate power supply and electronic load are already present in all laboratory tables. To make designing control of the converter control easier, the scope of the exercise can be limited to charging and discharging the batteries in their Constant Current (CC) area making voltage control unnecessary aside from safety limits.

For safety of the battery system current limits need to be used so that discharging the batteries will be done within specifications in all scenarios. Additionally, for the safety of the battery system, to prevent over charging or over discharging, voltage limits need to exist on the power supply and load, if used. An additional requirement for the exercise could be control of the power supply and load, if used, from MATLAB. The equipment is

connected to laboratory table wide network from which the equipment can receive commands. The equipment can be set manually so it is not a must have requirement, but an automatically set current limit would be beneficial to safety.

4 IMPLEMENTATION

Without the battery system and certain components required for communication with the B-Board the full system cannot be implemented yet and a preliminary plan for them will be given in chapter 6. The electrical model and control model can be implemented in Simulink without the previously mentioned parts and can be implemented in this thesis.

4.1 Converter Topology Design

The aim is to build a converter that can both charge and discharge a battery connected to a DC bus. In the system there is a DC power supply providing the DC bus that can both source and sink the current in this operation. The voltage of the DC bus is configurable and will be set higher than the battery voltage. This makes it possible that when charging the converter will step down the DC bus voltage and when discharging it will step up the battery voltage.

The 2 converter topologies mentioned in chapter 2.3 cannot fulfill the requirement on their own because they only operate in one quadrant. Both converters can be combined to provide both step up and step-down functionalities.

When connected to a system with a DC bus and a battery, pictured in **Figure 17**, the topology formed by the combination and shown in **Figure 18** can only step down with positive current and step up with negative current, but that is within the requirement of 2-quadrant operation. Combining two topologies that require 1 switching element each creates a topology requiring 2 switching elements which fulfills the requirement of simplicity, since it can be implemented on a single half-bridge Imperix module. One of these modules can be seen in **Figure 19**.

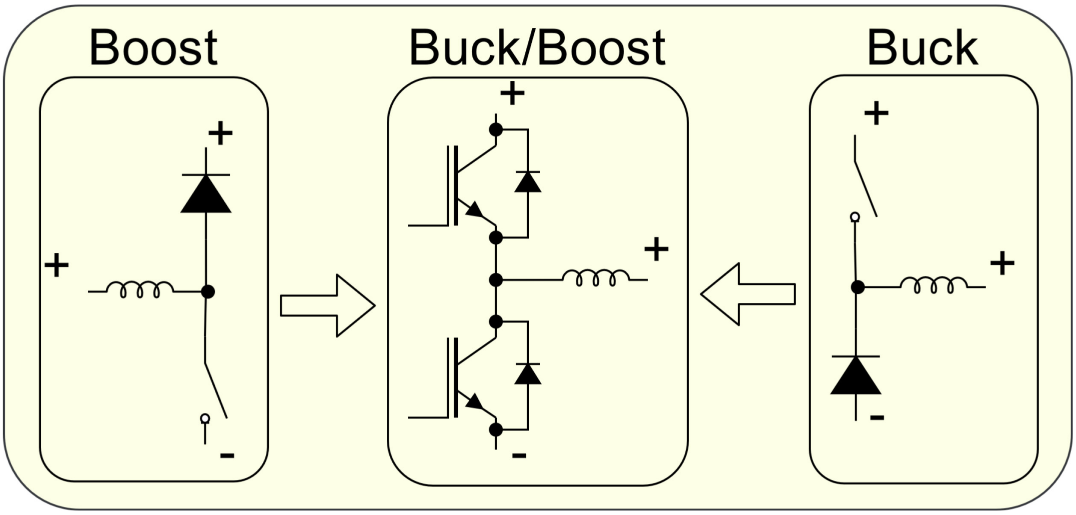

Figure 17. Both bucking and boosting topologies are simultaneously present in a half-bridge

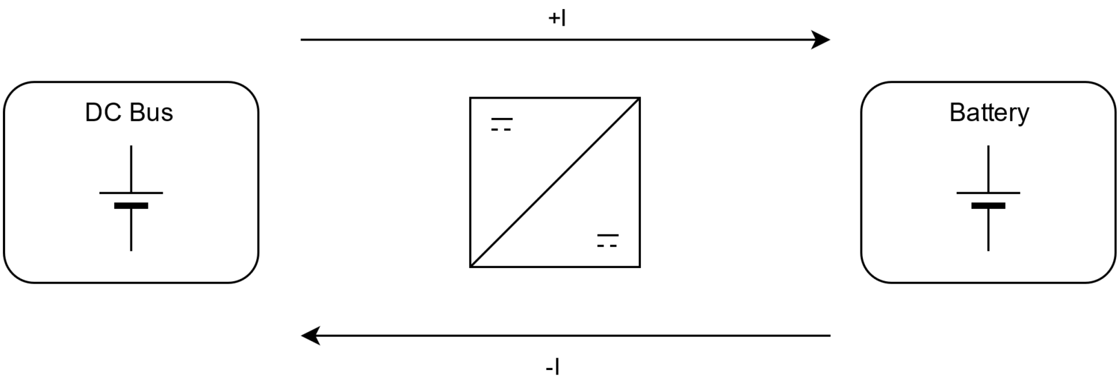

Figure 18. Block diagram of a battery charging/discharging system where charging is determined to be the direction of positive current flow

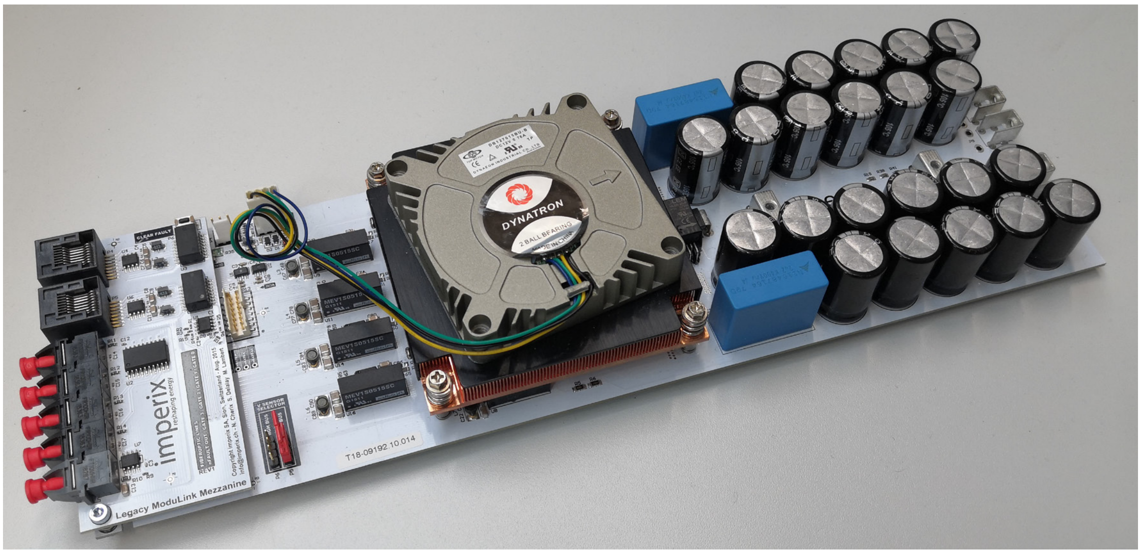

Figure 19. Imperix made half-bridge converter module used by New Energy Research Center

For the inductance used as the energy storing element in this converter pre-existing 2.5mH or 1mH inductors will be used. Any additional input or output capacitances will also be sourced from existing capacitors present at the laboratory and will be from a value range of 3.3μF to 10μF.

An additional step after selecting the topology is implementing it alongside the control scheme in MATLAB using MATLAB's Simscape Electrical blocks. This allows testing the control scheme with a simulated electrical model of the converter. In **Figure 20** the implementation of the converter is shown and in **Figure 21** it can be seen located in the model of the entire electrical system.

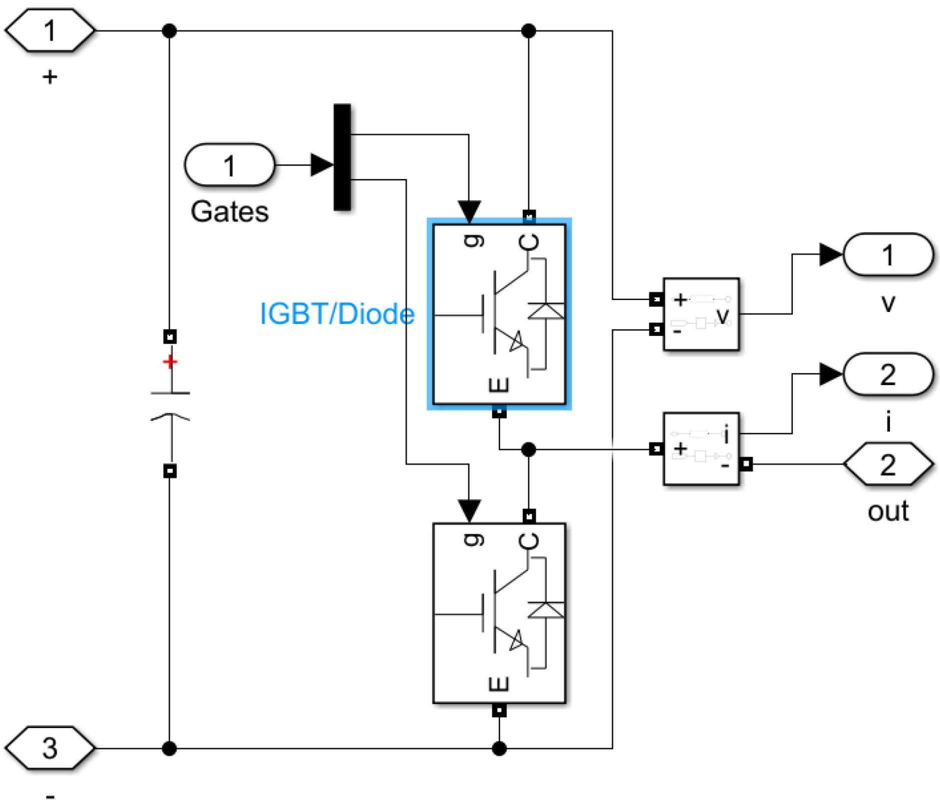

Figure 20. Electrical model of the selected converter topology

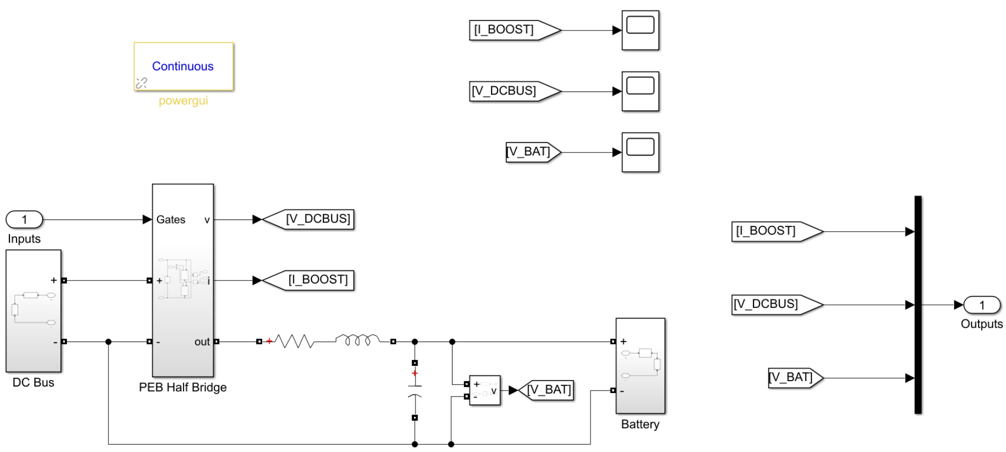

Figure 21. The entire electrical system modelled in MATLAB

4.2 Converter Control Design

All control design done in MATLAB for the Imperix system follows the same steps. The control flow goes from sensor inputs through the control logic into PWM outputs that gate the converter modules. The sensor inputs and PWM outputs are handled fully by Imperix made MATLAB blocks, but the control logic needs to be self-implemented, the Imperix and MATLAB blocks only offer the tools to build it. This control flow is shown in **Figure 22**.

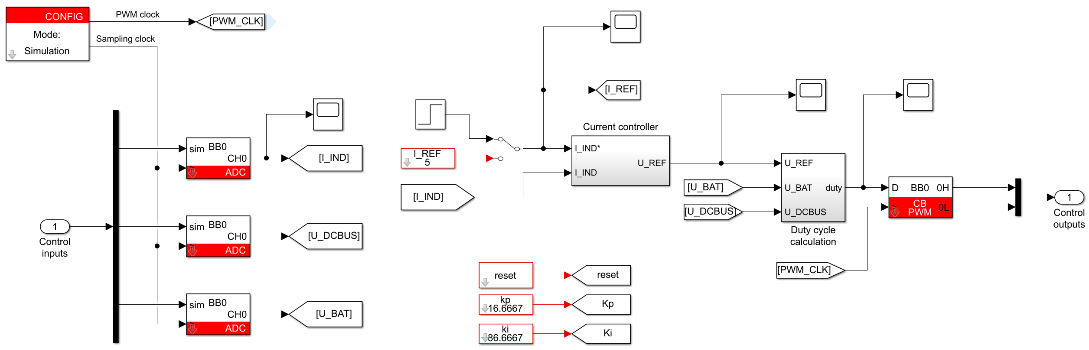

Figure 22. The entire converter control flow in MATLAB

Control design is done using MATLAB and Imperix provided MATLAB blocks. Requirements developed in chapter 3.2 specify the need for current control and lists user input on current control as a useful feature. Both features can be implemented can be implemented with the previously mentioned blocks. The MATLAB implementation of the current control can be seen in **Figure 23**. Proportional-Integral (PI) control was selected because it was recommended as a simple but reliable control scheme by Imperix on their Knowledge Base where a method for tuning the PI controller can also be found [8]. Implementation of PI control is also simple in MATLAB as it is a standard block.

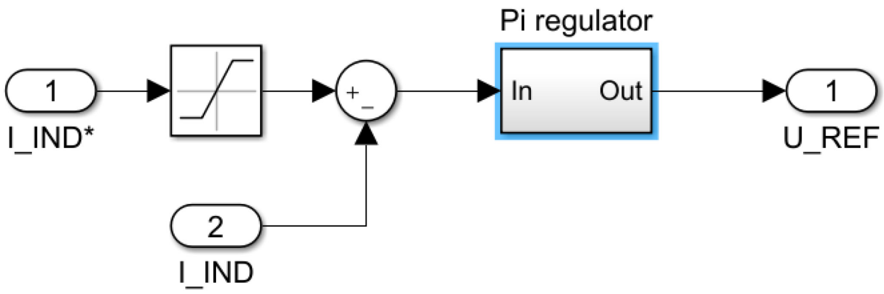

Figure 23. Current control implemented with a PI controller

This PI controller then feeds the *Duty cycle calculation* seen in **Figure 24** where a value between 0 and 1 is output into the PWM generator block, called *CB PWM*, driving the converter modules. In the same figure, the user input for the current control can be seen. It is labelled *I_REF* and it can later be changed while the control software is running. This functionality is provided by the Imperix blocks, as previously mentioned and the raw block can be seen in **Figure 14** and is called *Tunable parameter*.

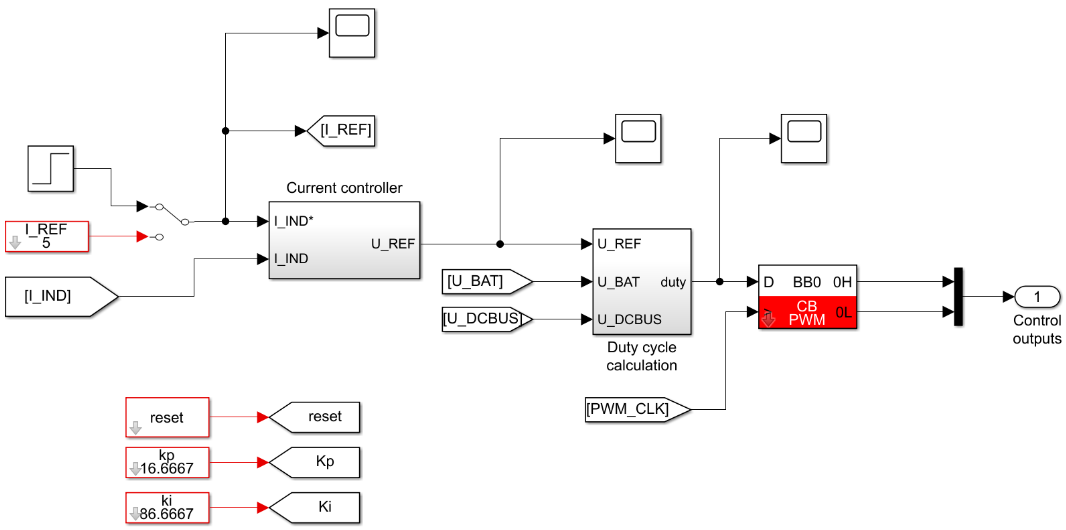

Figure 24. The control logic feeding the PWM generator

5 TESTING

In this chapter the converter system is tested as much as possible during this thesis. Because of the missing battery system and interfacing adapters the testing is limited to simulation done in MATLAB. Additionally, the process of developing control logic for the Imperix B-Board is tested in a more general sense so that implementing other control logic will be easier in the future.

5.1 Simulation of the Converter and Battery System

Once the electrical model seen in **Figure 21** is built and the control logic is implemented, they can be simulated in MATLAB's Simulink. Simulation specific blocks that will later be ignored by the source code generation, can be placed into the electrical model and control logic. The blocks used in this thesis to visualize and control the simulation are Scopes and Steps.

The virtual battery system has a Scope block attached to it so its simulated voltage can be observed. While applying a steady discharge current the battery voltage reduced as can be seen in **Figure 25**. The current control manages to keep the current steady even while the battery is discharging as shown in **Figure 26** and **Figure 27**. This means that if the simulation is accurate, the system could be used as a lab exercise for charging and discharging batteries in constant current mode.

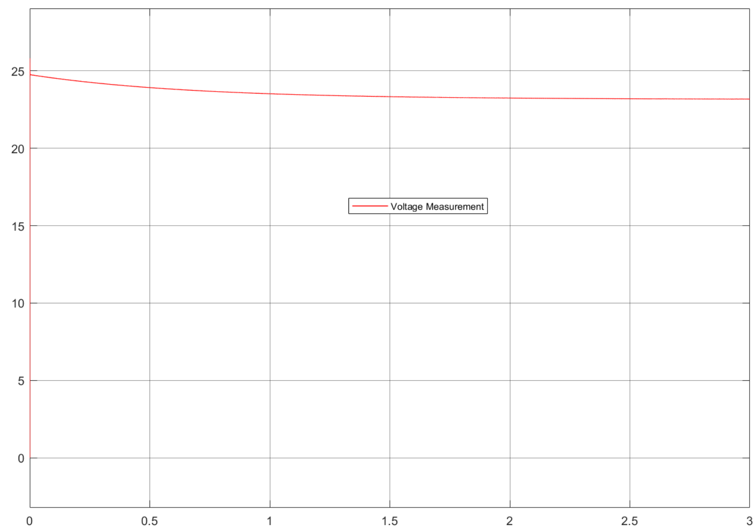

Figure 25. Simulated battery voltage discharging from 25V

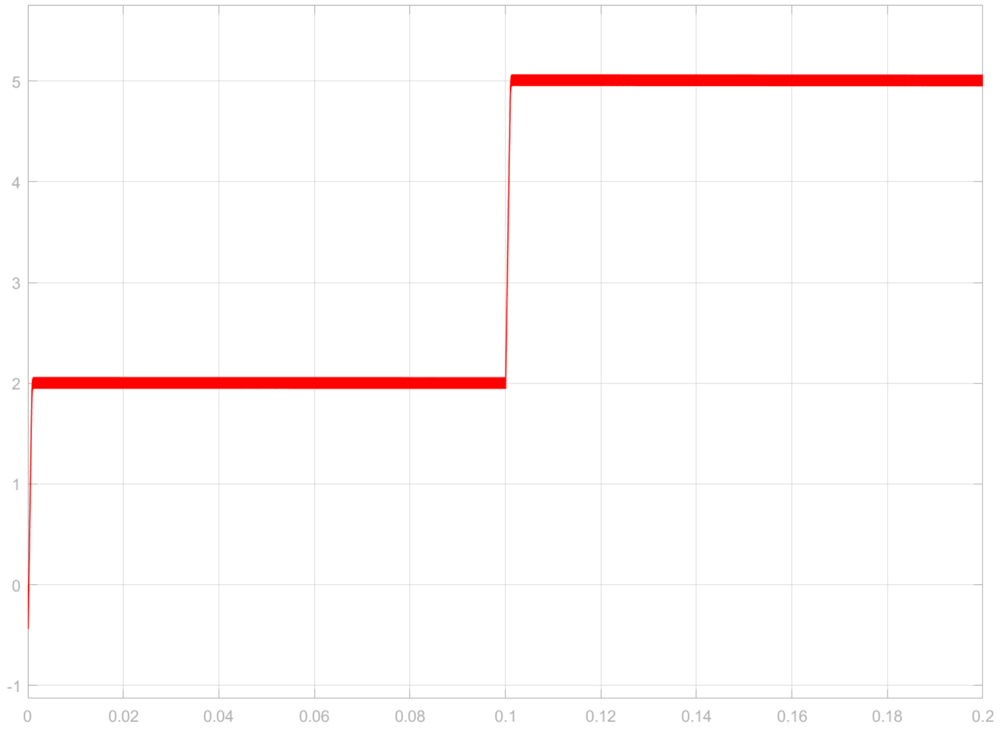

Figure 26. Current control test with a stepped positive current. The thickness of the line is due to simulated current ripple

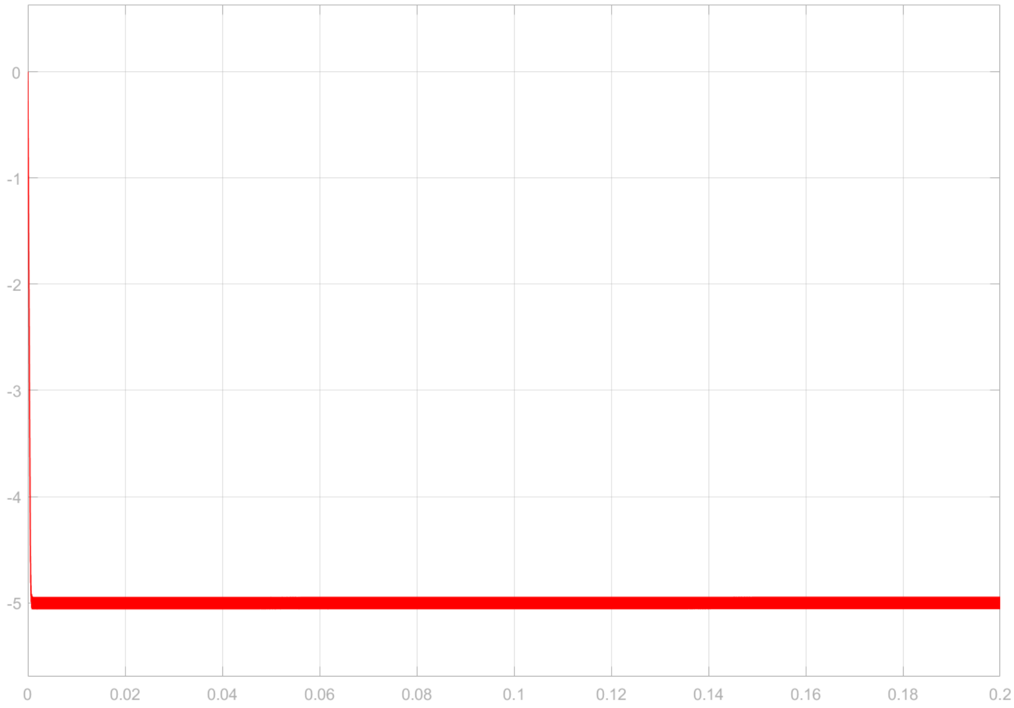

Figure 27. Current control test with negative current. The thickness of the line is due to simulated current ripple

5.2 Testing the Development Environment

During the development of the control logic and electrical model and their simulation the development process was tested. This includes taking notes about important steps to make during development, settings to select and locating traps present in the process. Some results of this testing are given as examples in this chapter of the thesis.

To start development of the control logic and electrical model a ready-made template provided by Imperix, shown in **Figure 28**, should be used. The template contains scripts that load the necessary libraries and creates the areas where to place the electrical model and the control logic shown in **Figure 24**. All these steps are mandatory and using the template ensures a working base on which to start building the models. Imperix provides 2 templates, one for the deprecated BoomBox and one for B-Box RCP or B-Board PRO. The correct version for B-Board needs to be used because they contain different scripts.

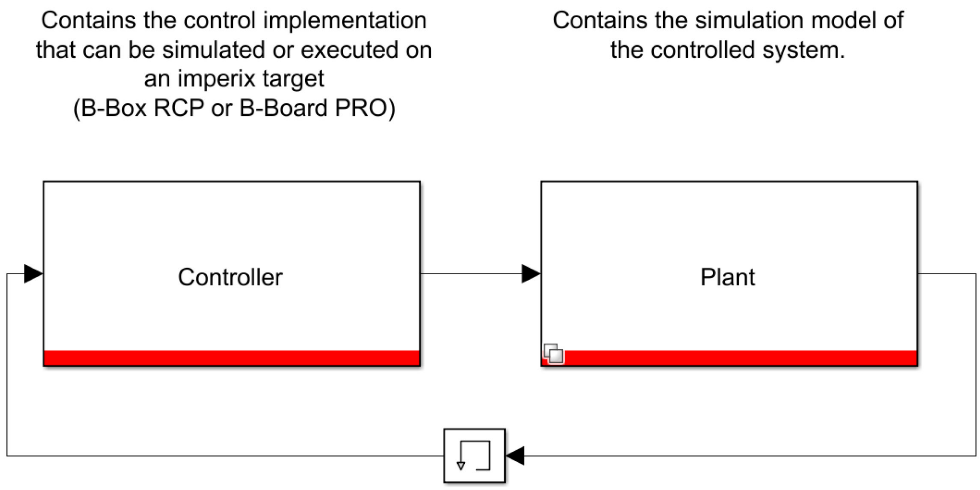

Figure 28. Imperix's template where the control logic and electrical model can be built

When switching between simulating and generating source code, two settings need to be changed. One within the model and one in MATLAB Simulink. The *Config* block in the control logic model needs to be toggled between the modes and the solver in Simulink needs to be changed to *variable step* when simulating and *fixed step* when generating source code. These steps are shown in **Figure 29** and **Figure 30**

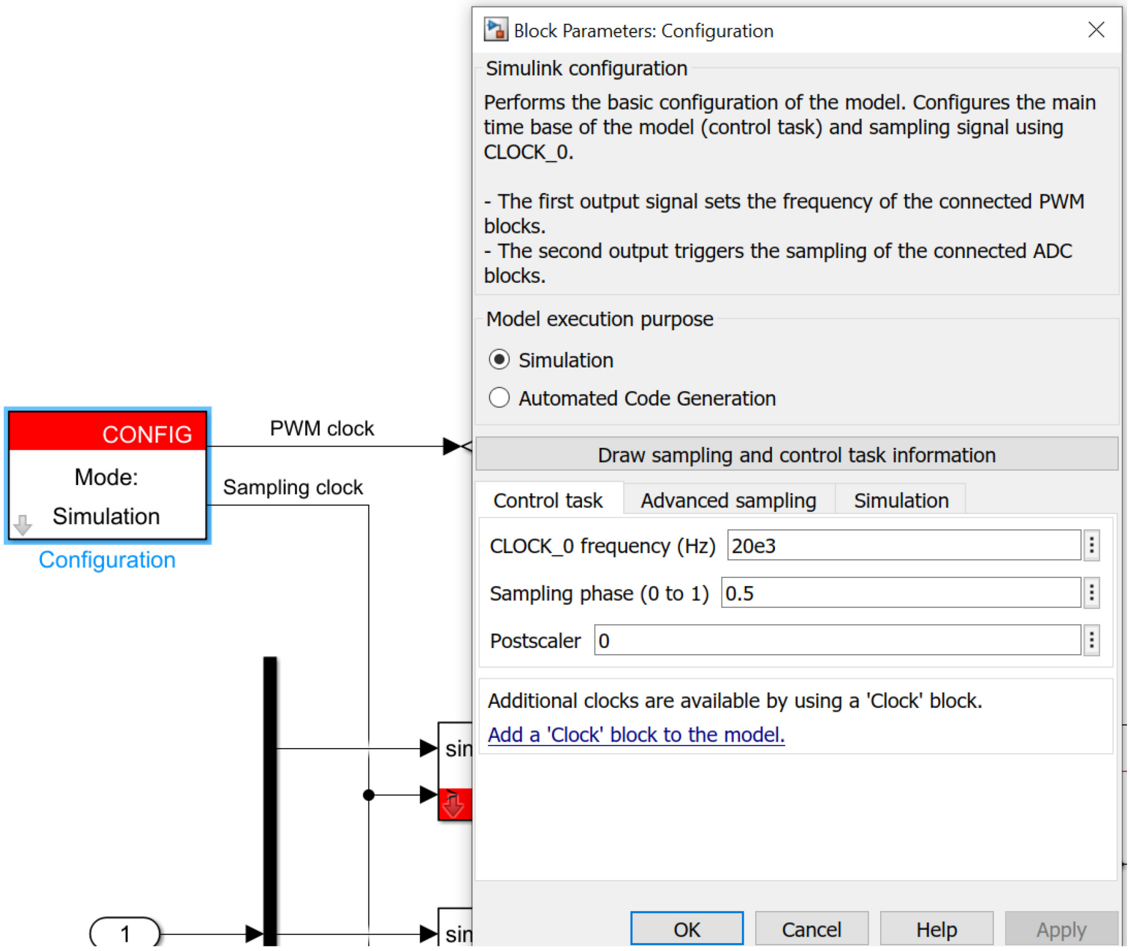

Figure 29. Important settings in the Config block

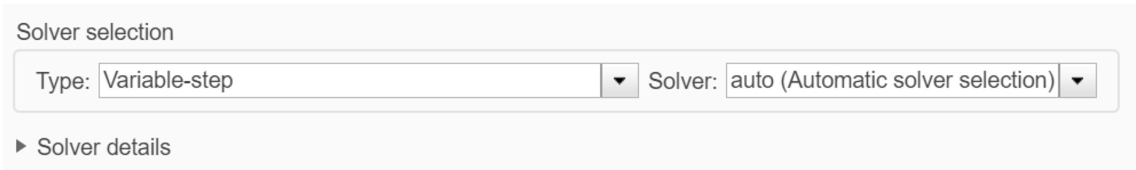

Figure 30. Solver selection in Simulink's settings

6 CONCLUSIONS AND FUTURE WORK

Because all the required adapters and components for the commissioning were not decided in this thesis a plan detailing what is needed to be done in order to finish the commissioning is devised in this chapter. Additionally, some ideas that could still be implemented to improve the possible lab exercise are introduced, possible future usage for the converter system is discussed and conclusions about the commissioning process are drawn.

6.1 Selecting the Battery System and Missing Components

The specification for a suitable battery system was written in chapter 3.1, but no such battery system was implemented during this thesis. If the developed converter system and laboratory exercise is going to be used in the future a battery system needs to be selected according to the written specifications.

In order to finish the commissioning of the B-Board PRO physically, so it can be used to control converter modules certain adapters need to be acquired. The sensor inputs only exist as screw terminals on the B-Board breakout board and need to be adapted to RJ-45 terminals that are compatible with the existing Imperix sensors. These breakout boards are available as commercial products, Imperix themselves sell one or they can be made in-house relatively simply. Additionally, a bipolar 15V power supply needs to be included with every B-Board to power the sensors [9].

The more difficult adapter to acquire is the optoelectronic adapter for converting the electrical gating signal to optical, that the converter module can receive. This task is simplified by the unidirectional characteristic of the gating signal, the converter module does not send anything it only receives the signal. Such optical transmitters also exist as commercial products. They only have a different fibre optic connector. If this were adapted to the correct one, they could be used. It is also possible to make these adapters in-house, the fiber transmitters are available from electronic component suppliers and the driver circuit required is simple, as seen in **Figure 31**. The type used by Imperix is called Versatile Link [10]. All the elements mentioned in this chapter could them be mounted into a plastic enclose. In **Figure 32** this concept is displayed in block diagram form.

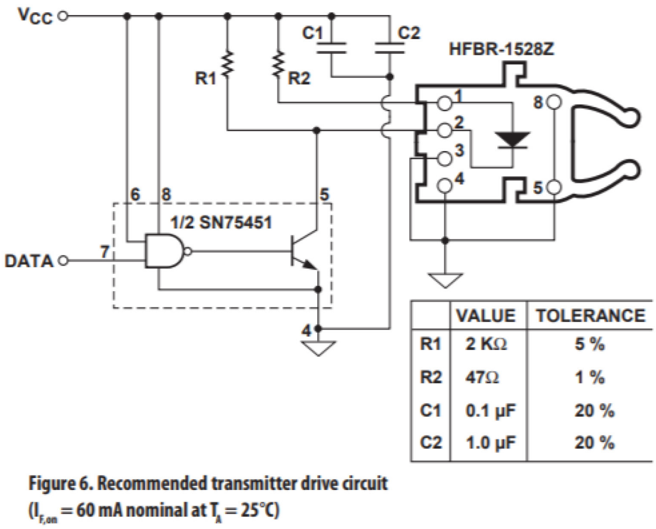

Figure 31. Transmitter driver circuit as recommended by the manufacturer

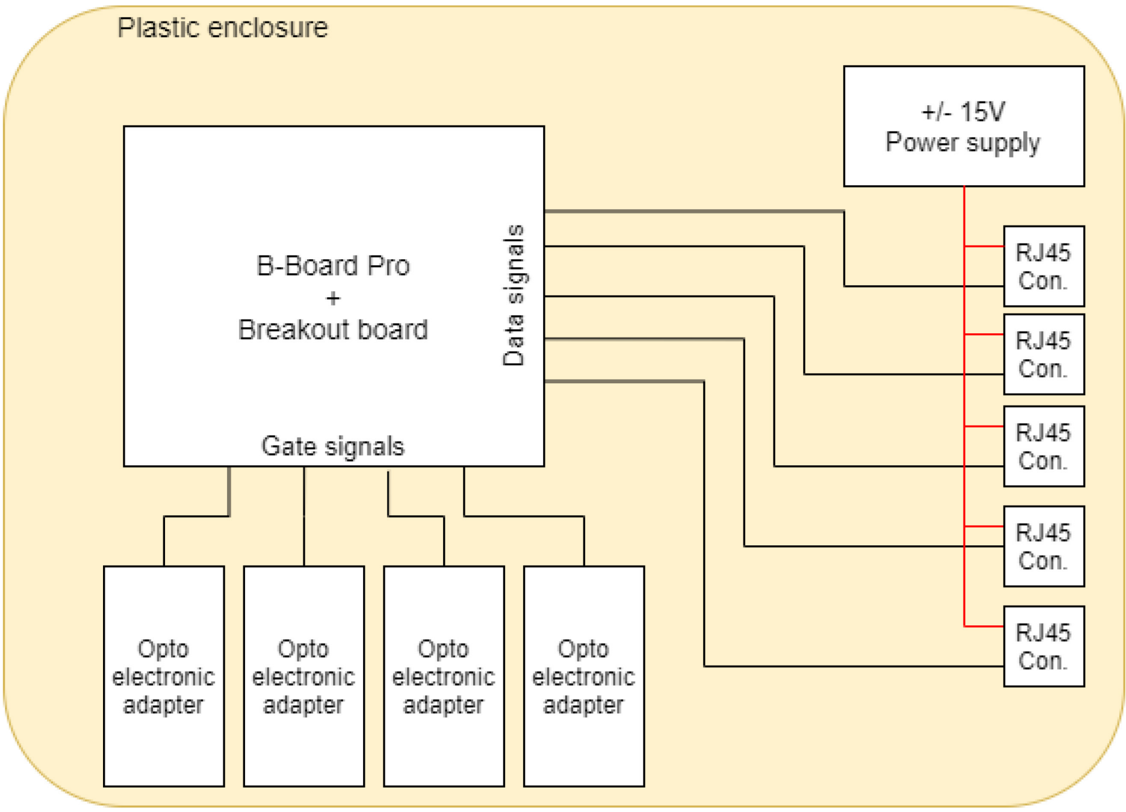

Figure 32. Block diagram of a possible B-Board PRO setup

6.2 Integrating Equipment Control

An additional quality-of-life feature of controlling the equipment used in the possible laboratory exercise directly from MATLAB though the table-wide network. Code for controlling a Delta Elektronika power supply while charging and discharging batteries has previously been written in Python and an excerpt of it can be seen in **Code Excerpt 1.** The python libraries required to control the other lab equipment at the laboratory tables are the same, only the individual commands might need to be changed. During a short look into the programming guides for both power supplies, it was noted that they even share some common commands. This Python code could then be directly executed from the MATLAB model of the converter for automatic setting of all the necessary parameters on the equipment.

Code Excerpt 1. Python code for controlling a Delta Elektronika power supply through the network

```
# charging
if operatingMode == 1:
    setOutputVoltageLimit(batterySetup["chargeMaxVoltage"],"ON")
    setOutputVoltage(batterySetup["chargeMaxVoltage"])
    SET_VOLT = readVoltage()
    previousSettings["voltage"] = SET_VOLT
    if operatingCurrent < LIM_CUR:
        setOutputCurrentLimit(operatingCurrent,"OFF")
    setOutputCurrent(operatingCurrent)
    SET_CUR = readCurrent()
    previousSettings["current"] = SET_CUR
```

6.3 Additional Uses for the Developed Converter System

The selection of a bidirectional DC-to-DC converter for charging and discharging batteries was not random. It goes together well with other interests of the research group. Battery technology is a part of New Energy Research Group’s expertise and an extension of battery technology in Electric Vehicles is the use of the vehicle’s battery in reverse. The battery is discharged into the electrical grid and this technology is broadly called

Vehicle-to-Grid (V2G). The designed converter is not directly usable in V2G applications, it cannot handle the power required to do so, it is not connected to the electrical grid, and it is not sophisticated enough. But the Imperix system could be used to prototype a converter with such capabilities in the future and knowledge gained in bidirectional converter design and proficiency in using the tools provided by Imperix possibly benefits the research group in the future.

6.4 Conclusions

The B-Board PRO units were purchased to allow more students to complete laboratory exercises at one time and to save costs compared to the more expensive B-Box RCP. While the capabilities of the systems are same, the B-Board is found inside the B-Box, additional work was found to be needed in order to make use of the B-Boards. Once the work is done, the development process will be already tested and proven working so the controllers can be taken into use straight away to increase the teaching capacity.

During the development of the converter system there are many directions in which to go. There are many kinds of topologies for bidirectional converters varying in complexity for example. Writing requirements before starting the development process is good aid in design because the requirements clearly guide the development process. Only current control was needed, so no additional more complex control schemes were required, and work could move onwards.

Like many projects, this thesis was constrained by time and resources. The battery system or the necessary adapters could not be acquired during the writing, but using simulation was a great help in testing the developed converter system without having to wait for hardware to arrive. Even while the Imperix system is meant for rapid prototyping and allows quick assembly of physical converter systems, simulating is still faster, safer and can be done remotely if needed.

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