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Industrial Electrical Engineering and Automation

# Bidirectional DC/DC converter
## for application in an electric vehicle for better battery management

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# Abstract

In each electric vehicle there is an energy storage part and a propulsion part to drive the vehicle in the desired direction. To make them compatible with each other and at the same time have a good efficiency, there is need for a system that transfers energy from the batteries to the motor. In electric drive systems this energy transfer is done with different converters and the converter that is studied in this thesis is one that sits between a battery pack and a common bus with a fixed voltage.

This thesis covers a proposed DC-DC converter topology as well as its components. The chosen topology will be explained in detail, how it works and its different stages of operation. The report contains investigations and argumentation to what components would be best suited for the proposed topology and why.

Important formulas and derivations concerning the converter is also shown and discussed in the report. The different power losses in the converter have been analysed and formulas for losses in each component is presented.

At the end of the result chapter, a test case is presented with values calculated using formulas from this report as well as a complete model of the topology created in LTspice.

This type of DC-DC converter is certainly possible to build but there are some concerns regarding how efficient it is. Since proposed converter have a wide range of battery voltage that it is compatible with, it is difficult to optimize components and reduce losses.

Keywords: Energy management, Electronics and Electrical technology, DC/DC converter, Vehicle electrification.

## Terminology

DC = Direct current
AC = Alternating current
HV = High voltage
LV = Low voltage
EV = Electric vehicle
HEV = Hybrid electric vehicle
FET = Field effect transistor
BJT = Bipolar junction transistor
MOSFET = Metal oxide silicon field effect transistor
IGBT = Insulated gate bipolar transistor
FPGA = Field-programmable gate array
PWM = Pulse-width modulation
CCM = Continuous conduction mode (Inductor current never falls down to zero)
BCM = Boundary conduction mode (Inductor current hits zero and then changes direction directly)
DCM = Discontinuous conduction mode (Inductor current falls down to zero)
ESR = Equivalent series resistance
EMI = Electromagnetic interference

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# 1 Introduction

Our world is under constant development and along with it, the automotive industry. More and more car manufacturers are moving towards building electric vehicles and today almost every big car company has got at least one model in their line-up that can be offered with either a fully electric drive system or as a hybrid.

To make electric drive possible the power has to be provided from somewhere. This is done by the use of portable energy sources such as batteries. To make the energy consumption as good as possible, a good way to transfer energy from the battery to other parts of the system is needed. That is where the converters come in handy.

## 1.1 Background

Due to the relatively low energy density of today's batteries, compared to gasoline, shown in [1], [2]. Many of today's electric cars often use one big battery pack or a couple of smaller packs in serial which causes some problems and limitations.

The problem with big battery packs is when it comes to repairs. For example if one part of the battery breaks, the whole assembly often has to come out to either repair or swap the broken part. To avoid this problem, several smaller batteries can be combined and coupled to an common bus with a fixed voltage. For this to work and to be able to control the flow of energy from and to the battery, a DC/DC-converter is needed. The converter, which sits between the battery and the bus, makes it possible to use different types of batteries with different voltage levels and converting them up- or down to match the desired voltage of the DC bus. The bus can then feed the whole system with help from the batteries.

The thesis is done for a company called "DuRussels Automotive AB" which is a fairly recently started company who works with electrics, battery technology, embedded systems, prototypes within the automotive industry, and consulting.

The company is currently in the phase of starting a new project within energy storage and is looking for help in making the researching part of the project more smooth. The thesis work is done to make future development work easier as a part of the project is to design a voltage converter for battery management in an electric vehicle to try and solve parts of the problem described earlier.

## 1.2 Purpose

The whole purpose of the thesis is to make battery management much easier and more efficient. With the thesis available, the company have a foundation to begin with. This both saves time and resources which is very important to a company starting a new project.

Being able to swap out smaller broken parts instead of larger ones where only a small part is broken is also good from an environmental and sustainability perspective because less material goes to waste.

## 1.3 Main goals

The main goal of the thesis is to find a DC/DC-converter design that is able to convert a wide range of voltage, both HV and LV, and also be bidirectional for the batteries to be able to get charged. In order to design a DC/DC-converter, a topology and its components have to be chosen so that it can handle the expected power range of 100KW to 300KW.

## 1.4 Problem statement

1. Is there any topology that can be found that suits the goals of the thesis and if so, how does it function?
2. What components are best suited for the chosen topology?

## 1.5 Justification of the thesis

With a constant growing automotive industry where HEVs and EVs become more and more dominant, this thesis work is chosen with the hope of making a small impact. To be a part of the development for a better battery management and for something that is more environmentally friendly can be considered as very relevant in times like this where the environment is a hot topic.

## 1.6 Limitations

A brand new topology will not be designed. Instead the thesis will be based on an already existing topology. Furthermore due to the thesis time limits, only a few component types will be analyzed and no specific products will be selected.

Choosing a controller for the converter and programming it to function correctly will not be a part of the thesis and simulations will only be done if it is possible to do within the time frame. A prototype will not be constructed as time is insufficient.

# 2 Technical background

In this chapter, some basic theory of electrical components and different types of converters is covered to easier understand the rest of the report. Most of the content in this chapter is gathered from various different reports and other sources. If the reader already have good knowledge in this area, this chapter can be skipped.

## 2.1 Electrical components

The theory behind passive components like resistors, capacitances and inductances and how they work is considered as basic knowledge and this chapter will only cover some of the more complex components such as transistors or diodes.

### 2.1.1 Transistors

A transistor is a crucial component in many electrical circuits and it has some different functions. One of its functions is its possibility to act like a switch where it can be turned on to conduct current through it with small losses and turned off to block current from flowing in the direction of the transistor. Transistors can be used in different combinations, often together with other electrical component and be controlled by smart controllers to fulfill various task with a very high efficiency. More of this is covered later on when the converters are described.

There are two main types of transistors, field-effect transistors and bipolar junction transistors. They both have about the same electronic structure but work a little different from each other.

A FET has three connections: source, drain and gate. Current flows through a channel either called N-channel or P-channel depending on what semiconductor material that is used, see Fig. 1. When operating at higher frequencies, a N-channel transistor is prefered wherest a P-channel transistor is good for medium frequency applications. One end of that channel is called typically called drain and the other end source. The current flowing from drain to source can be controlled by applying a voltage to the gate connector. The field-effect transistor is explained in [3].

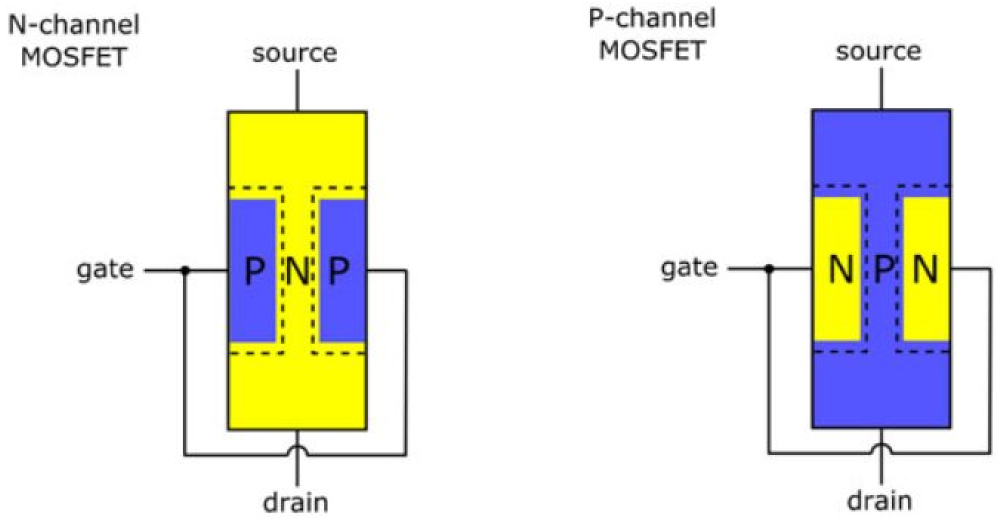
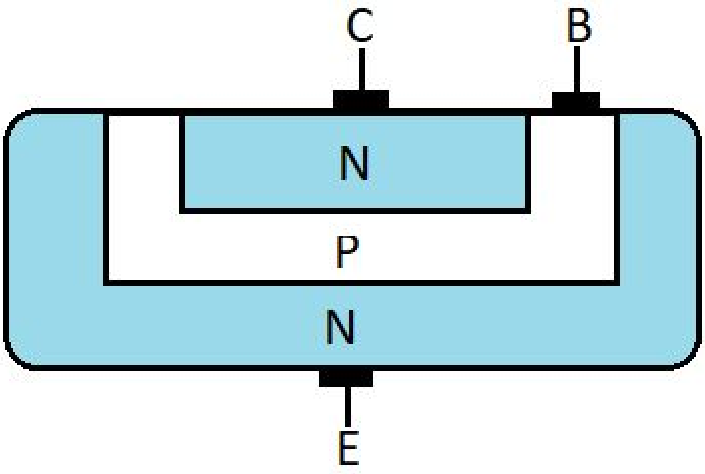


Fig. 1 Model of the different type of field-effect transistors. [4]

The BJT has three regions called: Emitter region, collector region and base region. Fig. 2 shows a NPN BJT where the emitter region is n-type, base region is p-type and collector is n-type. The BJT can also be PNP, where the emitter and collector is p-type and base is n-type. The emitter and collector always have the same type and the base is always the opposite type. A NPN bipolar transistor is used when switching the positive connector of the load and PNP is used when switching the negative connector of the load.



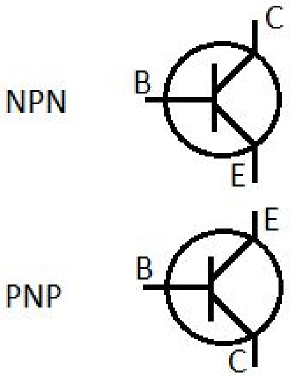


Fig. 2 Model of a NPN BJT.

Fig. 3. Typical symbols of BJTs.

At each region there is a connection E (emitter), B (base) and C (collector). The BJT is current controlled which means that changing the current that is going through B to E, see Fig. 3, changes the current going through C to E.

A commonly used field-effect transistor and one that will be studied in this thesis is the MOSFET. The MOSFET is often used in applications where there are low voltages involved due to it having a better efficiency at those voltages. Some advantages and disadvantages of the MOSFET is presented in [5]. The main advantages, and the ones that often is considered crucial, is that its capable of very high switching speeds and also has a very good efficiency at low voltage applications.

Another common transistor which also will be studied in this report is the IGBT. The IGBT is an attempt to combine the best parts of a FET and a BJT and is explained very well in [6]. Combining them both makes it possible for the transistor to handle high voltages and high currents. It also has low transconductance losses due to low ON resistance. These are only some advantages of the IGBT.

Chart 1. shows a comparison list of relevant transistors.

| Device Characteristics | BJT | MOSFET | IGBT |
|---|---|---|---|
| Voltage Rating | High | Low | High |
| Current Rating | Low | High | High |
| Driver Control | Current | Voltage | Voltage |
| Switching Speed | Medium | High | Low |

A summary of the different transistors is shown in Chart 1.

### 2.1.2 Diodes

A diode is an electrical component that only conducts current in one direction. Some of the applications for these diodes are rectifying alternating current, emitting light and detecting light. Most of the semiconductor diodes are made of a crystalline piece of semiconductor material with a PN junction connected between two electrical terminals. Most of these diodes are made of silicon.

Another type is the Schottky diode where a junction of the semiconductor with a metal is made. Furthermore, there is the PIN diode which is a bit different in the construction.

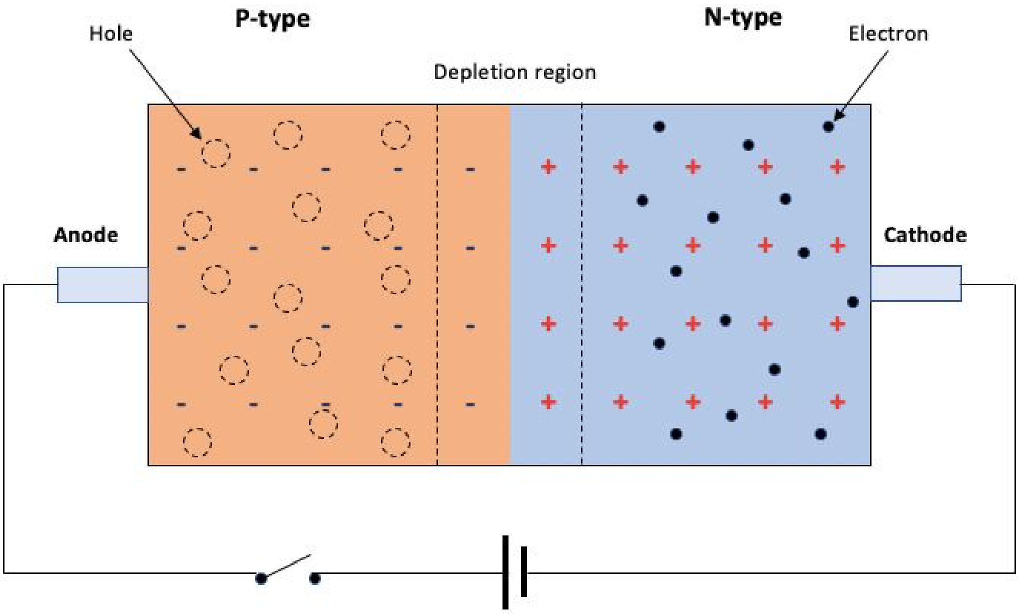


Fig. 4 PN junction.

The PN diode are made of a semiconductor material, most commonly silicon. But there are also PN diodes that are made of germanium and gallium arsenide. The germanium diode have a lower forward voltage than the silicon diode. Normally the germanium diode have a voltage drop around 0,3 V, whereas the silicon diode normally have a voltage drop around 0,7 V. This makes the germanium diode more suitable for low power applications. Germanium is a rare element which makes this type of diode more expensive and therefore its also used less. Gallium arsenide diodes are most often used in weak signal amplification applications since they generate less noise than other diodes.

The semiconductor material is made by doping the pure material such as silicon with a dopant. The p-type and n-type semiconductor material is made dependent on what dopant is used. When the PN diode is made, the p-type and n-type semiconductor are bonded together and the PN junction is made, as explained in [7]. The diode now consist of two sides, the p-side where there are an excess of holes, and the n-side where there are an excess of electrons, as shown in Fig. 4. Also a depletion area now is created between the two sides.

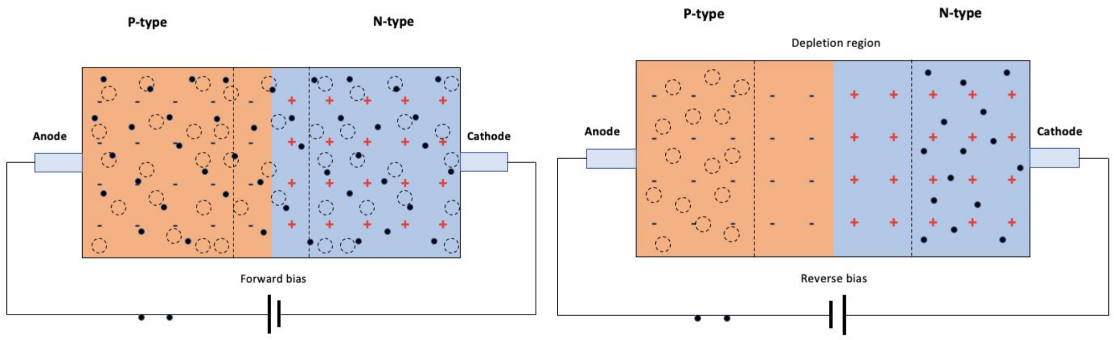


Fig. 5 & 6 Forward biased and reversed biased PN junction.

When the PN diode is forward biased, a positive voltage is connected to the p-type materials terminal. If a greater voltage than the forward voltage is applied, the diode starts to conduct current, as shown in Fig. 5. This is due to the supply of electrons to the n-type materials terminal. The electrons starts to diffuse toward the junction. At the same time the p-type materials terminal starts to remove electrons from the holes, which makes the holes diffuse to the junction as well. This lowers the separation of the p-type and n-type materials and excess electrons moves through the n-type and p-type materials and out the terminal. The diode is now conducting current.

If the PN diode is reversed biased instead, the diode will not conduct current (except perhaps a small reversed leakage current). Unless the reverse breakdown voltage is exceeded, which would destroy the diode. Now there is a positive voltage connected to the n-type materials terminal which attracts the electrons away from the junction, while the holes are attracted away from the junction in the p-type material, as shown in Fig. 6. This makes the depletion layer even wider than it was before and prevents the diode from conducting current.

The Schottky diode have a junction between a semiconductor material and a metal contrary to the PN diode. The Schottky diode junction is the equivalent to the PN junction and the current transmission is carried out in similar ways. But the PN diode is a bipolar component contrary to the Schottky diode which is a unipolar component, as explained in [8]. This implicates that both holes and electrons assist in the current transmission in the PN diode unlike the Schottky diode where only one type of carrier is used to transmit the current. The characteristics of a Schottky diode is that it have low turn-on voltage which reduces the total power loss in the diode. Furthermore the Schottky diode have fast recovery time that make the diode suitable for high frequencies application. The fast recovery time also help reduce the power loss at high frequencies. Considering these characteristics some of the applications where Schottky diodes often are used are radio solar cell applications, power rectifier applications and radio frequency applications.

Another type of diode is the PIN diode, which operates in a similar way as the diodes mentioned above. However, the PIN diode looks a little different in its construction due to the junction being formed by a heavily doped P+ layer and a heavily doped N+ layer with a lightly doped N- layer in between, as explained in [8]. This N- layer is also known as the I-layer, I meaning intrinsic, which is why the diode is called a PIN diode. The depletion region or space charge region is now penetrated into the lightly doped N- layer and gets quite wide. The maximum blocking voltage is determined by the width and doping of the I-layer. Though the breakdown voltage is increased the N- layer also increases the ohmic resistance in the diode meaning more heat will generate during conduction state. This means PIN diodes will need more heat dissipation than other diodes. Since the PIN diode have a wide depletion region and can block higher voltages, this type of diode is often used in high voltage rectifiers.

## 2.2 Converters

Being able to control the voltage and current coming to or from a powersource has been a challenge for as long as electronics existed. There are many ways to switch between different voltages and there are many applications where it is necessary to do so. For example when using batteries to power devices that require another voltage level than the one of the battery.

In Fig. 7 the fundamental idea of a converter is presented. The converter in this case is shown as a “transfer box”. What this box contains can vary a lot but its function should always be the same: convert voltage up or down.

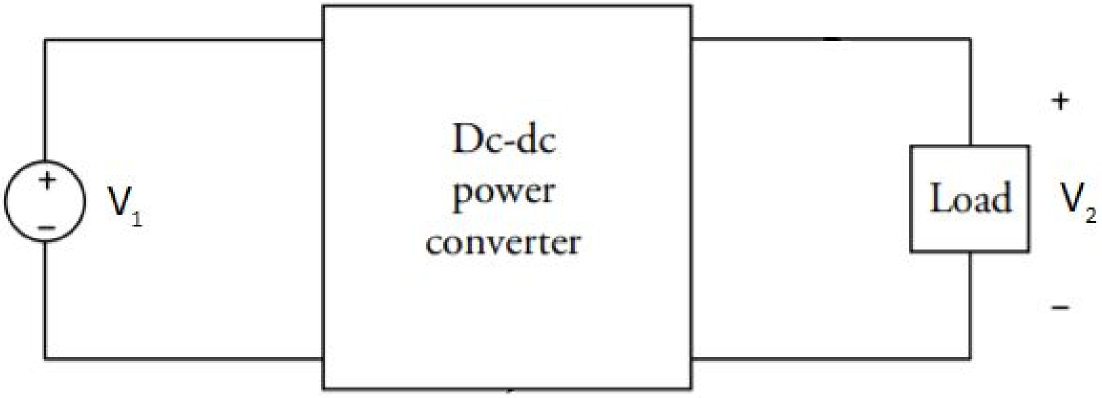


Fig. 7 displays the fundamental idea of a converter. [9]

A simple way to convert voltage to different levels is to use an linear regulator which is a device that keeps constant voltage and dissipates the unwanted energy as heat with the help of a voltage divider, an amplifier and a “pass transistor”. A way more efficient, yet more complex, way to convert voltages is via switched converters which will be explained in the following subchapter. Their basic topologies will be shown and commented as well as their functionality. Note that the following topologies are just examples of how the different converters can look. There are many other topologies that will have the same functionality but may look a different.

### 2.2.1 Buck converter

A buck converter, or a step-down converter, is designed to provide an output voltage that is lower than the input voltage. In Fig. 7 this would mean that (v1 > v2). where for example v1 could be a 12V car battery and v2 could be a phone charger, charging at 5V.

Fig. 8 shows the topology of a buck converter where $v_d$ is greater than $v_O$ and the current is flowing in the direction of the arrow. M1 in the figure is a transistor and acts as a switch. When M1 is on and conducting the diode M2 is blocking and the inductance L is charged from $V_d$. Then when M1 is off, since the inductor current can not stop flowing instantly, the diode will start conducting and the inductor current will slowly start to decrease until the transistor M1 is turned back on again and the process is repeated. The inductance in the circuit reduces current ripple and the capacitance acts like a backup energy source smoothing out the output voltage, lowering the voltage ripple.

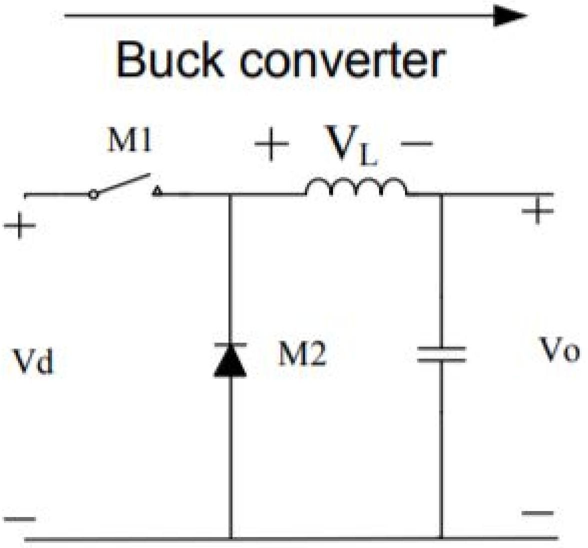


Fig. 8 Topology of a buck converter. [9]

Doing this, controlling how long the transistor is turned on, lets you control the output voltage $V_O$. The time where the transistor is turned on is called $T_{ON}$ and the time its off and  the diode is conducting, is called $T_{OFF}$. The duty cycle, D, tell us how long the transistor is on during one period ($T_{on} + T_{off}$) and can be calculated by (1).

$$D = \frac{T_{on}}{T_{on}+T_{off}} \qquad (1)$$

Through a bit of mixing around with different formulas and equations describing the electrical components of the buck converters topology and assuming that the converters runs in CCM, equation (2) can be derived. How this is done will not be included in this thesis but that and much more about the buck converter is covered in [10].

$$V_o = D \times V_d \qquad (2)$$

Equation (2) shows that $v_O$ is only dependent on the duty cycle and since the duty cycle is in percentage, it can only vary between $0 \leq D \leq 1$ meaning that the possible voltages $v_O$ can obtain is: $0 \leq V_o \leq V_d$ .

### 2.2.2 Boost converter

A boost converter, also called step-up converter, has the exact opposite function of a buck converter. The boost converters job is to increase the voltage on the output side. Looking at Fig. 7 this would mean ($v_1 < v_2$). A good example where a boost converter can be used is in battery powered applications where space is limited so batteries cannot be couple in series to achieve a higher voltage. Instead the converter can boost the batteries voltage to a desired level.

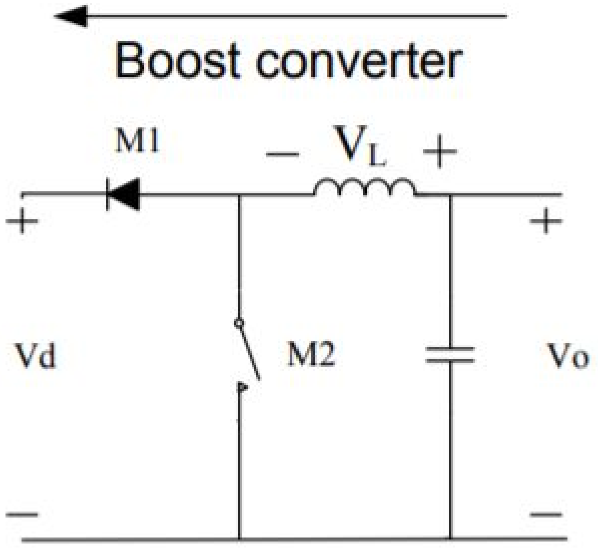


Fig. 9 Topology of a boost converter. [9]

The topology of the boost converter can be seen in Fig. 9. As shown, the boost converter is design quite similar to the buck converter in Fig. 8 with the differences being: the transistor and the diode swapped places, the inductor changed polarity because of the current now flowing in the opposite direction. The inductor and the capacitor is in the circuit for the same reason as in the buck converter, to reduce current and voltage ripple.

The operation of the boost converter is based on the same principle as buck converter, using the fact that an inductor can not stop its current from flowing instantly. Also same as in the buck converter, the inductance reduces current ripple in the circuit and the capacitance reduces output voltage ripple. During $T_{ON}$ when the transistor M2 is closed, the inductance L is charged. Then when M2 is open, during $T_{OFF}$, the inductor will release its charge through M1. The longer the transistor is on (closed) the higher the voltage over the inductor will grow and theoretically with ideal components, it could grow to infinity. In reality this is not the case since the inductance will eventually get saturated.

Same as with the buck converter, an equation (3) can be derived that describes the correlation between the input voltage and the output voltage dependent on the duty cycle.

$$V_d = \frac{V_o}{(1-D)} \tag{3}$$

Looking at equation (3) it is clear that $V_d$ will be bigger than $V_o$ in every case except when D = 0, giving: $V_o = V_d$. This is due to the duty cycle, D, varying between $0 \leq D \leq 1$. In reality the converter has a minimum and a maximum duty cycle dependent on the input and output voltage. More about this in a later chapter.

### 2.2.3 Buck-boost converter

In some applications, like the one this thesis work is researching, it is necessary to be able to push current in both directions. For example in an electric powered vehicle where the converter have to be able to run in motoring mode where it powers the motor and generator mode where its charging a battery pack. This can be achieved by combining a buck converter and a boost converter. The result is a two quadrant buck-boost converter that can operate either in buck mode or boost mode depending on the situation.

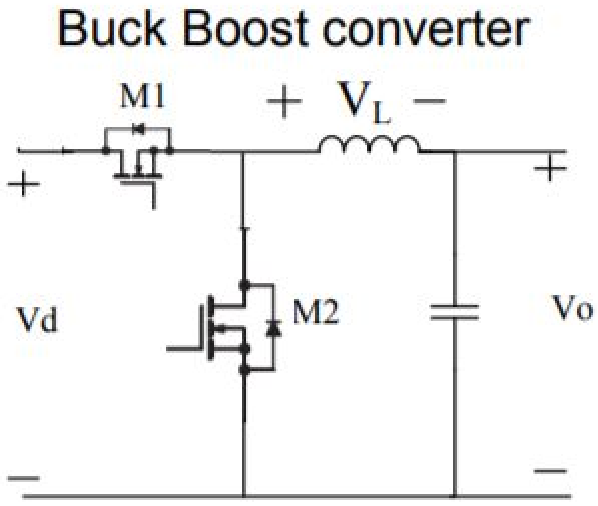


Fig. 10 Topology of the buck boost converter. [9]

The topology in Fig. 10 is almost the same as the ones described in Fig. 8 and Fig. 9. It is basically just a combination of the two topologies which makes it possible for current to flow in both ways in one converter, thus making it bidirectional. Note that swapping position of M1 and L makes the buck-boost converter become a boost-buck converter.

## 2.3 Controller

To be able to control and regulate any kind of switched converter, a programmable controller is needed. Electrical components like transistors, which is crucial in all switched converters, is turned on and off via gate drivers which have to be controlled.

Some good examples of controllers that often are used is FPGAs or microcontrollers such as Arduino. FPGAs are often better and in terms of speed since its physical gate formation can be programmed and thus operate faster. At the same time, the FPGA needs more programming to work properly and the code often is more complex. A microcontroller often uses a more simple code and built in functions like PWM to control the converter making the controlling part much easier. A regulator is often coded into the controller to make the converter stable and give fast precise results. The comparison is from [11].

This thesis will not cover any coding or simulation of the controller and because of that, only this brief introduction of the controller is presented.

# 3 Method

This chapter will describe a bit how the thesis work has been carried out. It will describe the different parts of the thesis as well as how they all transcend into each other.

Since the thesis work is mostly theoretical, all work has been done at distance i.e. not at the company with counseling either via phone or email. Because much of the work has consisted of reading and analysing scientific articles, white papers and even other thesis works, doing the thesis on distance has worked out very well and has been really smooth.

All the way through doing the thesis work, choosing topology and components, writing the report etc., a gantt chart (Fig. 11) has been used and followed as accordingly as possible. This has been a good way of keeping track of what to do and when, making it easier to complete the work within the time frame of the project.

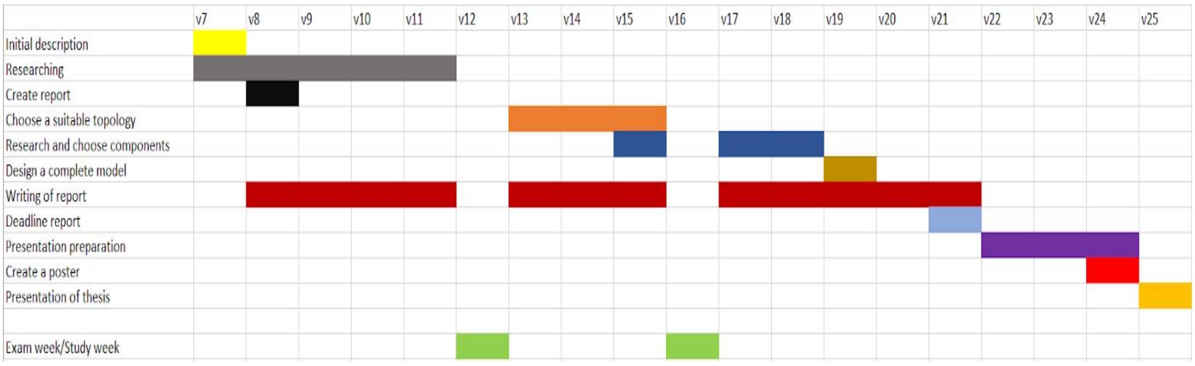


Fig. 11 Gantt chart of the thesis work.

The first five weeks of the thesis work was mostly research, finding out what topologies there is out there and if they might work in this application, how they work and what applications they were used in. Much of the research that was found were from other thesis reports and much of it were dc-dc converters with power grid applications. Many of the reports had applications with low power ratings and finding converters that could handle power ratings up to 300 kW was quite hard.

After doing the initial research it was time to narrow down a bit on the research and start considering what topology would be best for this application. A deadline of choosing a topology to work with was set to v.15 as shown in Fig. 11. When a topology have been selected, components accordingly to that topology also have to be chosen with the correct power ratings for the application. Since there are many components of different types and brands, they have to be researched to find out what fits best into the application. The deadline of choosing what components to use in the converter was set to v.18.

With a suitable topology picked and components chosen, a model of the complete converter can be drawn up in a program like LTspice or Kicad. One week, v.19, have been assigned to do this, completing the final design of the converter.

The final 5-6 weeks of the thesis work is to complete the report, create a technical poster and prepare for the final presentation of the thesis.

## 3.1 Source Criticism

[3], [6], [7] and [13] are published books and are considered safe sources.

[4] is an article from an published book written by an electrical engineer and can be considered a safe source.

[9] is a published Master's thesis from Chalmers University and can be considered viable and correct source.

The sources [2], [8], [11], [12],[15] ,[16], [17], [19] and [22] are from different companies which is more or less well known. [8] and [16] are sources from Semikron which is certenaly considered a safe source. [12] is from Texas instruments, a big and well known company. [2], [11], [15], [17], [19] and [22] are from a smaller companies than Semikron and Texas instruments, but after cross referenced the interesting information, the conclusion can be made that the information is safe. Both big and small companies rely on their customer base and providing correct information is a big part of keeping the customers.

[1], [18] and [20] are articles from digital papers for electrical engineers which makes lots of the readers well educated and the information must reach a certain level.

[5], [10], [14] are informative blog articles written by people with good education and experience within electrical engineering, often above master degree. That, combined with some cross referencing on the explained facs makes these sources considered as trustworthy and correct.

[21] are from IEEE Xplore and is considered a safe source since its a part of IEEE.

# 4 Analysis & Results

This chapter will cover the chosen topology and go over the different stages of operation. The different parts of the converter will be explained and important parameters will be discussed. Components will also be mentioned, how to choose them and what to consider when doing so.

## 4.1 Topology

The chosen topology is shown in Fig. 12. It is a symmetric bidirectional buck-boost converter. The name implies that the converter is capable of having a battery pack V1 with either higher or lower voltage than the load V2. Furthermore the converter will be able to both power the load with the battery and also run current backwards, charging the battery. The load of the converter will in this application be a common DC bus with a fixed voltage of, for example 400V. More about the chosen topology can be found in [12].

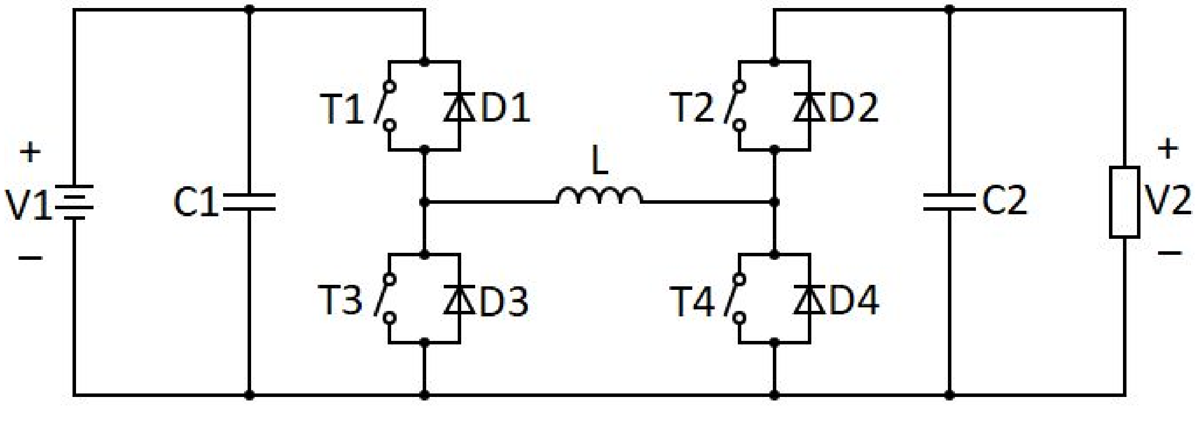


Fig. 12 The selected DC-DC topology with ability
to boost or buck voltage from source to load and vice versa.

The inductor L is the main component in this type of circuit. It is the inductor, in combination with the other components, that makes it possible to change the voltage to higher or lower levels. The ability to charge energy in the inductors magnetic field gives another source of power besides the battery. With this secondary source one can either choose to power the load only from the inductor in buck mode, or combine the battery and the inductor to power the load in boost mode. The inductance also help smoothing out the current in the circuit because of its characteristics, not being able to change its current flow instantaneously. To reduce voltage ripple, capacitors C1 and C2 are included in the circuit.

The transistors T1-T4 are displayed as switches in Fig. 12 since they will act like switches, either fully blocking or fully conducting current. Transistors have built in diodes to protect the transistor from high reversed voltages. These built in diodes are not as good or efficient as a stand alone diode which is why there is an extra diode in parallel to each transistor referenced D1-D4. The built in diodes are not displayed in Fig. 12.

Chart 2. Shows transistor state during the different modes.

| | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| Boost Powering Mode | ON | OFF | OFF | PWM |
| Buck Powering Mode | PWM | OFF | OFF | OFF |
| Boost Charging Mode | OFF | ON | PWM | OFF |
| Buck Charging Mode | OFF | PWM | OFF | OFF |

Chart 2 represents the transistor states during the different modes of operation. In each mode only one of the transistors will be run in pulse width modulation (PWM) mode, turning “ON” and “OFF”, and the other three will either be completely “ON”, acting like a short circuit, or completely “OFF” acting like an interruption, meaning current cannot pass. PWM is a built in function in many microcontrollers and it controls the width of each pulse depending on the difference between the input and output voltage, a bigger difference means longer pulses. More about this in the chapter about duty cycle.

Since the topology have a simple design with only a few components and only one transistor in PWM mode at the time, the control of the circuit will not be too comprehensive. Furthermore the efficiency will most likely be higher compared to more advanced converters containing more components. One major downside of the converter topology is that it lacks a galvanic isolation which is preferable in high voltage applications to achieve a safer construction. To solve the issue with galvanic isolation, a complimentary circuit could be added onto the converter circuit as a next step in the development. This could be done with, for example, a full-bridge inverter/rectifier circuit with an 1:1 transformer. However, that development will not be covered in this thesis.

The following four subchapters will describe the different modes the converter will operate in depending on the voltage V1 and voltage V2. For simplicity, the voltage V1 will be referred to as the "battery voltage" and the voltage V2 as the "load voltage". The schematic from Fig. 12 is coloured to give a distinct reflection of how the current moves through the circuit and each mode is explained to give a good understanding of the topology. Each mode have two phases of operation to achieve the desired voltage which both will be covered. There are also two capacitors in the topology schematic and their purpose is to reduce voltage ripple. The direction of the current through these capacitors are not always showed in the following figures. This is because the current direction can vary in one and the same phase. However, the average current value of each capacitor will equal out to zero within each period.

### 4.1.1 Boost Powering Mode

The converter will run in boost powering mode if the battery voltage is lower than the desired load voltage. This mode will be active when, for example, the vehicle is accelerating and the battery voltage is lower than the voltage on the DC bus.

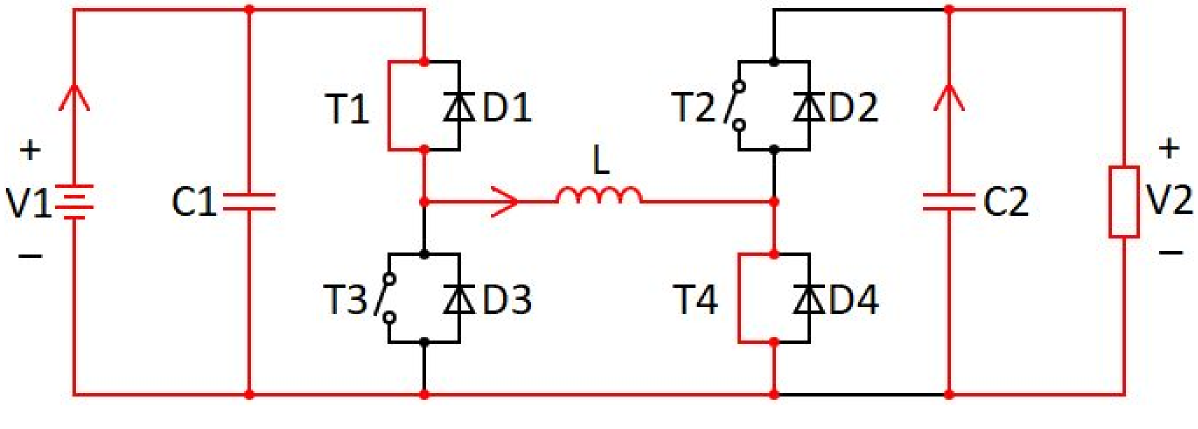


Fig. 13, shows the current flow of the converter in Boost Powering Mode, phase one.

In the first phase of boost powering mode the transistors T1 and T4 are "ON" and will conduct current from the battery, simultaneously as charging the inductor L. Simultaneously the capacitor C2 is discharging making current flow through the load and reducing the ripple, as shown in Fig. 13. Transistor T2 and T3 are “OFF” and will not conduct any current during this phase. All diodes D1-D4 is reversed biased and neither will conduct any current.

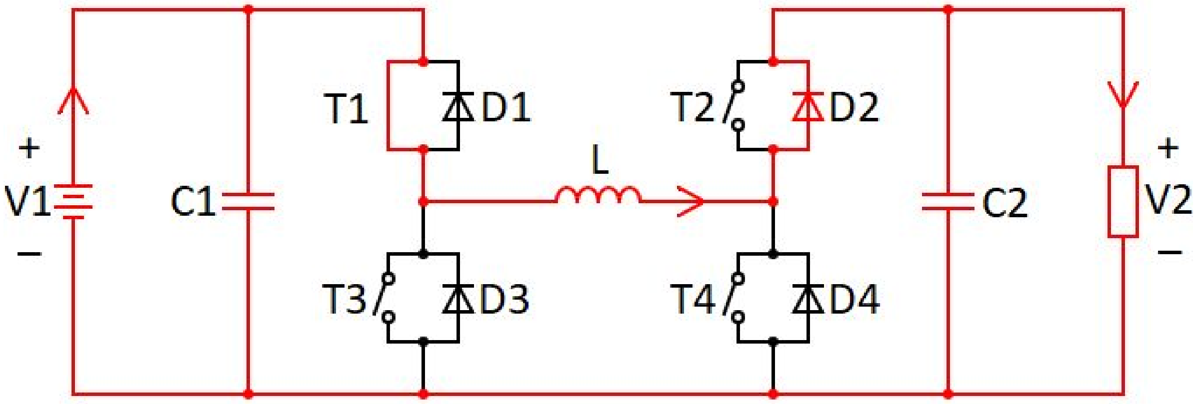


Fig. 14, shows the current flow of the converter in Boost Powering Mode, phase two.

In the second phase of boost powering mode the transistor T1 will still be “ON” but now the transistor T4 is turned “OFF” forcing the current to go through the diode D2. The battery and the inductor will now power the load together making the voltage over the load higher than the battery voltage, as shown in Fig. 14.

### 4.1.2 Buck Powering Mode

The converter will be in buck powering mode when the battery voltage is higher than the load voltage and the battery is powering something like a motor in an EV via the DC bus.

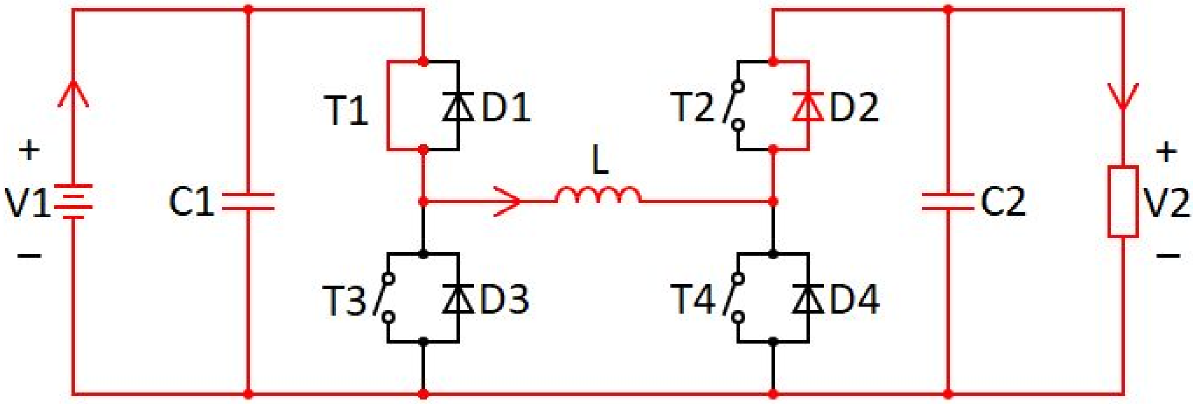


Fig. 15, shows the current flow of the converter in Buck Powering Mode, phase one.

In the first phase of buck powering mode the transistor T1 is turned “ON” and the other three transistors is “OFF”. This makes the current run through the inductor L, charging it, and then through the diode D2, as shown in Fig. 15. This makes the battery power the load at the same time as its charges the inductor L.

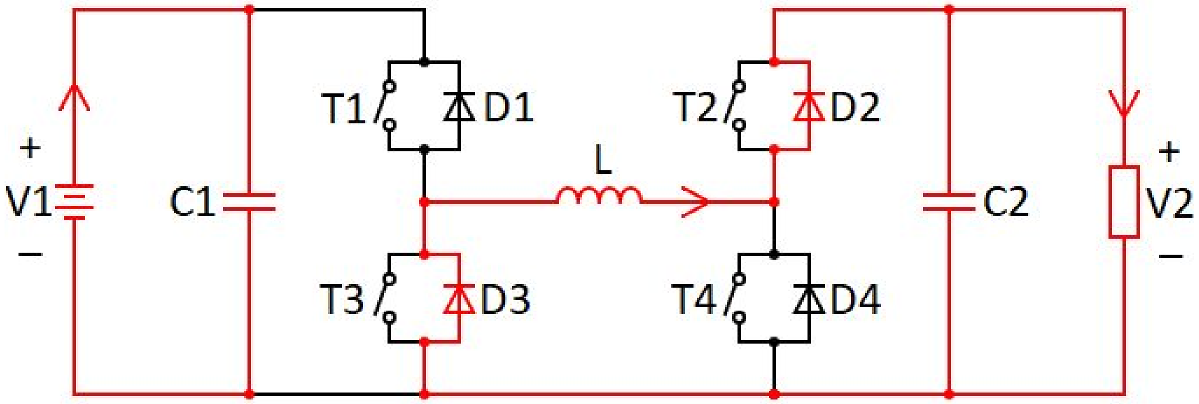


Fig. 16, shows the current flow of the converter in Buck Powering Mode, phase two.

In the second phase of buck powering mode the transistor T1 is turned “OFF” making the battery charge the capacitor C1, as shown in Fig. 16. The load is now powered only by the inductor L. The current flow through diodes D2 and D3 to make a complete circuit.

### 4.1.3 Boost Charging Mode

The converter is in boost charging mode when the battery voltage is greater than the load voltage and current is moving from the load to the battery as shown in Fig. 17 and Fig. 18 depending on which phase its in. This mode occurs for example when a vehicle with a 400V battery pack is charged from the grid with 230V (in sweden). Then the voltage needs to be boosted up to be able to charge the battery.

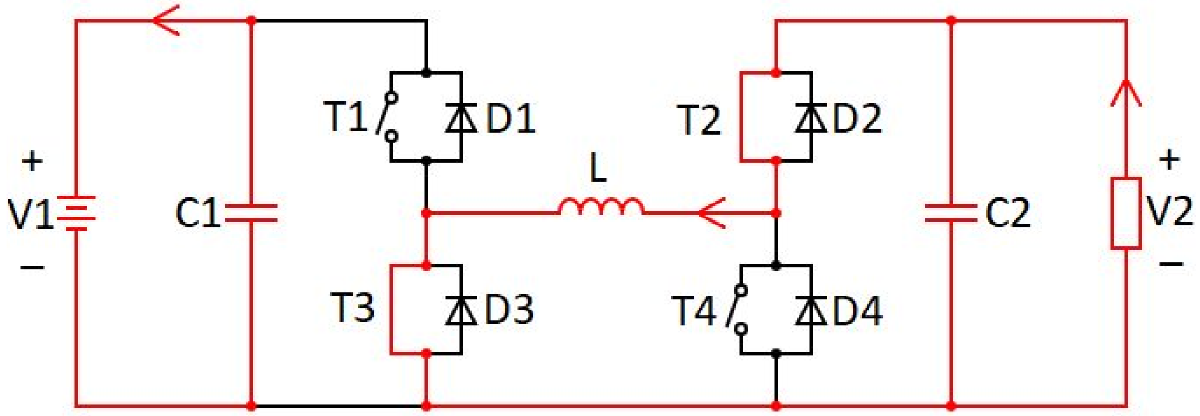


Fig. 17, shows the current flow of the converter in Boost Charging Mode, phase one.

In the first phase of the boost charging mode, current is flowing as shown in Fig. 17. Transistors T2 and T3 are “ON” and conducting, making the current go through the inductance and charging it. On the right side of the converter, the current to charge the inductance is supplied mainly from the load. Meanwhile on the left side, capacitor C1 is releasing energy into the battery to reduce voltage ripple.

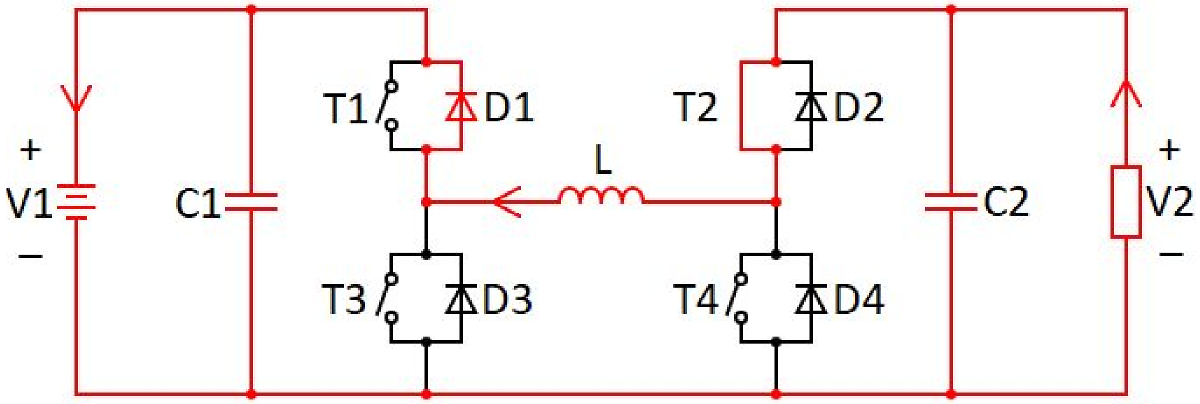


Fig. 18, shows the current flow of the converter in Boost Charging Mode, phase two.

The second phase of the boost charging mode is shown in Fig. 18. In this phase, transistor T2 is “ON”, diode D1 is conducting and the inductance is discharging, pushing current towards the battery. The voltage over the battery is boosted since the inductor voltage is added with the load voltage.

### 4.1.4 Buck Charging Mode

The converter is in this mode when the load voltage is greater than the battery voltage and the current is flowing from the load to the battery as shown. The converter is working in this mode when the battery is charged by a source with higher voltage. For example, when a 100V battery pack is connected and charged via the common DC bus of 400V.

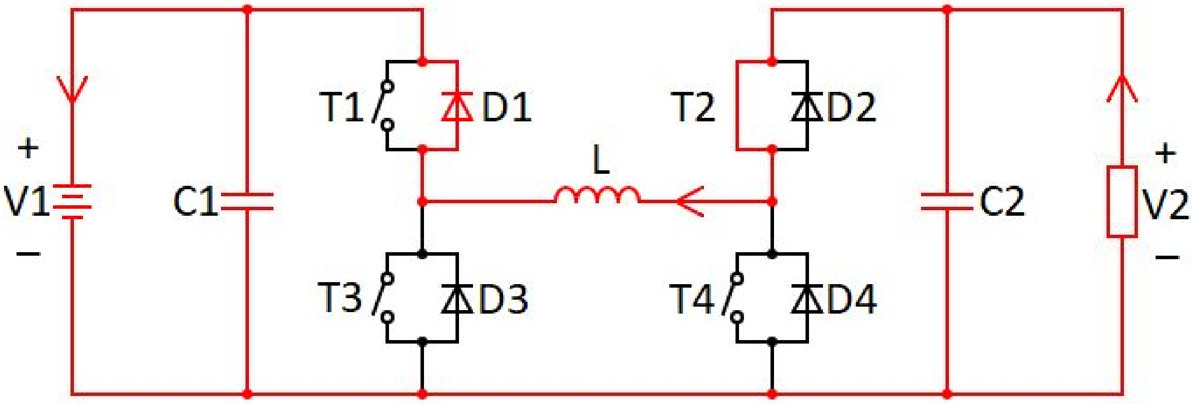


Fig. 19, shows the current flow of the converter in Buck Charging Mode, phase one.

In phase one of the buck charging mode, current is flowing as shown in Fig. 19. Transistor T2 is "ON" and diode D1 is conducting. On the right side of the converter, current is moving from the load and then through the inductance, charging it, and then into the battery.

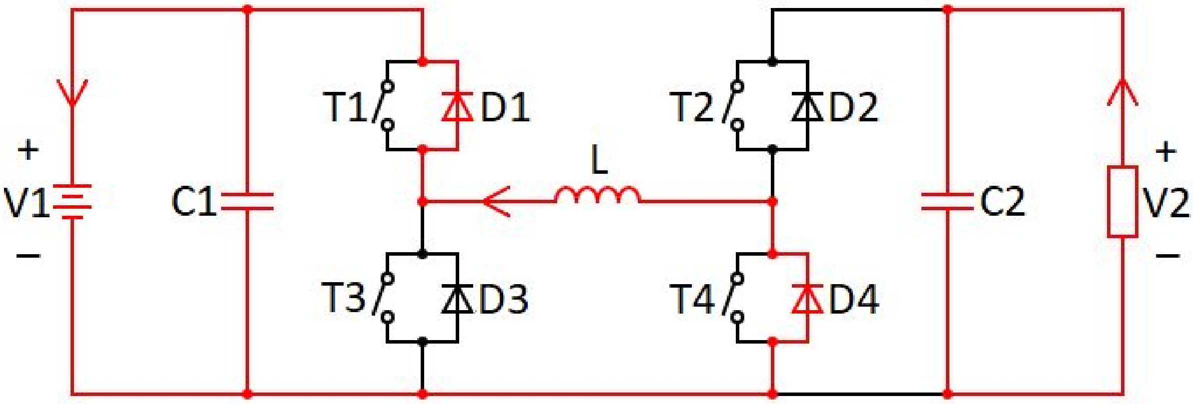


Fig. 20, shows the current flow of the converter in Buck Charging Mode, phase two.

The second phase of the buck charging mode is shown in Fig. 20. In this phase, the inductance is discharging its energy into the battery. Meanwhile on the right side of the converter, capacitor C2 is being charged up by the load. During this phase, all the transistors are fully "OFF" and the diodes D1 and D4 is conducting. The voltage over the battery in this phase is lower than in the previous phase since the energy is now only supplied by the inductance. The voltage over the inductance will slowly decrease until transistor T2 is turned on again and the converter is returned to phase one, once again charging the inductance.

## 4.2 Components

When choosing what type of components to use there are always pros and cons that have to be considered and evaluated. For each component to work in the topology, it has to have the right power ratings and be able to withstand the voltage and/or current going through the system without breaking or burning up.

### 4.2.1 Transistors

The first thing to figure out when choosing a transistor is what type that is most suited. Second thing to look at is data sheets from different models and manufacturers to see and compare specifications to try and figure out which ones will perform best in the specific application.

Even though a MOSFET is a good choice of transistor, it is often used in lower voltage applications due to its good efficiency and finding one capable of handling the power that this applications requires is yet impossible.

A BJT can usually handle a high voltages, but when operating at these higher voltage levels the current is often limited to a few amperes which in this application will not be enough. It has a lower switching speed compared to the MOSFET and a more complex gate-driver since its current controlled.

The transistor that is chosen for the topology in this thesis is the IGBT. As mentioned earlier in the technical background, the IGBT is a combination of the best parts of both the BJT and a FET enabling it to handle high currents and high voltages which is perfect for an EV application like this where the power easily can exceed a few hundred KW's. The IGBT is voltage controlled which makes the gate-drivers a little less complex as well as resulting in moderate switching speeds. The "ON" resistance in the IGBT is usually low resulting in lower transconductance losses, something that is really important when operating at high power.

One downside of the IGBT is that its in generally more expensive compared to a MOSFET or a standard BJT because of its complexity. This can be a problem when working on a project when the budget is small and if there are several transistors in the topology, the total cost adds up fast.

### 4.2.2 Diodes

Transistors have integrated diodes that are used to let current through in the reversed direction to keep the transistor from breaking. These diodes are not optimal to use in an application like a converter. Therefore, an additional diode is connected parallel to each transistor. This is done to reduce the strain on the integrated diodes.

The PN diode lays the groundwork for many other diodes since other diodes looks similar in the construction with small modifications compared to the PN diode. Most commonly the PN diode is used for detection of radio signals, detecting light, emitting light and rectification of alternating currents. However, this type of diode is mostly used for low power applications and will not be suitable for a high power converter.

The Schottky diode have some advantages compared to the ordinary PN diode that could be crucial when choosing what diodes to use in an application like a converter. One of them is that it has a lower forward voltage drop than other diodes. This is important because it will reduce the heat dissipation from the diode, especially when there are really high currents. Another advantage with the Schottky diode is that is have a fast reverse recovery time, as mentioned in [13]. This means that it can handle fast switching times without having problems with reverse currents due to the switching frequency. One of the disadvantages with the Schottky diode is that it has a higher reverse leakage current than some other diodes, which means losses increase. Another more evident disadvantage is that the Schottky diode have relatively low reverse voltage ratings. Due to the increased leakage current during high voltages Schottky diodes is most efficient when operating in a lower voltage than the rating of this converter. The Schottky diode would be the obvious diode choice if high switching frequencies where needed but for converters operating with higher voltage and current this type of diode will not be an option.

When dealing with applications that operates above 100V the PIN diode would probably be the best choice since it is advantages becomes most effective with high voltages. The PIN diode is manufactured to conduct high currents and withstand large reversed voltages. Though the PIN diode have the big disadvantage of producing quite a lot of heat this will need to be solved with proper heat dissipation. Another disadvantage of the PIN diode is that due to the wide space charge region, which is needed to withstand large reversed voltages, lots of charge is stored in the diode. This gives the diode a higher recovery time when changing from forward biased to reversed biased, which in turn forces the switching speed to be lower. Tough lower switching speeds will result in less switching losses the conduction losses will get higher. Considering the characteristics of a general PIN diode this type of diode is still the obvious choice for a high power converter.

### 4.2.3 Capacitor

Choosing the correct type of capacitor for a circuit is really important to achieve good results whether it is used in filter applications or in converters. In this application, the capacitors will aid in reducing voltage ripple. This chapter will describe different factors to have in mind when choosing the right capacitor as well as looking at pros and cons of some basic capacitor types.

For each application there are different requirements for the component to fulfill. Some important factor which determines if a capacitor fits in a circuit are:

- Capacitance value. All types might not be able to obtain the desired capacitance value of the application.
- Voltage rating. The capacitor must be able to withstand the voltage rating off the application and not break down.

- Polarization. Some capacitors are polarized, meaning they have a positive side and a negative side, and if connected the wrong way they would break immediately.
- Temperature coefficient. This describes how much the capacitance value changes with a change in temperature.
- Tolerance. This explains how much the capacitance value can differ from its nominal value and is often given in percentage. This factor is very important in, for example, filter application where the capacitance value have to be very exact to obtain a good filter result.
- ESR. An ideal capacitance would only have capacitance and no resistance but in reality a capacitor also have a small resistance (ESR) which leads to losses. This resistance is often modeled in circuits as a resistor in series with the capacitance.
- Lifetime. This is an important parameter to check and compare to the price of the capacitor. This is mostly to make sure that it is priceworthy but also to avoid having to change it too often which itself isn't sustainable.

The different types are often named after their dielectrics which is the insulating material between the two conducting materials in the capacitor.

First out is the Electrolytic capacitor which is a polarized capacitor. It can either have a solid or a non-solid dielectric. It usually have high voltage ratings and are capable of high capacitance values but are known to have big variations. There are a couple of different categories within the electrolytic capacitors and they all have slightly different properties. Because of its polarization and its variation in tolerance, this capacitor is often used in DC-DC converter applications for decoupling purposes.

Another common capacitor type is the Ceramic capacitor. This capacitor is known for its good stability and low losses. It has a low ESR and lower tolerance compared to electrolytic capacitors. It is generally very small in physical size and often have difficulties reaching high capacitance values. It is not polarized which means that it can be used in AC applications and is often seen in filters and EMI dampening applications.

The last type that will be mentioned are Film capacitors. They are non polarized with low ESR and often very good voltage ratings. They are good at handling high peak currents thus making this capacitor an excellent choice for snubber applications. It has a fairly long lifetime and decent capacitance values. This capacitor is often used in switched dc-dc voltage converts.

The capacitor that is chosen for this application is the Polymer electrolytic capacitor. It is polarized which will work perfect since the current through the capacitance in the converter only will be DC. It has a solid dielectric as an insulator which contributes to a longer lifespan and good properties at both higher and lower temperatures. It is often used in higher quality motherboards and DC-DC converters.

More about different types of capacitors and their properties is described in [14].

### 4.2.4 Inductor

This chapter will cover the process of choosing an inductor and also describe some relevant standard types along with their pros and cons.

When choosing what type of inductor to use in an application there is a lot of things to have in mind. Some examples of such things is presented below and also in [15], along with many other things concerning different types of inductors.

- Switching frequency
- Output power rating
- Inductor application and topology design
- Physical size and mounting options
- Temperature rise and environment
- Winding and core material

This list can be much longer and what is most important differs a bit between different applications but these are some of the most important factors overall.

Other things to look at and compare are parameters. Some useful parameters to look at is:

- Rated current, how much current that the inductor can handle physically without burning up.
- Saturation current, how much current it can handle before the inductor gets saturated. In other words, how much current it can handle before the core can not store any more energy in its magnetic field.
- DC resistance, specifies the resistance for the conductive materials in the inductor. This is especially important in switched converts like DC-DC converters where efficiency is important. With a couple of hundred KW's, the conductive losses according to $I^2 \cdot R$ gets big really fast.

There are, of course, many other parameters that can be compared but since this application is about DC-DC converters, these parameters are some of the most important.

If an air-core inductor type is used there will not be much losses in the inductor since there is no metal core and the only losses will come from conductive losses in the windings which is good. A major downside with the air-core inductor is that it is hard to obtain high inductance values because of the low permeability in air. To obtain a higher value, the inductor have to have more turns in its winding and thus become larger physically.

Iron core inductors are capable of having a high inductance value due to its iron core amplifying its magnetic field but along with that iron core comes disadvantages in form of additional losses such as core losses that increase with higher frequency. Because of this, this type of inductor is often used in applications with low frequency and where high power ratings is required.

Ferrite core inductors is pretty similar to an iron core inductor in its construction but instead of an iron core, now the core is made of a ferromagnetic material which has a much higher permeability resulting in an even higher magnetic flux density, capable of much higher inductance values than many other inductor types. Ferrite core inductors generally have relatively low losses. Because of its characteristics, the ferrite core inductor is a great choice for higher quality transformers or switched converters like DC-DC converters.

Out of the three core types mentioned above a ferrite core inductor would be preferable because of its characteristics.

## 4.3 Important formulas

In this subchapter, some important equations will be presented and discussed. Many of the following formulas will be very useful later on when it comes to simulating the topology. Note that this thesis will not include any simulation but since the purpose of the thesis is to lay a good starting foundation for a bigger project, this topology will later on be simulated. Equations (4), (5), (6), (7), (8) and (9) mentioned in this chapter is from [12].

### 4.3.1 Duty cycle

Duty cycle is explained a bit in the technical background chapter of this thesis and as said, the duty cycle is defined as the time, in percentage, that the transistor is “ON” i.e. conducting. This is shown in equation (1).

The first thing to calculate are the boundaries, minimum duty cycle and maximum duty cycle. These boundaries are important to know because this is where the converter will operate at its extremes.

The minimum duty cycle is calculated when the converter is operating in buck mode, see equation (4), where $V_{out}$ is the desired output voltage and $V_{inmax}$ is the maximum input voltage for the converter.

$$D_{buck} = \frac{V_{out}}{V_{inmax}} \tag{4}$$

The maximum duty cycle is calculated when the converter is operating in boost mode and is shown in equation (21). Same as the buck calculation, $V_{out}$ is the desired output voltage and $V_{inmin}$ is the minimum input voltage for the converter.

$$D_{boost} = 1 - \frac{V_{inmin}}{V_{out}} \tag{5}$$

These duty cycle boundaries will be used in later calculation when determining, for example, output capacitor values. These duty cycle formulas will only work for when the converter is operating in CCM. If the converter is not operating in CCM, a regulator can be added to constantly measure in/output voltage and compensate the duty cycle.

### 4.3.2 Selecting inductance value

First of all, what frequency a system is running changes what size the passive components have to be and this applies for both inductors and capacitors. With a higher frequency, passive components like capacitors and inductors can be smaller and the other way around, lower frequency requires larger components. The reason for this is, with lower frequency the component have to store more energy at a time since the period time is longer. With a higher frequency, less energy is able to go in the component before the current is switching direction and energy is once again leaving the component.

Choosing a switching frequency is necessary to calculate many of the following formulas and is always a trade-off between component sizes and power losses since the losses often go up with higher frequency. More about losses for each component is covered in the chapter “losses” later on in the report.

The value of the inductance have to be chosen so that it can handle both buck mode and boost mode. To make sure of this, the critical inductance value $L_{Crit}$ is calculated for buck mode according to equation (6) and for boost mode according to equation (7). To make the converter operate in CCM, the inductance value L should be selected so that it is bigger than the largest $L_{Crit}$, i.e. bigger than both $L_{CritBuck}$ and $L_{CritBoost}$.

- Choosing $L = L_{Crit}$ makes the converter operate in BCM.
- Choosing $L < L_{Crit}$ makes the converter operate in DCM.
- Choosing $L > L_{Crit}$ makes the converter operate in CCM.

The critical inductance value when the converter is in buck mode is shown below in equation (6).

$$L_{CritBuck} = \frac{V_{out} \cdot (V_{inmax} - V_{out})}{K_{ind} \cdot V_{inmax} \cdot I_{out} \cdot f_{sw}} \quad (6)$$

Where $V_{out}$ is the desired output voltage, $V_{inmax}$ is the maximum input voltage, $I_{out}$ is the desired maximum output current, $K_{ind}$ is a coefficient that describes how much ripple currents that is allowed relative to the maximum output current and $f_{sw}$ is the chosen switching frequency of the converter.

The critical inductance value when the converter is in boost mode can be calculated with equation (7).

$$L_{CritBoost} = \frac{V_{inmin}^2 \cdot (V_{out} - V_{inmin})}{K_{ind} \cdot V_{out}^2 \cdot I_{out} \cdot f_{sw}} \quad (7)$$

Where $V_{out}$ is the desired output voltage, $V_{inmin}$ is the minimum input voltage, $I_{out}$ is the desired maximum output current, $K_{ind}$ is a coefficient that describes how much ripple currents that is allowed relative to the maximum output current and $f_{sw}$ is the chosen switching frequency of the converter.

### 4.3.3 Selecting capacitance value

There are two capacitors in the chosen circuit. One will act as an input capacitor, help stabilizing the system and the other one will act as an output capacitor, reducing output ripple. If the capacitor is an input capacitor or an output capacitor varies depending on what mode the converter is in and because of this, both capacitors will be calculated as if they were output capacitors since that requires a higher capacitance value.

To make sure that the capacitor is sufficient, the capacitor value C have to be calculated for both modes, buck and boost, and then C should be selected so that it is bigger than the largest calculated value from equation (8) and equation (9). These calculation takes the maximum allowed voltage ripple into consideration.

The minimum required capacitance value when the converter is in buck mode can be calculated with equation (8).

$$C_{outmin} = \frac{K_{ind} \cdot I_{out}}{8 \cdot f_{sw} \cdot \Delta V_{out}} \qquad (8)$$

Where $\Delta V_{out}$ is the maximum allowed output voltage ripple, $I_{out}$ is the desired maximum output current, $K_{ind}$ is a coefficient that describes how much ripple currents that is allowed relative to the maximum output current and $f_{sw}$ is the chosen switching frequency of the converter.

The minimum required capacitance value when the converter is in boost mode can be calculated with equation (9).

$$C_{outmin} = \frac{I_{out} \cdot D_{boost}}{f_{sw} \cdot \Delta V_{out}} \qquad (9)$$

Where $\Delta V_{out}$ is the maximum allowed output voltage ripple, $I_{out}$ is the desired maximum output current, $D_{boost}$ is the maximum duty cycle and $f_{sw}$ is the chosen switching frequency of the converter.

### 4.3.4 Test Case

This chapter will put together a test case with voltage and current ratings based on the wanted output power of around 300KW. Hypothetical desired values will be set for the input voltage range and output voltage. A frequency will be chosen as well as maximum output current. The selected values for these parameters is shown in chart 3. With these parameters set, rest of the important values such as inductance and capacitance values can be calculated with the formulas described in a previous chapter “Important formulas”.

Power losses will not be included in this test case since that requires that specific components have to be selected and their datasheets inspected for various resistances and other parameters. Before calculating losses, a simulation would be preferable. A brief summary of the different losses that occurs in a converter will however be covered in the next chapter.

Chart 3. Shows desired values of important parameters.

| | |
|---|---|
| Minimum input voltage, $V_{inmin}$ | 100V |
| Maximum input voltage, $V_{inmax}$ | 1000V |
| Desired output voltage, $V_{out}$ | 400V |
| Maximum output Current, $I_{out}$ | 800A |
| Switching frequency, $f_{sw}$ | 10KHz |
| Allowed voltage ripple, $\Delta V_{out}$ | 10% => 0,1*400 => 40V |
| Allowed current ripple, $K_{ind}$ | 20% => 0,2 |

With the chosen values, the input range of the converter will be 100-1000V and an output power, without any losses accounted for, of 320KW. In reality, the output power would be a little lower since it have to be multiplied by the efficiency of the system.

To start off, the minimum and maximum duty cycle have to be calculated with equation (4) and equation (5) using the chosen values in Chart 3.

$$D_{buck} = \frac{V_{out}}{V_{inmax}} = \frac{400}{1000} = 0,4$$

$$D_{boost} = 1 - \frac{V_{inmin}}{V_{out}} = 1 - \frac{100}{400} = 0,75$$

After the duty cycle is calculated it is time to choose an inductance value. A bigger inductance value makes it possible to have a larger output current and a smaller value often makes the inductance smaller in size. To calculate the minimum value that is required for an specific output current, equation (6) and equation (7) is used.

$$L_{CritBuck} = \frac{V_{out} \cdot (V_{inmax} - V_{out})}{K_{ind} \cdot V_{inmax} \cdot I_{out} \cdot f_{sw}} = \frac{400 \cdot (1000 - 400)}{0,2 \cdot 1000 \cdot 800 \cdot 10000} = 150\mu H$$

$$L_{CritBoost} = \frac{V_{inmin}^2 \cdot (V_{out} - V_{inmin})}{K_{ind} \cdot V_{out}^2 \cdot I_{out} \cdot f_{sw}} = \frac{100^2 \cdot (400 - 100)}{0{,}2 \cdot 400^2 \cdot 800 \cdot 10000} = 11{,}7\mu H$$

The largest required inductance value appears to be when the converter is in buck mode. As previously mentioned, to make the converter operate in CCM; choose an L that is bigger than $L_{\text{Crit}}$. A good estimation could be 10% larger. The chosen inductance value in this test case is: $165\mu H$.

Now that the inductance value is chosen, capacitor values have to be picked. This is done almost similar to choosing inductance values. First calculate the required values for both buck and boost mode and then pick a value that is a bit higher to be on the safe side. Calculation of the minimum capacitance in buck and boost mode can be done using equation (8) and equation (9).

$$C_{outmin} = \frac{K_{ind} \cdot I_{out}}{8 \cdot f_{sw} \cdot \Delta V_{out}} = \frac{0{,}2 \cdot 800}{8 \cdot 10000 \cdot 40} = 50\mu F$$

$$C_{outmin} = \frac{I_{out} \cdot D_{boost}}{f_{sw} \cdot \Delta V_{out}} = \frac{800 \cdot 0{,}75}{10000 \cdot 40} = 1{,}5mF$$

The largest of the two values have to be picked and in this case it is when the converter is in boost mode. The chosen capacitor value is 1,65mF which is 10% larger than the minimum required value in boost mode and applies to both capacitors C1 and C2 to keep the converter as symmetric as possible.

Calculated value is shown in chart 4 below as well as a LTspice model of the complete system with values from this test case.

Chart 4. Shows calculated values from this test case.

| | |
|---|---|
| Minimum duty cycle, $D_{buck}$ | 0,4 |
| Maximum duty cycle, $D_{boost}$ | 0,75 |
| Inductance value, $L$ | $165\mu H$ |
| Capacitance value, $C$ | 1,65$m$F |

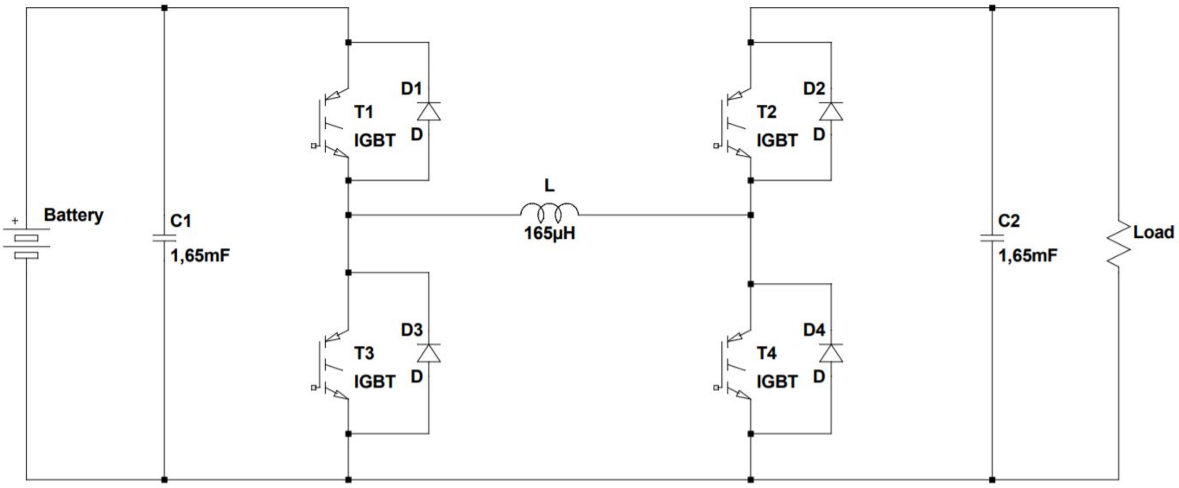


Fig. 21 is displaying the chosen topology with values from the testcase.

## 4.4 Losses

When handling hundreds of kilowatts losses will be of big impact. If there are too much switching and/or conductive losses this will result in lots of excessive heat that needs to be cooled, to not overheat and destroy components. This needs to be avoided as much as possible due to the extra cost this implicates, on one hand the cost of cooling components and on the other hand the direct loss of power that dissipates as heat.

### 4.4.1 Switching losses

The transistors in the converter operate as switches to give an as effective circuit as possible. An ideal switch would instantaneously change from “ON” state to “OFF” state and vice versa. This is nevertheless true due to the small delay when turning the switch “ON” or “OFF”. When the switch is turned “ON” the current increases and the voltage decreases under a short period of time. Since either the voltage or the current is zero this will results in a power loss. The same thing happens when the switch is turned “OFF” but now the voltage increases and the current decreases instead.

The loss, $E_{on}$ and $E_{off}$, for turning “ON” or turning “OFF” the switch is given in the datasheet of the transistor. These two losses needs to be multiplated with the switching frequency $f_{sw}$ to get the power loss $P_{sw}$ caused by the switching, as shown in equation (10).

$$P_{sw} = (E_{on} + E_{off}) \cdot f_{sw} \qquad (10)$$

Since the switching loss occur each time the transistor is turned “ON” or “OFF” a lower switching frequency would reduce the switching loss. But with lower switching frequency the other components in the converter would need to have greater values to being able to store more energy. This would both increase the cost of components as well as the physical size. Dependent on temperature, voltage and current the switching losses might look a bit different, and the equation above might need to be scaled. More about this in [16].

This type of switching mentioned above, where the voltage and current intersect each other and causes a loss, is called hard switching. Hard switching is the most common way to switch power converters since it is considered to be low-cost because few components are needed and it is easy to understand. In reality hard switching might be more costly than estimated, due to the shortened life-span of the transistors and efficiency losses, as explained in [17]. Another way of switching is soft switching, where the voltage or current is at, or is near zero when the switch is turned “ON” or “OFF”. This reduces the switching loss since one of the factors are gone or at least diminished from the power equation, equation (11). Nevertheless, soft switching, or resonant switching, is much more complex than hard switching since the switch timing is key to it is efficiency, and the moment the switch is turned “ON” or “OFF” needs to be coordinated with the switched waveform. This also require a much more advanced control circuit that add to the complexity, as discussed in [18]. Soft switching is something that could be useful in a converter application like the one in this thesis, but this topic needs to be further analyzed and tested in simulations and on prototypes before the determination of its usefulness.

$$P = U \cdot I \qquad (11)$$

### 4.4.2 Conductive losses

The ideal transistor that acts like a switch would either be fully conducting or be fully blocking the current. Furthermore there would be no voltage drop over an ideal switch/transistor when it conducts and the resistance is considered as infinite when the current is blocked. This would mean that there are no conductive losses in the transistor. However, that is not true due to a small voltage drop over the transistor when conducting and a small leakage current when blocking.

The generated power loss $P_{T.cond}$ in a transistor is the product of the current $i_{ce}$ through the transistor and the voltage $v_{ce0}$ across the transistor. Since the converter is operating with PWM the transistors will not conduct all the time, therefore, the duty cycle and the switching frequency $f_{sw}$ have an impact on the conductive losses. Including duty cycle in the equation will give the average power dissipation, as shown in equation (12). In this case the duty cycle is represented by the integration time $T_{T.cond}$. Where T refers to the time and T.cond refers to the transistor in conduction mode.

$$P_{T.cond} = f_{sw} \int_{0}^{T_{T.cond}} [v_{ce0}(t) \cdot i_{ce}(t)]\, dt \qquad (12)$$

The leakage current $i_{leak}$ will also have a impact on the losses. Here the voltage $v_{ce}$ is the voltage during blocking current and will be the dominant factor. This loss can be calculated in a similar way as the loss for conduction, as shown in equation (13).

$$P_{leak} = f_{sw} \int_{0}^{T_{leak}} [v_{ce}(t) \cdot i_{leak}(t)]\, dt \qquad (13)$$

The total losses $P_{T.tot}$ in the transistor will be calculated with equation (14) which really is just a summarization of the previously mentioned losses.

$$P_{T.tot} = P_{sw} + P_{cond} + P_{leak} \tag{14}$$

### 4.4.3 Diode losses

An ideal diode is either conducting current or blocking it completely, which means it would have no losses. But exactly as in the transistor case this is not true. Similar to the transistor the diode show a small voltage drop when conducting, which results in a power loss. Furthermore the diode have a recovery time when going from conduction mode to blocking mode. This recovery time allow a small leakage current to result in yet another power loss.

The power loss $P_{rec}$ produced by a diodes recovery time is calculated from equation (15). The loss $E_{rec}$ can be found in the datasheet and needs to be multiplated with the switching frequency $f_{sw}$ to obtain the average power loss. This might need to be scaled as the transistors switching losses and more about this can be found in [16].

$$P_{rec} = E_{rec} \cdot f_{sw} \tag{15}$$

This loss is only dependent on how often the diode have to recover, in other words the switching frequency, and not how long time its reversed biased. This is due to the leakage current in this case is a charge that gets stored in the junction of the diode when it is conducting. The recovery time of a diode is the time it take for the diode to discharge this junction charge.

The diodes conduction loss $P_{D.cond}$ is calculated similar to the transistors conduction loss as shown in equation (16). As in the transistors case, the voltage drop $v_D$ over the diode in conduction mode is multiplied with the current $i_D$ through the diode. The integration time $T_{D.cond}$ is the time that the diode is conducting. The integral is multiplied with the switching frequency to get the total conduction loss in the diode.

$$P_{D.cond} = f_{sw} \int_{0}^{T_{D.cond}} [v_D(t) \cdot i_D(t)]\, dt \qquad (16)$$

The total loss $P_{D,tot}$ of a diode is calculated as shown in equation (17).

$$P_{D.tot} = P_{cond} + P_{rec} \qquad (17)$$

### 4.4.4 Inductor losses

The total loss, shown in equation (18), produced in the inductor can be divided into three parts; the loss in the core, the loss from the DC resistance and the loss from AC reactance.

$$P_{ind} = P_{core} + P_{dcr} + P_{acr} \qquad (18)$$

The first loss in equation (18), the core loss $P_{core}$ is most often given in the data sheet of the inductor. If the core loss not can be found in the datasheet there is ways to calculate this loss but it can be quite difficult depending on the frequency amongst with other things. A more thorough explanation of this can be found in [19] and [20].

In the inductor windings a power loss $P_{dcr}$ occur due the DC current and the windings resistance $R_{DC}$. This loss can easily be calculated with equation (19). The resistance $R_{DC}$ is given in the data sheet.

$$P_{dcr} = I_{rms}^2 \cdot R_{DC} \qquad (19)$$

Furthermore there are also AC losses $P_{acr}$ produced by the inductor. These are dependent on the switching frequency which is mentioned in [20], though it could be simplified and calculated with equation (20).

$$P_{acr} = I_{rms}^2 \cdot R_{AC} \qquad (20)$$

### 4.4.5 Capacitor losses

In a capacitor there are some resistive losses $P_r$, same as in the other components and it also has a leakage current that depends on what insulator that is being used. Furthermore there is also a dielectric loss $P_d$. The total power loss $P_{cap}$ from a capacitor can be calculated with equation (21).

$$P_{cap} = P_d + P_r \tag{21}$$

The generated resistive loss $P_r$ can be calculated with equation (22). The dielectric loss $P_d$ is a bit more comprehensive to calculate. In [21] and [22] a more thoroughly explanation can found about how to calculate the losses in a capacitor.

$$P_r = R_{ESR} \cdot I^2 \tag{22}$$

# 5 Conclusion

After searching in course literature, reports, books and various other papers on the internet it could be found out that there was no complete DC-DC converter that suited the thesis project purpose. This is probably due to the high power ratings and the specific functions required. Converters with applications like the one in this thesis is often developed and constructed within companies, for example car manufacturers, for specific projects and then kept secret within the company to try and rival out other companies.

In the analysis & result part of the thesis, a topology is proposed that could work for this type of application and in the end of the chapter, a test case is created that contains a LTspice model of the topology, complete with calculated values. The only way to really find out if it would work is via simulation and testing which is not a part of this thesis. Because of its capability to use a wide range of input voltages that can either be higher or lower than the output bus voltage, it would probably be more expensive to manufacture and the efficiency would not be as good as if a more specified converter was used. But then again, that would mean losing its desired functions.

What type of components to use in the topology have been proposed based on research with consideration of the wanted power ratings and converter functions. The results are summarised below:

- Capacitor: Polymer Electrolytic Capacitor
- Inductor: Ferrite Core Inductor
- Transistor: IGBT
- Diode: PIN Diode

In the capacitor and inductor choice there are some different types that could work but these two are the ones chosen. What type that actually works best would be found out when a prototype is built and tested.

The transistor and diode type choices were much more obvious since there really are no other type that can handle the converter power ratings in an EV.

## 5.1 Future work and further research

As mentioned before, this thesis work is mainly to lay down a good starting ground for a DC-DC converter that later will be applied in an EV to try and make battery management better. There is still a lot more to do in the development of the converter and some of those things will be presented here.

One major thing to research further would be how to implement galvanic isolation. Look at different options and how it could work together with the selected topology, either modifying the topology to have an integrated isolation or maybe go with an extension that is not within the topology.

A controller platform and design have to be researched and chosen for the converter to work properly and deliver stable values. The controller then have to be programmed accordingly.

The topology with all its components as well as the controller design have to simulated in an simulation program, preferably simulink, to see that everything works together as planned and that it delivers its desired function.

When all the things above is done and with positive results, a prototype can be built. First it is wise to build an lower power unit to really see that everything works out as planned and then if that works, build a full scale, high power prototype.

Last is testing and this is where the final results are evaluated and the converter can go into the bigger project. A good idea would be to do some EMI testing as well to see that the converter meets the standards and not interfere too much with its surroundings.

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