Redesign of Control and Power Electronics for a Test-Bench for Small Internal Combustion Engines

Kristofer Gramner
José María Fernández Lahoz

Master of Science in Engineering Technology
Electrical Engineering

Luleå University of Technology
Department of Computer Science, Electrical and Space Engineering
Redesign of control and power electronics for a test-bench for small internal combustion engines

Kristofer B. Gramner, José Mª Fernández Lahoz

Luleå University of Technology

July, 2011
This report is about the redesign of control and power electronics for a test-bench for small internal combustion engines.

Since 2008, Luleå Tekniska Universitet is participating in the Shell Eco-Marathon competition, which is a contest in which you should build a car that drives the longest possible distance on the smallest amount of fuel. LTU has entered this competition a number times with a car called Baldos. In order to improve the performance of the motors in the cars that are going to compete they rent a test-bench to be able to test the motors efficiency and improve them. This is expensive so it is desired to have some sort of test-bench at the university. They have tried to build a test-bench but the electronics broke. So the goal is to redesign the electronics in order to have a working test-bench.

First the basic theory behind motor controllers are discussed. After that the theory of DC motors, PWM signals, the H-bridge, switching elements, and the particular problems that we will have to solve like power dissipation, overvoltages, speed control and how to do different measurements. We also introduce a simulation model in Pspice which helped us to predict how the test-bench would work. In addition we explain the relation between the model and the reality. This theoretical explications help us to explain the different decisions that were taken for the final design.

Moreover, we show how our design evolved. We speak about hardware, presenting all elements that we used, their characteristics, and the justification in the cases where it is necessary. Furthermore, we also introduce the software that we have used. We show the basic design and explain the communication between the different elements that we have.

In addition we show different simulations of the model that we made, the characteristics of the DC motor that we used and also a study about the effect of the parasite capacitance in a DC motor.

Finally we show the result in form of the new electronics for the test-bench, share different conclusions, and explaining how the design worked. We also add final impressions and possible improvements.
Now that we have finished the master thesis, we can say that to work on this project was an enriching experience in an academic and personal level. This project was able to mix theoretical and practical aspects that were really interesting. First of all, we think that we complemented each others knowledge in a good way. We didn't have any problem as a team and we are really happy that we have had the opportunity to work together.

At this point we want to thank our project director, Kalevi Hyyppä because he trusted us to perform this task. He has been a very big help for us in all moments of the project, and he has give us very useful help. We are really grateful to him because of that. In addition we also like to thank Fredrik Häggström because he let us use his converter design and because he gladly answered every question we had about it. It was really helpful. The same with the authors of reports like ”Fördjupningskurs mekatronik” or ”Navmotor som generator” because their content was a big assistance for completing the project.

Furthermore we would like to appreciate the help of the Baldos Team. They answered our questions and they produced different pieces for us. And finally thanks to all of the LTU organization, responsible for Kristofer’s education and of a so positive experience of one year living in a foreign country for José.

Kristofer B. Gramner and José María Fernández Lahoz
## Work Distribution

<table>
<thead>
<tr>
<th>Work description</th>
<th>Kristofer Gramner</th>
<th>José Mª Fernández Lahoz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research (DC Motor, H-bridge, etc)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Simulations of H-bridge, half bridge and 1 quadrant operation circuit</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Simulations of real drivers of H-bridge</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Design a Pspice Model of DC motor and combustion engine</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Make test of motor capacitance</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Simulations of snubber nets</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Selection of voltage source</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Make the basic test-bench design</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Look for components design 1</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Create schematic design 1</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Calculate resistances and bootstrap capacitor for the drivers of design 1</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Check components design 2 and other components needed</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Design snubber net and look for components</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Work description</td>
<td>Kristofer Gramner</td>
<td>José Mª Fernández Lahoz</td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>-------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Mount and test electronic board</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Select Heat sink</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Modify box</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Modify Heat sink for putting the board</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Design PID control</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Write C code</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Repair Voltage problem</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Build a new circuit for measuring speed</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Write chapter 1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Write chapter 2</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Write chapter 3</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Write sections 3.3.8 to 3.3.10</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Write chapter 4</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Write chapter 5</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Write chapter 6</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Write Appendix A</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Write Appendix B</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Write Appendix C</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Write Appendix D</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Amperes</td>
</tr>
<tr>
<td>AD</td>
<td>Analog-to-Digital</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
</tr>
<tr>
<td>BJT</td>
<td>Bipolar Junction Transistor</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller Area Network</td>
</tr>
<tr>
<td>D</td>
<td>Duty cycle</td>
</tr>
<tr>
<td>DC Motor</td>
<td>Direct Current Motor</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromotive Force</td>
</tr>
<tr>
<td>GND</td>
<td>Ground</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field-Effect Transistor</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional, Integral and Derivative</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional and Integral</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions Per Minute</td>
</tr>
<tr>
<td>TVS</td>
<td>Transient Voltage Suppression</td>
</tr>
<tr>
<td>UART</td>
<td>Universal Asynchronous Receiver/Transmitter</td>
</tr>
<tr>
<td>V</td>
<td>Volts</td>
</tr>
</tbody>
</table>
# Contents

Chapter 1 – Introduction

1.1 Background .................................................. 1

1.2 Purpose ...................................................... 4

1.3 Work specification .......................................... 4

Chapter 2 – Theory .............................................. 5

2.1 DC motor ..................................................... 5

2.2 Speed control ................................................ 6

2.3 H-Bridge ....................................................... 7

2.3.1 Basic working ............................................ 7

2.3.2 Switching elements ..................................... 11

2.3.3 Driver circuit ............................................. 13

2.3.4 Protection circuit. Snubber nets ...................... 15

2.3.5 Other protections. TVS diode ....................... 20

2.4 How to burn energy ......................................... 21

2.4.1 How to burn energy: Option 1 ...................... 22

2.4.2 How to burn energy: Option 2 ...................... 25

2.4.3 Final Selection ............................................ 28

2.5 Global Voltage Source .................................... 29

2.6 Capacitor ...................................................... 30

2.7 DC Model ..................................................... 32

2.8 Modelling the combustion engine ...................... 35

2.9 Torque measurement ....................................... 38

2.10 Speed measurement ....................................... 42

2.11 PID control ................................................ 44

2.12 Fuel consumption measurement ....................... 46

Chapter 3 – Hardware ........................................... 47

3.1 The basic design ............................................ 47

3.1.1 Requirements - H-bridge ............................ 48

3.2 Design 1 ...................................................... 51

3.2.1 MOSFET ................................................... 51

3.2.2 Freewheeling diode ................................... 52

3.2.3 MOSFET driver ......................................... 52
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.4 Interface between microcontroller and H-Bridge</td>
<td>56</td>
</tr>
<tr>
<td>3.2.5 Supply for drivers and isolation devices</td>
<td>57</td>
</tr>
<tr>
<td>3.2.6 Microcontroller</td>
<td>57</td>
</tr>
<tr>
<td>3.2.7 Summary</td>
<td>58</td>
</tr>
<tr>
<td>3.3 Design 2</td>
<td>58</td>
</tr>
<tr>
<td>3.3.1 Converter</td>
<td>59</td>
</tr>
<tr>
<td>3.3.2 Measurement circuits</td>
<td>62</td>
</tr>
<tr>
<td>3.3.3 Microcontroller</td>
<td>66</td>
</tr>
<tr>
<td>3.3.4 Voltage supply for logics</td>
<td>69</td>
</tr>
<tr>
<td>3.3.5 Voltage source</td>
<td>69</td>
</tr>
<tr>
<td>3.3.6 Load</td>
<td>69</td>
</tr>
<tr>
<td>3.3.7 Filter capacitor</td>
<td>69</td>
</tr>
<tr>
<td>3.3.8 Heat sink</td>
<td>74</td>
</tr>
<tr>
<td>3.3.9 Snubber nets</td>
<td>76</td>
</tr>
<tr>
<td>Chapter 4 – Software</td>
<td>83</td>
</tr>
<tr>
<td>4.1 Microcontroller</td>
<td>83</td>
</tr>
<tr>
<td>4.1.1 UART - Serial communication</td>
<td>83</td>
</tr>
<tr>
<td>4.1.2 Motor Control PWM</td>
<td>85</td>
</tr>
<tr>
<td>4.1.3 Speed control</td>
<td>85</td>
</tr>
<tr>
<td>4.1.4 Load control</td>
<td>86</td>
</tr>
<tr>
<td>4.1.5 AD-converter</td>
<td>86</td>
</tr>
<tr>
<td>4.1.6 Status monitor</td>
<td>86</td>
</tr>
<tr>
<td>4.1.7 PID</td>
<td>86</td>
</tr>
<tr>
<td>4.2 LabVIEW software</td>
<td>86</td>
</tr>
<tr>
<td>Chapter 5 – Result</td>
<td>89</td>
</tr>
<tr>
<td>5.1 The board</td>
<td>89</td>
</tr>
<tr>
<td>5.1.1 Assembly</td>
<td>89</td>
</tr>
<tr>
<td>5.1.2 Testing</td>
<td>94</td>
</tr>
<tr>
<td>5.2 The test-bench</td>
<td>97</td>
</tr>
<tr>
<td>5.2.1 Assembly</td>
<td>97</td>
</tr>
<tr>
<td>5.2.2 Testing</td>
<td>100</td>
</tr>
<tr>
<td>Chapter 6 – Conclusion</td>
<td>105</td>
</tr>
<tr>
<td>6.1 Future work</td>
<td>105</td>
</tr>
<tr>
<td>Appendix A – Measurement of motor capacitance</td>
<td>107</td>
</tr>
<tr>
<td>Appendix</td>
<td>Title</td>
</tr>
<tr>
<td>----------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>B</td>
<td>DC motor specifications</td>
</tr>
<tr>
<td>C</td>
<td>Completed model for simulations</td>
</tr>
<tr>
<td>D</td>
<td>High speed AD-converter</td>
</tr>
</tbody>
</table>
CHAPTER 1

Introduction

1.1 Background

Since 2008, Luleå Tekniska Universitet is participating in the Shell Eco-Marathon competition, which is a contest in which you should build a car that drives the longest possible distance on the smallest amount of fuel. For that, a group of final-year students and their supervisors were in charge of building a hybrid car with small dimensions for participation in the contest, the Baldos car.

Figure 1.1: Baldos car, winner in 4 categories in the Shell Eco-Marathon of 2008.[1]
In the Shell Eco-Marathon of 2008 Team Baldos won 4 different prizes in the class Urban Concept, including least CO$_2$ emission and best fuel efficiency. Baldos was able of running a distance of 299 km with only 1 liter of gasoline. The new version of Baldos, Baldos II, that was build in 2009 was designed and approved for street use in Sweden. Furthermore, in 2010, a new car developed by the new Baldos team, participated in the Shell Eco-Marathon and it was called Skilzí. It looked completely different than the old Baldos cars, since this car participated in the Prototype class instead of the Urband Concept class. The reason for this is that the appearance of the cars in the Urban Concept class must be close to todays production cars. The Prototype cars are designed to be an experimental vehicle in which you can test new technology and because of this Skilzí had less weight and it was able of running a longer distance with the same amount of fuel.

In order to improve the efficiency of these cars, the Baldos Team has to make modifications to the combustion engine that they are using. These motors has a maximum power of about 1 kW and the modifications consists of for example using different kinds of fuel or modifying the injection system in order to get a higher compression of the air-fuel mixture. As a result, in 2010 a group of students developed a test-bench for this type of combustion engine. The device consisted of a bench with a mounted electrical motor that is connected to the internal combustion engine with an axis. The purpose of the electrical motor is to produce a torque in the opposite direction of the internal combustion engine and essentially causing the internal combustion engine to slow down. By measuring the speed and controlling the the amount of torque supplied by the electrical engine, the test-bench will be able to keep a desired speed and measure how much torque the internal combustion engine can deliver at that speed.
1.1. Background

Figure 1.3: Skilzi car.[1]

Figure 1.4: Test-bech developed in the project ”Fördjupningskurs i mekatronik - E7019E”. [2]

Electronics and software was designed in order to control the speed of the internal combustion engine by using the electrical engine to produce a counter torque and to measure the efficiency of the engine with the use of sensors connected to a PC with the program LabVIEW\textsuperscript{TM}. But not all functions were implemented in the software and there were problems with the electronics for the control of the electrical DC-engine/generator that takes care of the braking. The electronics simply couldn’t handle the braking procedure and was destroyed when the braking procedure started. The reason for this was presumed to be the voltage spikes that occurred when the coils of the electrical-engine was shorted together in order to brake the engine, and a hardware design that wasn’t prepared to handle the spikes.
This implementation of the test-bench uses an AVR-CAN development card from Olimex Ltd., with a AT90CAN128 micro-controller from Atmel®, for the control of the electrical-engine. In a report about the work done on the test-bench[2] the persons that made this implementation suggest as an improvement that this choice should be reconsidered, but they doesn’t really say why they suggest this.

1.2 Purpose

• To build a working test-bench that is able to measure the efficiency of small internal combustion engines, mainly the engines used in the Baldos-project.

1.3 Work specification

• Redesign and build new control and power electronics, including software for control, for the test-bench. So that the electrical DC-motor/generator can be used to brake the internal combustion engine, either by regulating the rotation speed or the torque of the internal combustion engine.

• Reconsider the choice of micro-controller that is used for the control of the electrical-motor/generator.

• Implement so that the electrical-motor/generator can be used for starting the internal combustion engine through LabVIEW™.
2.1 DC motor

We are going to start with a brief explication about the theory of a DC motor, the electrical machine that we are going to use in our test-bench. First of all, our motor is a DC motor with independent excitation caused by a permanent magnet. A basic scheme of this is shown in figure 2.1.

And the equations that explain its working are:

\[ T_{em} = k_T i_a \]  \hspace{1cm} (2.1)
\[ e_a = k_E w_m \]  \quad (2.2)

\[ v_t = e_a + R_a i_a + L_a \frac{di_a}{dt} \]  \quad (2.3)

Where \( i_a \) is the armature current, \( e_a \) is the back electromotive force (Counter EMF) produced by the rotation of armature conductor at speed \( w_m \) in presence of the field flux \( \phi_f \), \( T_{em} \) is the electromagnetic torque produced by the interaction of the field flux and the armature current, \( R_a \) is the internal resistance of the DC motor and \( L_a \) is the armature inductance of the DC motor.

Furthermore:

\[ k_T = k_t \phi_f \]  \quad (2.4)

\[ k_E = k_e \phi_f \]  \quad (2.5)

Where \( k_t \) is the torque constant of the motor and \( k_e \) the voltage constant. Since we have a permanent magnet motor, \( \phi_f \) is constant, and for that reason, \( k_T \) and \( k_E \) are constants too. Since the motor construction does not change, it turns out that these two constants (\( k_E \) and \( k_T \)) are all essentially the same number. \( v_t \) is the input voltage when it is working as a motor. But when it is working as a generator, the input is an external \( T_{em} \) which is creating a \( v_t \) that will be fed to an electrical load.

### 2.2 Speed control

There are two basic options for changing the speed of a DC motor. One is by changing the \( v_t \) applied between the motor terminals, and the other by changing \( \phi_f \). In our motor the second option is not possible and we will have to change the voltage \( v_t \).

By doing Pulse Width Modulation (PWM) on the voltage supplied from a voltage source to the DC motor, it is still possible to control the voltage seen by the DC motor even though the source is a fixed voltage source. This is possible if there exists a small inductance in the motor winding and the switching period is fast enough so that the current in the winding won’t decay too much when no voltage is supplied. By changing how much time of the period that the voltage is supplied, it is possible to change the voltage seen by the motor. The voltage that the motor will see is the average voltage of the supplied PWM signal. If a voltage is supplied half of the time, then the voltage seen by the motor is half of the voltage that the fixed voltage source supply. An example can seen in figure 2.2.
2.3 H-Bridge

2.3.1 Basic working

If we only need to control the speed of the electrical machine when it’s running as a motor in one direction, we will only need a circuit that can handle single quadrant operation. In figure 2.3 a basic schematic of this kind of circuit is seen. The switch can be used to connect and disconnect the voltage source with the motor, and the function of the diode is to avoid voltage peaks caused by the inductance of the motor. If we have current flowing from the source to the motor and suddenly open the switch a big voltage peak would appear. Because di/dt would be infinite and the inductance of the motor would try to prevent that, resulting in an infinite rise in voltage too. The freewheeling diode permits that current continues flowing, avoiding an open circuit over the motor.
Figure 2.3: Control in one quadrant. [3]

We can see the typical shape of current and voltage in the motor terminals in figure 2.4.

Figure 2.4: Voltage and current waves with one quadrant operation.

A disadvantage of that kind of circuit is there isn’t any way of controlling the DC motor when it is running as generator, with an external torque applied to it. For having that type of control we will need a circuit that can handle two-quadrant operation, also called a half bridge. The schematics of this circuit is shown in figure 2.5.
With this type of configuration, we can do the speed control of the DC machine running as a motor in the same way as with the previous circuit, using only the switch placed at the top, and the diode at the bottom as a freewheeling diode. The other switch has to be kept open. In contrast, if we need a control with the electrical machine working like a generator, we will need to put the PWM signal in the switch at the bottom, and the diode on the top will be the freewheeling diode. In the same way as with the motor configuration, the other switch has to be open.

In this case, the switch makes a short circuit over the motor, and the freewheeling diode connects the motor with the supply voltage. Depending of the speed of the motor, we can have a generated $V_{EMF}$ really high when the speed is high too. For that reason, we have chosen a supply voltage quite high, because if we don’t have it, the control of current is not possible in that situation. If we look picture 2.5, another problem consists of the increase of voltage level in the capacitor at the input because of the current that the generator is sinking into it. As we will see, a way of solving that problem would be to connect a resistor for burning that energy, in series with another transistor for being able of controlling the amount of dissipated energy in the power resistor.

Finally, if we need a completed control being able to run the motor in both directions, as both a motor and generator, we will need two half bridges, one for each direction. This circuit is called an H-bridge. In figure 2.6 we can see the circuit of an H-bridge with a extra resistor for burning energy, and in figure 2.7 and figure 2.8 the different ways of controlling the electrical motor with an H-bridge.
Figure 2.6: Control in four quadrants: H-Bridge.[3]

Figure 2.7: Current and voltage possibilities with H-bridge.[3]
2.3. H-Bridge

If we want to control the motor as explained with the half bridge, we will work with the left part of the bridge in the same way as for the half bridge, while the right part will have the switch at the top turned off all time, and the switch at the bottom turned on all time. For working in the opposite direction, the right part should work as the half bridge and the left part should have the switch at the top turned off and the switch at the bottom turned on.

2.3.2 Switching elements

One of the most important elements in an H-bridge are the switches and in most H-bridges they consist of some type of transistor. There are many types of transistors and the three most important types are the BJT (Bipolar Junction Transistor), the MOSFET (Metal Oxide Semiconductor Field-Effect Transistor) and the IGBT (Insulated Gate Bipolar Transistor). In order to choose the best type of transistor for the application we can use table 2.1, which show some characteristics of the different types, to compare them.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BJT</th>
<th>MOSFET</th>
<th>IGBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Easy</td>
<td>Difficult</td>
<td>Difficult</td>
</tr>
<tr>
<td>Power</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Switch frequency</td>
<td>Low($\leq 100kHz$)</td>
<td>High($\leq 10MHz$)</td>
<td>Medium</td>
</tr>
<tr>
<td>Safe operation area</td>
<td>Close</td>
<td>Wide</td>
<td>Wide</td>
</tr>
<tr>
<td>Breakdown Voltage</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 2.1: Comparison between different transistors.
For the most part, the key decision to make for an H-bridge is the selection of the switching elements. There are many factors to be considered, the most important ones are the operating current, the operating voltage and the switching (PWM) frequency. For our test-bench we will work with medium power, and when choosing between MOSFET and IGBT we will take the first option because it has been employed in other projects in LTU and we have more experiences for knowing its behavior. The power MOSFET is a vertically oriented four layer silicone structure alternating p-type and n-type doping. Figure 2.9 shows the typical structure of a channel-n power MOSFET.

![Figure 2.9: Structure of a Power Mosfet.][3]

As we can see in the picture, the four layers of the channel-n power MOSFET are n+, p, n- and n+. The p-channel power MOSFET would consist of the opposite distribution. In addition, for activating an n-channel power MOSFET we will need a positive voltage between gate and source, while for a p-channel this voltage has to be negative in order to turn the transistor on.

Furthermore, the n+ layer on the bottom together with the p layer creates a pn-junction that allows current to flow from source to drain, making the MOSFET function like a diode. If we turn the transistor on, we will be able to sink current in the same direction, but with less voltage drop than with a diode, and consequently, less power dissipation.

As we will see, the activation of an n-channel power MOSFET in the high side of the bridge is quite complicated because we need the power supply voltage at the input of the motor and that means that the gate voltage will have to be at a higher level than the supply voltage in order to turn the MOSFET on. However, the on resistance of an n-
channel MOSFET is significantly lower than for a channel-p. For that reason we will use n-channel power MOSFETs because of the lower power dissipation that we will get with them. In contrast, we will need a more complicated driver for activating the transistor.

Another very important element for switching is the anti-parallel or catch diode. With a power MOSFET we have an intrinsic diode in the device. However, it would be better to turn on the transistor instead of using the internal diode because it would result in less losses. But we still need a diode and the reason is simple. During the on-time the motor will build up an electromagnetic field inside it. When the switch is turned off, that field has to collapse, and until that happens, current must still flow through the windings. That current cannot flow through the switches since they are off but the current will try to find a way and if the intrinsic diode is not fast enough the voltage will start to rise. The catch diodes are placed in the design to provide a low-resistance path for that collapse current and thus keep the voltage at the motor terminals within a reasonable range.

The catch diode has to be very fast. Schottky diodes can be perfect for this task. That kind of diode has a very low forward-voltage drop. It is possible because Schottky diode uses a metal-semiconductor junction as a Schottky barrier instead of a semiconductor-semiconductor junction as in conventional diodes. As a result, this Schottky barrier results in both very fast switching and low forward voltage drop. It is a majority carrier semiconductor device. The main big limitation of this diode is the low reverse rating and a relatively high reverse current.

### 2.3.3 Driver circuit

As we explained before, a power MOSFET needs a voltage between gate and source in order to be activated. It is quite easy to do for the transistors in the down side of the bridge because the source is grounded due to the design. For this reason, we only would need a positive voltage in the gate of 10-12 V in order to activate the transistor. That kind of circuits used to have BJT transistors because high speed of commutation are needed, and sometimes, we need to amplify the logic output for putting the mosfet in on state. In figure 2.10 we can see a circuit that works in that way. In this figure, $V_s$ is the supply voltage, $V_G$ is the needed voltage for turning the transistor on and $V_i$ is the control signal of the MOSFET. When $V_i$ is high, $Q_1$ is in ON and $Q_2$ OFF, and for that reason the MOSFET will be ON. On the other hand, when $V_i$ is low, we will have the opposite working, with the MOSFET turned Off.
However, in the high side we will have more problems because the source of both transistors is connected to the motor terminals. When the motor is spinning, the voltage in one of the terminals is changing all time too. In that case, the voltage which we would need in the source is changing too, because we always need 12 V more in gate than in source.

A solution for solving that problem consist in a circuit that is putting a fixed voltage between gate and source although the voltage in the source would be moving in time. The main element in this circuit is the bootstrap capacitor. A simple circuit with that capacitor is showed in figure 2.11.
When \( v_l \) is high, \( Q_1 \) and \( M_2 \) are ON, and \( M_1 \) OFF with the capacitor in charging time, while when \( v_l \) is low, \( M_1 \) is ON thanks to the voltage that the capacitor is adding, while \( Q_1 \) and \( M_2 \) are OFF. Fortunately, nowadays there are a lot of integrated solutions for getting that kind of circuits already made. For example, the IR2110 permits the activation of 2 transistors, one in the high-side and other in the low-side.

### 2.3.4 Protection circuit. Snubber nets

Snubber nets are used for decreasing loses of commutation in the element of switching. Furthermore this circuit can protect the device of overvoltage or over currents. The biggest losses in a transistor occur when it is being turned ON or turned OFF. If we want to turn off a transistor, first is necessary to increase its voltage to the OFF voltage that we have in our circuit, and after that the current starts to decrease. As a result, we have voltage and current in the same time, which means power dissipation in the switch element.

When we want to turn the transistor on again, we will need to have the same current as we have in the ON period, and after that the voltage of the transistor will start to decrease. For this reason we will get more power dissipation in the transistors. Figure 2.12 illustrates this phenomenon.
A solution for the problem when we change from ON to OFF would consist of the circuit of figure 2.13.

The capacitor C reduces the time of change of voltage, although that change will have a delay. When the transistor is turned-ON again, the capacitor is discharged through the
resistor. The bigger the capacitor is, the less losses we have. We can see the difference in figure 2.14.

![Graphs showing different behavior in the transistor depending on the capacitor size of the snubber net.](image)

*Figure 2.14: Different behavior in the transistor depending on the capacitor size of the snubber net.*

However, if the capacitor is too big, we can dissipate too much power in the resistor.
A value that optimizes that aspect is this:

\[ C = \frac{I_l t_f}{2V_s} \]  

(2.6)

Where \( V_s \) is the final value of voltage in the transistor when it is turned off, \( I_l \) is the current that we have in the ON time, and \( t_f \) is the fall time of the transistor. About the resistor, we need that the capacitor discharges in the ON all its energy. Therefore, we can choose a more conservative value like \( t_{on} > 5RC \) for being safer.

On the other hand, for avoiding over voltages, we can put another kind of snubber net that is showed in figure 2.15. As we can see, the overvoltage produced by the stray inductance is decreased when we put a capacitor in series with it. We put a diode between both elements for avoiding the flow in the opposite direction. The capacitor will increase its voltage level in a small proportion. The thing that we want to get is to put the energy stored in the stray inductance directly in the capacitor. For knowing the value of the capacitor, we have to use the formula 2.7 of conservation of energy.

\[ \frac{C_{OV} \cdot \Delta V_{CE,MAX}}{2} = \frac{L_\sigma \cdot I_0^2}{2} \]  

(2.7)

Where \( C_{ov} \) is the capacitance of the overvoltage capacitor, \( I_0 \) is the current in the circuit, \( L_\sigma \) is the stray inductance and \( \Delta V_{CE,MAX} \) is the maximum variation of voltage in the transistor during the turn-off.

When the effect of the stray inductance disappears, the capacitor will go back to the first voltage level discharging its additional charge in a resistor. The amount of energy which will be burned will be in the same order as the energy that is burned in the resistor of the turn-off snubber. For that reason we can put a similar resistor for this kind of net. The different shapes of voltage and current waves are shown in figure 2.16.
Finally, for avoiding over current because of the diode reverse recovery current, and also for reducing the losses of turning on the transistor we can use the circuit shown in figure 2.17.
However, to put an additional inductor sometimes is not necessary because we have stray inductance in the conductors of the circuit which can make this function.

In figure 2.18 we can see the 3 kind of snubber nets together for a half bridge:

2.3.5 Other protections. TVS diode

Due to the inductance of the DC motor and other stray inductances that we have in the circuit, we will have voltage peaks that could be very dangerous for the transis-
tors. Overvoltage snubber nets can help to decrease those peaks, but sometimes it is not enough. Another solution for avoiding voltage peaks consist of using TVS diodes (Transient Voltage Suppressor).

This kind of diode is able to sink a lot of current itself when the avalanche breakdown voltage has been reached in its terminals. In addition, this device is able of acting really fast. The surge power and surge current capability of the TVS diodes are proportional to the PN junction area. TVS diodes are constructed with large cross sectional area junctions for absorbing high transient currents.

### 2.4 How to burn energy

One of the most critical moments for the system is when the combustion engine starts. In this moment, the DC motor is changing its operation mode. If before it was spending energy for its movement, after the starting of the combustion engine, the DC motor is receiving energy from the ICE. According to the instructions, the design of the test-bench has not to take care of the fuel consumption that the combustion engine is using. For that reason, we will think in the worst possible situation for the brake. Hence, we will think that the motor is able to accept the maximum fuel consumption for each speed instantaneously, for getting the maximum torque and power in each speed. In figure 2.19 we can see the typical curve of torque, power and fuel of a combustion engine.

![Characteristic curve of a combustion engine](image)
As a conclusion, if we want to keep a speed of the combustion engine, the electrical motor will have to brake with a torque equal to the torque that the ICE is providing. This breaking torque is proportional to the current in the coil of the DC motor, and for this reason, there will always be current through the coil while the combustion engine is operating. Hence, we can make a current control in the output of the DC motor for controlling the braking. In addition, we have to think what to do with the energy that the combustion engine is sending towards the electrical motor. We have several options for doing that. One option would consist on burning the energy directly in a resistor, and another would be to store that energy in a supercapacitor or batteries. This second option has a problem, because the electrical motor is sending current to the storage system continuously, and the voltage could increase dangerously. For that reason, we would need a resistor for burning energy when we have reached a determinate voltage level in the supercapacitor or batteries. Below we will show both options in detail.

2.4.1 How to burn energy: Option 1

This option consists of a current control which is burning energy directly in a resistor. Since we only want to burn the energy that the combustion engine is sending to the resistor, we should disconnect the supply of the electrical motor that we used when it was running as a motor. If we don’t, we can put even more current in the resistor from this supply, and it isn’t good. Hence, we would need to disconnect this power supply when the electrical motor is running as a generator, and in the same moment, we have to put on ON state the transistor in the loop of the power resistor. The configuration, with the DC motor as generator, is showed in figure 2.20

![Circuit for burning energy in a resistor.](image-url)
If we only think in one sense of rotation, the scheme would be like in figure 2.21.

Figure 2.21: Circuit for burning energy in a resistor using a Half bridge.

If we have in account that when $T_{A+}$ is in ON, $T_{A-}$ will be in OFF and vice versa, we will have 2 different cycles, which we can see in figures 2.22 and 2.23.

Figure 2.22: Equivalent circuit with $T_{A+}$ ON and $T_{A-}$ OFF.
Figure 2.23: Equivalent circuit with $T_{A+}$ OFF and $T_{A-}$ ON.

For knowing the current that we have in the stationary, we can use the voltage in the coil, and the property of the coil in DC circuits that said that the medium voltage in the coil in DC circuits is always zero. The voltage in the coil in the cycle with the power resistor, and in the next is:

$$V_{L_a} = V_{e_a} - ((R + R_a)I_a) \quad (2.8)$$

$$V_{L_a} = V_{e_a} - (R_a I_a) \quad (2.9)$$

In figure 2.24 we can see the shapes of current and voltage in the coil of the motor.
2.4. How to burn energy

Using the condition of zero medium voltage in the coil, we can know the current $I_A$. ($t_{on}$ and $t_{off}$ is referred to the transistor $T_{A+}$)

\[(R + R_a)I_a - V_ea\]  
\[t_{on} = (V_ea - R_aI_a)t_{off}\]  
\[D = \frac{t_{on}}{(t_{on} + t_{off})}\]  
\[((R + R_a)I_a - V_ea)D = (V_ea - R_aI_a)(1 - D)\]  
\[I_a = \frac{V_ea - R_a}{(D \cdot R)}\]

2.4.2 How to burn energy: Option 2

Current control using batteries (supercapacitor) and a power resistor for controlling the voltage in the battery (supercapacitor).

First of all, we have to say that with the batteries and the control of voltage with the power resistor, we will have something like an ideal voltage source when the DC motor is running as a generator. If we think in an ideal voltage source, the configuration is shown in figure 2.25.
If we only work with one sense of rotation, we can get the value of $I_a$ in the same way that we did in the last expression, where we burned the energy only in a resistor.

Figure 2.26: Circuit for burning energy, storing energy in batteries (supercapacitor) and burning it in a resistor in order to control the voltage using a Half-bridge.
2.4. How to burn energy

The voltage in both cycles are:

\[ V_{La} = V_{ea} - (R_a I_a) - V_{ideal} \]  \hspace{1cm} (2.14)

\[ V_{La} = V_{ea} - (R_a I_a) \]  \hspace{1cm} (2.15)
(\(t_{on}\) and \(t_{off}\) is referred to the transistor \(T_{A+}\))

\[
(V_e a - (R_a I_a)).t_{off} = ((R_a I_a) + V_{ideal} - V_{ea}).t_{on}
\]

\[D = \frac{t_{on}}{(t_{on} + t_{aff})} \quad (2.17)\]

\[
(V_e a - (R_a I_a))(1 - D) = ((R_a I_a) + V_{ideal} - V_{ea})D
\]

\[
I_a = \frac{(V_e a - (V_{ideal}D))}{R_a} \quad (2.19)
\]

### 2.4.3 Final Selection

How we will see in the section were we will explain the combustion engine model for Pspice, the ICE used in Baldos project is able to supply 1.37 N.m as a peak of torque in its commercial version. It means that we will need a torque of braking a little bit higher than this value of torque. As explained in APPENDIX B, the constant of the DC motor is about 0.05 \(K_E = K_M\). As a result, we will need a control of current with at least 30 Amperes (> 1.37/0.05) like superior limit. For an inferior limit, we will have a current for braking a small torque like 0.25 Nm, hence, the minimum current of our control will be around 5 Amperes.
If we think in the speed, according to the Baldos team it would be nice to reach speeds near to 7000 RPM, while the minimum speed of the ICE will be 1400 RPM according to the datasheet. For these speeds, the voltage $V_{ea}$ will be between 7.3 and 37 V. Using the formula of current for the option 1 of burning energy (equation 2.13), we can find the relation between the value of $R$ and the other parameters of the equation:

$$R = \frac{V_{ea} - R_a}{D \cdot I_a}$$  \hspace{1cm} (2.20)

We will determine the maximum value of $R$ in the situation of maximum speed and small torque of braking ($D=1$). In all other cases, the resistance would be smaller. This value of resistance is showed in the equation 2.21, taken in account that $R_a$ of our DC motor is 0.14 Ω(Appendix B).

$$R = \frac{37 - 0.14}{5} = 7.3\Omega$$  \hspace{1cm} (2.21)

With this value of $R$ there will be problems if we need handle big currents, because the instant voltage in the resistor will be very dangerous ($7.3 \cdot 30 = 229$V in the worst case of the example). To choose components which are able to keep this level of voltage is really difficult.

By contrast, if we make a good voltage control like in the second option, we won´t have this problem as we will see. Using the formula of current in that equation 2.19, we can choose a good value of voltage:

$$V_{ideal} = \left(\frac{V_{ea} - (R_aI_a)}{D}\right)$$  \hspace{1cm} (2.22)

For the case of high speed and low torque of braking we will need this value of voltage:

$$V_{ideal} \geq 37 - 0.14 \cdot 5 \geq 36.3V$$  \hspace{1cm} (2.23)

This voltage won´t be a big problem for the components of the bridge. For this reason we will chose this option finally.

At the beginning we thought to use the supercapacitor of Baldos project, but finally it wasn´t possible because the supercapacitor wasn´t available. For that reason, we choose to use batteries because it is the cheapest option. Otherwise, we will need to put capacitors in parallel with the batteries and the bridge for several reasons that we will see in the next section.

## 2.5 Global Voltage Source

To supply all elements we need a voltage source. Furthermore, as we can see in the chapter "How to burn energy" we need to sink current in some place. For that reason, we have two options for getting this combination. First, we can put a voltage source for
transfer energy and a supercapacitor in parallel for the generator moment. The other option would consist of batteries.

This second option is much cheaper, and for this reason it will be the final selection for our design. But we have to know several characteristics of batteries for having a good behavior in our tests.

First of all, a battery delivers energy because there is a chemical reaction inside it which gives electrical energy. But this chemical reaction is reversible, and we can put energy in the battery with the reverse chemical reaction as a result inside of the battery. But a battery isn’t an ideal voltage source, and we can’t put as much energy as we want. Furthermore, the chemical process is not ideal either and we will have loss of energy. This loss don’t permit to use all energy that initially is in the battery. We can simulate the loss with an internal resistor in series with the battery. The smaller internal resistor and the bigger capacity of energy inside of the battery, the more similar to a voltage source will the battery be.

For that reason, we will use Lead-Acid batteries like normal car batteries. They have a very small internal resistor, and a big capacity of energy. But we have to take care about the use of these kinds of batteries. First, we can’t charge the batteries with a very big current. When the battery is being recharged, and the level of power inside it is lower than 70% of the total capacity of the battery, it is possible to sink bigger currents than when the level of power is higher. Typically, the maximum allowed current value with an energy in the battery lower than 70% of total capacity is the capacity of the battery in Amperes hour (A.H) divided 3. If the energy is higher, the maximum allowed current value usually is the capacity of the battery in Amperes per hour (A.H) divided 10.

For that reason, it would be good to have the battery always with less of the 70% of the total energy inside it because we have to handle big currents in the output of the motor. There is a relation between the level of voltage in a battery, and the energy stored in the own battery. Experimentally, when a normal 2 V cell of a Lead-Acid battery is being charged, the voltage in the cell will be 2.27 V when the energy into the battery is near to the 70% of the total energy that is able to store the battery. How we saw in the chapter ‘‘How burn energy’’, we need at least 36 V. For that reason, we will use normal car batteries of Lead-Acid. We will put 3 batteries of 12 V each one in series. Therefore, the voltage that we will try to keep in the bridge will be $2.27 \cdot \frac{36}{2} = 41$ V. We will keep this voltage burning energy in a power resistor when the voltage is higher than those 41 V.

### 2.6 Capacitor

If we think in the two operation moment of the system, one with the DC machine working as a motor and the other as a generator, we can see that we will need a capacitor in both situations. Taking in account that the voltage source is going to be batteries, we have to know that the model of a battery is an ideal voltage source and an internal resistance in series with it. In the motoring way, this internal resistance creates a voltage drop in the
output of the battery when the motor is demanding a lot of current from the battery. It happens in the starting of the DC motor. A variation of 1 V in the voltage source can produce a change of 200 RPM in the final speed of the DC motor. For that reason we will need a capacitor in parallel with the battery. The internal resistor of the capacitor is smaller than in the battery, and for this reason the capacitor will be able to provide a big current without suffering a big voltage variation in the input of the DC motor.

Furthermore, in the motoring way, this capacitor will reduce the effect of the stray inductances in the wires between battery and H-bridge, filtering the voltage signals which come from the battery.

On the other hand, when the DC machine is working as a generator we will need a capacitor too. First of all, in figure 2.30 we can see the basic scheme of our system without the capacitor. In it we have the H-bridge, the model of the DC motor, the battery and the leg for burning energy with the power resistor and the transistor which is controlling the switching in this leg.

![Figure 2.30: H-bridge and voltage control without capacitor.](image)

As we have explained previously, if we handle the transistor Tr, we will be able of controlling the voltage in the battery. The DC machine will charge the battery always when the ICE is running. By contrast, the power resistor will discharge the battery when the Tr transistor is turned on.

But we will be in a trouble if we only use this configuration. The shape of current wave that we are sinking in the battery has a very big variation of amplitude and frequency.

In the point P of figure 2.30, the current will be almost a square wave as a result of the current control in the H bridge, where the current has 2 different ways. One is towards
the high-side transistors when the current goes from the motor to the battery. The other is towards the low-side transistors when they are putting a short circuit in the DC motor. While the current of the motor is in this second way, there is not any current through the point P.

Furthermore, we have to do the subtraction of the current that is sunk in the power resistor. This current is also in a PWM cycle, and for this reason the frequency of the current in the battery will have even a bigger frequency. Because of the internal resistance of the battery, we cannot put this kind of wave in it. The big variation of current would heat up the battery to dangerous levels.

The only solution for solving this problem consists on putting a capacitor acting as a filter in parallel with the battery and also with the bridge. With this capacitor we will get to sink a current in the battery that will be the medium current of the old wave of current with high frequency.

![Figure 2.31: H-bridge and voltage control with capacitor.](image)

### 2.7 DC Model

For simulating our design, we will use the program Pspice. This program is much appropriated for electronic circuits. We can even find parts which are able to simulate real components in manufacturer websites. But thinking in our project, we need to simulate an electrical motor. This element combines electrical and mechanical parts. If we want to simulate it with Pspice, we will need to simulate the electrical part, and also the mechanical part, but using an equivalent electrical circuit for this part. About the electrical part, we have a circuit which contains the input voltage to the motor ($V_s$), the inductance and the internal resistance of the motor and finally other voltage source which will de-
pendent of the rotational speed of the motor ($V_{EMF}$). Therefore, this voltage source will be dependent of the mechanical part. All elements of the electrical part are in series. In figure 2.32 we can see the circuit, and the equation 2.24 we can see the equation which describes the behavior of the circuit.

\[ v_S - v_{EMF} = L_a \cdot \frac{d}{dt} i_a + R_a i_a \]  (2.24)

About the mechanical part, the electrical torque that the motor is adding is proportional to the current $I$ that is flowing for the electrical part of the motor. This torque produces an angular speed according to the inertia $L$ and the friction $B$. We can see the relation in the equation 2.25.

\[ T = J \cdot \frac{d}{dt} w + B \cdot w \]  (2.25)

Seeing this equation, we can establish an equivalent electrical part where $w$ is the current and $T$ is a voltage source. The inertia can be simulated through an inductance with the same value of inertia. In the same way, the friction can be simulated with a resistance which will have the friction value. All elements are in series, and we can see the electrical equation in the equation 2.26, which is quite similar to mechanical equation.

\[ v_{torque} = L_j \cdot \frac{d}{dt} i_w + R_B i_w \]  (2.26)

In the table 2.2 we can see the equivalences between the mechanical and the electrical part.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mechanical</th>
<th>Electrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Torque</td>
<td>$T$</td>
<td>$v_{Torque}$</td>
</tr>
<tr>
<td>Velocity</td>
<td>$w$</td>
<td>$i_w$</td>
</tr>
<tr>
<td>Inertia</td>
<td>$J$</td>
<td>$L_J$</td>
</tr>
<tr>
<td>Friction</td>
<td>$B$</td>
<td>$R_B$</td>
</tr>
</tbody>
</table>

*Table 2.2: Equivalences between the mechanical and the electrical part.*

The equivalent circuit able to simulate the mechanical part is shown in figure 2.33.

![Mechanical part DC motor.](image)

*Figure 2.33: Mechanical part DC motor.*

For joining both parts, we have to make a dependent voltage source for $V_{torque}$ with the current of the circuit in the electrical part ($v_{Torque} = K_Ti_a$). On the other hand, the voltage source of $v_{EMF}$ has to be dependent of the angular speed $w$. Therefore, we will have a $v_{EMF}$ equal to $K_Ew$. In figure 2.34 we have the completed circuit.
2.8 Modelling the combustion engine

As we said in the introduction chapter, the test-bench has the function of measuring the efficiency of combustion engines used in Baldos project, which will have some modifications. For that reason it would be very interesting to simulate the completed system, with a combustion engine model, similar to the engine that we will use in the real test. For doing that, we need the values of the commercial version of the motor. If we see the datasheet we can obtain these parameters which are shown in the table 2.3.

<table>
<thead>
<tr>
<th>Name</th>
<th>BF-25EI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>24.5cc</td>
</tr>
<tr>
<td>Weight</td>
<td>2.1 kg [4.7 lb]</td>
</tr>
<tr>
<td>Bore/Stroke</td>
<td>24 x 24mm</td>
</tr>
<tr>
<td>Peak Horsepower</td>
<td>1.6hp @ 7,500 RPM</td>
</tr>
<tr>
<td>Peak Torque</td>
<td>0.14kgfm @ 5,000 RPM</td>
</tr>
<tr>
<td>RPM</td>
<td>1,400 - 9,000 RPM</td>
</tr>
<tr>
<td>Fuel</td>
<td>Automotive Unleaded Gasoline</td>
</tr>
</tbody>
</table>

Table 2.3: Combustion engine specifications.

From these values, we are going to obtain a curve of power and torque against rotational speed in an approximated way.
\(N_{min} = 1400\text{RPM}\) \hspace{1cm} (2.27)

\(N_{max} = 9000\text{RPM}\) \hspace{1cm} (2.28)

\(T_{max} \rightarrow 5000\text{RPM}\) \hspace{1cm} (2.29)

\(P_{max} \rightarrow 7500\text{RPM}\) \hspace{1cm} (2.30)

\(T_{max} = 0.14\text{Kgf.m} = 1.37\text{Nm}\) \hspace{1cm} (2.31)

We can see a normal shape of this kind of curve in figure 2.19. We have to think that the torque curve is a second order function dependent of the angular speed.

\[T(w) = Aw^2 + Bw + C\] \hspace{1cm} (2.32)

Power and torque are related by the formula 2.33:

\[P(w) = T(w).w \rightarrow P(W) = Aw^3 + Bw^2 + Cw\] \hspace{1cm} (2.33)

Furthermore, we have the conditions shown in expressions 2.34, 2.35 and 2.36:

\[T(785.398\text{rad/s}) = 1.37\text{Nm}\] \hspace{1cm} (2.34)

\[\left.\frac{dP(w)}{dw}\right|_{w=785.398\text{rad/s}} = 0\] \hspace{1cm} (2.35)

\[\left.\frac{dT(w)}{dw}\right|_{w=523.598\text{rad/s}} = 0\] \hspace{1cm} (2.36)

We solve the system with 3 equation and 3 unknown quantities. In the expression 2.37 we can see the results.

\[A = -1.01507 \cdot 10^{-6}\frac{\text{Nm} \cdot \text{s}^2}{\text{rad}^2}; B = 0.00106298\frac{\text{Nm} \cdot \text{s}}{\text{rad}}; C = 1.09171371\text{[Nm]}\] \hspace{1cm} (2.37)

Once we have the curve torque against angular speed, we are going to introduce in the DC motor model of Pspice a new element which will be able to simulate the internal combustion engine. In the mechanical part of the DC motor model we will include a new voltage source for simulating the torque which is added by the ICE.

This voltage will have the same polarity as the voltage source that simulate the electrical torque when the DC motor is running as a motor without any load.
The torque of this combustion engine will be dependent of the angular speed. For that reason, the voltage source that is simulating it will be dependent of the current $i_w$ of the DC model.

This dependence will be conditional. If we have a speed between 0 and 1400 RPM, the ICE won’t supply any torque because it won’t be turned on. Between 1400 and 9000 RPM, the relation between torque and speed will obey the curve torque-Angular speed that we have calculated previously. Higher speed than 9000 RPM won’t have any torque because in theory, the motor can’t reach that speed.

Furthermore, the combustion engine has inertia and friction coefficients. We can estimate that the inertia of the combustion engine and the inertia of the DC motor are the same. For that reason, we will put a new inductance $L_w$, twice as before, only with the DC motor.

About the friction, we have the value of power of the ICE to 7500 RPM. With the curve of torque calculated, we can know the power that is available in the axis. The difference between both values of power is using for overcoming the friction looses in the steady state.

\[
Power(7500\text{RPM}) - T(7500\text{RPM}) \cdot w = B \cdot w \tag{2.38}
\]

\[
Power(7500\text{RPM}) = 1.5\text{hp} \cdot 745.7\text{W/hp} = 1118.55\text{W} \tag{2.39}
\]

\[
T(7500\text{RPM}) = 1.30043\text{Nm} \quad (\text{From the curve "torque – speed"}) \tag{2.40}
\]

\[
w = 7500\frac{\text{rev}}{\text{s}} \cdot \frac{2\pi\text{rad/s}}{60\text{s}} \tag{2.41}
\]

\[
B = 157\mu\text{Nm} \cdot \frac{\text{s}}{\text{rad}} \tag{2.42}
\]

In figure 2.35 we can see the model completed, with the inertia and friction of the combustion engine and the new voltage source in the mechanical part that is simulating the torque of the combustion engine.
Figure 2.35: Modell of DC motor and Combustion engine together.

2.9 Torque measurement

The device for measuring the torque is the same as the device used in the project ”Fördjupningskurs i mekatronik - E7019E”[2]. The measured is based in the action - reaction principe. The force that is introducing the electrical motor has to be the same as the force that the fastening system has to have made in the opposite sense. That system is showed in figure 2.30.
The reaction torque of the electrical motor produces a force that is going to bend a strain gage. In the next equations we can see that torque is proportional to the displacement produced in the point of the gage where the force is applied.

\[ F \cdot 0.15 = M_y \] (2.43)

\[ \sigma_{max} = \left( \frac{M_y(x)}{W_b(x)} \right) \] (2.44)

\[ W_b = \frac{I_z}{y_{max}} \] (2.45)

\[ I_z = \frac{1}{12} b h^3 \] (2.46)

\[ y_{max} = \frac{h}{2} \] (2.47)

\[ W_b = \frac{b \cdot h^2}{6} \] (2.48)

\[ \varepsilon = \frac{\sigma_{max}}{E} \] (2.49)
\[ \varepsilon = \frac{F \cdot 0.15 \cdot 6}{E \cdot b \cdot h^2} \rightarrow \varepsilon \text{ and } F \text{ are proportional} \quad (2.50) \]

Where \( F \) is the force applied because of the reaction torque, \( M_y \) is the Bending Moment in Y axis. \( W_b \) is the Resisting Bending Moment, \( y_{max} \) is the farthest y coordinate of the centroid of the transversal section where we will have the highest strain(\( \sigma_{max} \)). Finally, \( b \) and \( h \) are the base and height of the transversal section. We can see this parameters in figure 2.37.

![Figure 2.37: Rectangular section.](image)

Once we have the relation between force and displacement, we need to measure that displacement. Strain gages have the property of changing the electric resistance value when its size is changing. For detecting that change in resistance, the device that we are going to use is the Wheatstone bridge. We can see the basic scheme in figure 2.38.
2.9. Torque measurement

\[ R_x \] is the value of the resistance that we need to know. The other 3 resistance values are known. How is showed in the LTU report "NAVMOTOR SOM GENERATOR"\[5\] in an experimental way, there is a linear relation between voltage between C and B points and displacement (figure 2.39). For that reason, this relation also is between torque and voltage.

![Wheatstone bridge](image)

*Figure 2.38: Wheatstone bridge, By Zedh (www.wikipedia.org).*

![Experimental relation between displacement of the strain gage and voltage on the Wheatstone bridge](image)

*Figure 2.39: Experimental relation between displacement of the strain gage and voltage on the Wheatstone bridge.[5]*
For that reason, we only need to measure the voltage, and the Instrumentation amplifier which is able to do that is showed in figure 2.40:

\[
\frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}}\right) \frac{R_3}{R_2}
\]

*Figure 2.40: Instrumentation amplifier for measuring voltage in the Wheatstone bridge.*[5]

### 2.10 Speed measurement

For measuring the angular speed of the motor, we are going to use the same device as in the project “Fördjupningskurs i mekatronik - E7019E”[2]. It consists of a slotted disk which is solidary to the rotation axis of electrical motor. In addition, we have an optical sensor, with emitter and receptor. A basic picture that illustrate this is in figure 2.41 and in figure 2.42 When the slot permits the light go from emitter to receptor, which used to be a photodiode or phototransistor, the electricity will flow.
2.10. Speed measurement

As a result, if we measure the reference voltage, we will have a square wave. We can know very easily the relation between the frequency of this wave, and the real speed of the motor. In our device, we have 10 slots. The period of the square wave will be 10 times lower than the period of rotation of the motor. By contrast, the frequency (f) will be 10 times bigger in the wave than in the motor. In expressions 2.51 and 2.52 we can see the final relation.

\[
n\text{[RPM]} = w \left[\frac{\text{rad}}{s}\right] \cdot \frac{60[\text{s}]}{(2\pi)[\text{rad}]} = \frac{2\pi}{T} \cdot \frac{60}{2\pi} \quad (2.51)
\]

\[
n\text{[RPM]} = \frac{2\pi}{10T_{\text{wave}}} \cdot \frac{60}{2\pi} = \frac{6}{T_{\text{wave}}} = 6f_{\text{wave}} \quad (2.52)
\]

We will measure this frequency with the program LabVIEW and also in the microcontroller.

Figure 2.41: Slotted disk which will spin between emitter and receptor in order to create a signal which frequency is proportional to the rotational speed.

Figure 2.42: Electrical schematic of the optical device for measuring speed.
\section{PID control}

For controlling the speed, the only manipulated variable that we have is the Duty Cycle of the transistors of the H-bridge. We don’t have access to a transfer function which related duty-cycle and speed. In addition, lots of perturbations and no linear relations will take place in our test. For that reason, we need to make an experimental control. The option for making the control consists on putting a PID control. For that, we need to look for the constants of this control through a probe-error procedure.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{pid_control_diagram.png}
\caption{Basic schematic of a PID control.}
\end{figure}

The PID control takes values of reference-speed and real speed. After that it calculates the error, and finally it calculates a Duty for getting this reference speed. The duty will be proportional to the error, to the integrate of the error and to the derivate of the errors. We can see this relation in the equation 2.53.

\begin{equation}
Duty - Cycle = D = K_pe + K_i \int e \cdot dt + K_d \frac{de}{dt} \tag{2.53}
\end{equation}

The control will be done with the microcontroller. For that reason, we can think that the sample time \((T_m)\) will be so small that we can simplified the last equation using difference to approximate the differential. We will get the discrete PID equation (2.57).

\begin{equation}
dD = K_pe + K_i e + K_d \frac{d(e)}{dt} \tag{2.54}
\end{equation}

\begin{equation}
D(k) - D(k-1) = K_p(e(k) - e(k-1)) + K_i e(k) T_m + K_d \frac{d(e(k) - e(k-1))}{dt} \tag{2.55}
\end{equation}

\begin{equation}
D(k) - D(k-1) = K_p(e(k) - e(k-1)) + K_i e(k) T_m + K_d(e(k) - 2e(k-1) + e(k-2)) \tag{2.56}
\end{equation}
\[ D(k) = D(k-1) + K_p(e(k) - e(k-1)) + K_i e(k) T_m + K_d(e(k) - 2e(k-1) + e(k-2)) \quad (2.57) \]

The shorter sample time we have, the better and the more accurate the control will be. A microcontroller is able to handle very short sample times. Unfortunately, the method for measuring speed that we used needs an sample time for noticing the change in speed. If the rotation speed is slow, the time that 2 slots need for crossing the same point will be longer. Since this time is much longer than the minimum sample time that the microcontroller can provide, to use a short sample time will be ineffective. But if the speed rises, the time that 2 slots need for going through the same point will be shorter than with a lower speeds. For this reason, for having a good control, it would be very appropriate to have a sample time which would be dependent of the speed.

For controlling the voltage we will use the same kind of control, but instead of speed, we will have voltage, and the duty manipulated will be the duty that we have in the power resistor leg. We have to look for the constants in an experimental way too.

But we must to be careful about one aspect. In our PID, we have an integral part, and we have saturation in the output. It means a minimum and a maximum Duty Cycle. When both phenomenons are present, we will have the problem of the windup. This problem consists on the big accumulation of error in the integral part of the control, when a large set point occurs, out of the range of possible outputs.

The solution for decreasing the effect of this problem we shouldn’t add the integral of the error when the set point that the PID is calculating is out of the range of possible values in the output.

If we only use the PI part of the PID \((K_d = 0)\), and we compare equations 2.53 and 2.57, we can see in the equation 2.59 the integral part of the error:

\[ D(k) = K_p e(k) + D(k-1) - K_p e(k-1) + K_i e(k) T_m \Leftrightarrow D = K_p e + K_i \int e \cdot dt \quad (2.58) \]

\[ K_i \int e \cdot dt = D(k-1) - K_p e(k-1) + K_i e(k) T_m \quad (2.59) \]

Furthermore, for the definition of integral error, we can put this error like in the expression 2.60.

\[ K_i \int e \cdot dt = K_i T_m \sum_{i=K}^{n} e(k) \quad (2.60) \]

Comparing the expressions 2.60 and 2.59, we can see a new relation shown in 2.61.

\[ K_i T_m \sum_{K=1}^{n-1} e(k) = D(k-1) - K_p e(k-1) \quad (2.61) \]
Therefore, we have to include in the program a logic calculation where if the output of the PID is not inside of the limits, the real duty that will be applied will be the limit stabilized. But we have to remove the integrated error that we have in that moment. For doing that, we will subtract the term $K_i T_m e(k)$ to the $D(k)$ that is out of limit. Looking at the equation 2.59 we can see that this integral error won’t be in the next iterations.

### 2.12 Fuel consumption measurement

For measuring the fuel consumption we will use the same system as in the project ”Fördjupningskurs i mekatronik - E7019E” [2]. The fuel consumption is so low in this kind of motor that it is impossible to have a good measurement of fuel consumption if we only use a flow meter. For that reason, we will use a system where we take the weight measurement of the tank of fuel, and knowing the variation, tank geometry and the density of the fuel, we can know how the fuel consumption that goes to the combustion engine is. The measurement of weight is done with a scale. With labview we take this value and the computer makes the calculations for knowing the fuel consumption.
CHAPTER 3

Hardware

3.1 The basic design

The basic design of the test-bench consists of a PC that is connected to a scale, sensors for speed and torque measurement and a microcontroller. The microcontroller handles the actual speed control and is therefore connected to an H-bridge, that controls the motor, and a speed sensor to have fast access to the current speed of the motor. A voltage source is also needed in order to be able to start the internal combustion engine.
with the test-bench. Figure 3.1 shows the basic design of the test-bench. This would be the final design, but many voltage sources aren’t able to sink current at all or are able to sink current but not for a long amount of time. Therefore there is also a controllable load connected in order to burn off the excess energy that is generated by the DC motor, when it is acting as a generator, and that can’t be fed back to the voltage source. Figure 3.2 shows the design with the controllable load included.

![Figure 3.2: Overview of the test-bench design with load.](image)

### 3.1.1 Requirements - H-bridge

Since the test-bench made in the earlier project already had a scale and sensors for speed and torque measurements installed. The focus was aimed at the H-bridge and the control of the DC motor. Figure 3.3 shows the basic design of the H-bridge with a microcontroller and speed sensor for motor control. The h-bridge is seen in the middle, consisting of four MOSFETs (Q1, Q2, Q3 and Q4), drivers for those and four schottky diodes (D1, D2, D3 and D4) acting as freewheeling diodes. The MOSFETs could easily have been change to some sort of other type of switch, but as explained earlier the MOSFET is best suited for our application. The reason for using schottky diodes is that the way they are designed make them faster than normal diodes.
Figure 3.3: Overview of the basic motor control design.

**MOSFET**

The basic requirements of the MOSFETs used as switches in the h-bridge, are that they should be able to keep the worst case current supplied to or generated by the DC motor, that they have a low on-resistance and that they have fast switching speed. As explained earlier most MOSFETs have an internal diode by design and it can be looked upon as if a diode is connected in parallel with the transistor. Which means that the MOSFET actually only blocks current in one direction. This might sound like a bad thing, but it also means that the MOSFET can act as a freewheeling diode and conduct current in the opposite direction even if the MOSFET isn’t actively turned on. However relying on these diodes for freewheeling is not good for two reasons. One is that it is actually better to actively
turn the MOSFET on during freewheeling rather than using the internal diode due to the fact that the internal diode has a higher resistance than a MOSFET that is turned on. The other is that these internal diodes aren’t fast enough and any inductances with currents flowing in them, that you are trying to switch, can cause the voltage to rise to a too high of a level until the internal diode has had the time to turn on.

**MOSFET drivers**

The basic requirements for the drivers are that they are able to switch the MOSFETs on and off, and that they are able to do it fast.

**Freewheeling diode**

The freewheeling diode has to have a fast turn on time and a fast reverse recovery time. The main purpose of the freewheeling diode is to conduct current when the MOSFET it is mounted over isn’t conducting. Since the MOSFET has the internal diode and can handle most of the current the most important purpose for the freewheeling diode is to turn on faster than the MOSFET and provide a path for the current until the MOSFET turns on.

**Microcontroller**

The basic requirements of the microcontroller are that it should be able to put out at least two Pulse Width Modulated (PWM) signals and take in the signal from the speed sensor. But it is desired that it can output four independent PWM signals in order to control each of the MOSFETS independently. However since there exists microcontrollers with a built in motor control function, which can be used to put out PWM signals with controllable dead-time between the signal going to the high-side MOSFET and the low-side MOSFET, it is desired that the microcontroller chosen for this project has this type of functionality.

**Transient protection**

Since transient voltages is believed to be the reason for the failure of the old electronics, some type of protection for this should be included in the new design. For example some sort of snubber circuits or Transient Voltage Suppression (TVS) diodes.

**Voltage source**

A voltage source is needed because the idea is to be able to use the DC motor to start the internal combustion engine. This means that the voltage source must be able to source current. But since the DC motor also should work in the opposite way by taking energy from the motor and transferring it to the source, the voltage source also has to be able to sink current or in some other way get rid of the excess energy.
3.2 Design 1

The main idea of the design is to create an separate H-bridge that can be controlled by a microcontroller. Because this would give the ability to change with what and how the motor is controlled later in time. This would make it easier to update the controller part of the test-bench without having to build a new H-bridge. Starting out with the basic design of an H-bridge, what is needed are; a type of power MOSFET, a type freewheeling diode, some sort of drivers for the MOSFETs and some sort of interface between the microcontroller and the H-bridge.

3.2.1 MOSFET

The first thing to choose is the MOSFET. Because the MOSFET will deside what type of driver that is needed. By looking at the data of the DC-motor that can be seen in Appendix B and making calculations, as shown earlier, the decision was made that the MOSFET has to be able to handle a continuously current of minimum 30A and a voltage of minimum 37V. But due to the possibility of current and voltage spikes occurring in the bridge it would be desired to have a MOSFET that can handle values well above those limits.

N- or P-channel

Most H-bridges uses N-channel transistors in both the high-side and the low-side even if it probably would be easier to use P-channel transistors in the high-side since those doesn’t require you to boost the gate voltage above the source voltage in order to turn them on. N- and P-channel MOSFETS are often called NMOS and PMOS. Many MOSFETs are available in both N-channel and P-channel versions so it would not be a problem to find a P-channel MOSFET to use. It is the way that P-channel MOSFETs are built that makes them easier to use in the high-side, but it also makes the on-resistance of them higher than the on-resistance of their N-channel counterparts. Also all the capacitances are a little bit higher in the P-channel type and that causes the switching times of the transistor to be a little bit longer than for the N-channel type. This is why most H-bridges that needs to handle more currents use N-channel MOSFETs even if it makes the design of the drivers a little bit more complex.

Device

The MOSFET chosen was IRFP4310Z a HEXFET® power MOSFET from IRF which is suited for a number of different applications, for example high speed power switching. It has an on resistance between drain and source of maximum 6mΩ, can handle a continuously drain current of 134A at 25°C and has a breakdown voltage from drain to source of 100V.[6]
The freewheeling diode has to be able to handle about the same current as the MOSFET but only for the time that it takes for the MOSFET to turn on. After that the current will be shared between the MOSFET and the diode. If the MOSFET has a low on resistance then most of the current will go through it when it is conducting.

**Device**

The devices chosen to be used as the freewheeling diode was MBR60H100CT from On semiconductor®. Which is a schottky barrier rectifier that can handle a current of 60A and are able to block a voltage of 100V.[7]

**3.2.3 MOSFET driver**

Since it was decided that all MOSFETs in the H-bridge should be of the N-channel type, or NMOS, the high-side driver has to be able to boost the voltage going to the gate above the source voltage. In this case and for most power MOSFETs the gate-source voltage has to be 10V or larger in order to be sure to have the MOSFET in the ON state.
3.2. **Design 1**

Fortunately there exist a wide range of drivers from different manufacturers that is able to do this. It must not only be able to boost the voltage, but the driver also has to be able to handle enough current to turn the MOSFET on fast. The more current you can supply to the gate, the faster you are able to turn the MOSFET on.

**Figure 3.5: Half-bridge driver.**

**Device**

The device IFR2010 from IRF was chosen as a driver. It is a high and low side driver with decent current capabilities, +/− 3.0A at the output, relatively short propagation delays between input an output and with a high side that can operate at up to 200V.[8] It relies on a external capacitor called a boot-strap capacitor in order to be able to supply the gate of the MOSFET with the charge needed in order to turn the MOSFET on.
Bootstrap selection

IRF recommend using the following equations to calculate the minimum bootstrap capacitance required.\cite{9} If $V_{GS\text{min}}$ is the minimum voltage that must be maintained between the gate and the source when the MOSFET is on then:

$$\Delta V_{BS} \leq V_{CC} - V_F - V_{GS\text{min}} - V_{DS\text{on}} \quad (3.1)$$

when:

$$V_{GS\text{min}} \geq V_{BS\text{UV}} \quad (3.2)$$

Where; $\Delta V_{BS}$ is the minimum voltage drop for the bootstrap capacitor when the high side is on, $V_{CC}$ is the supply voltage, $V_F$ the forward voltage drop of the bootstrap diode, $V_{DS\text{on}}$ the voltage drop over the low side MOSFET and $V_{BS\text{UV}}$ the negative undervoltage threshold for the $V_{BS}$ supply of the driver.

There are a number of factors that influence the decrease of $V_{BS}$ in our driver:

- MOSFET turn on required Gate charge ($Q_G$)
- MOSFET gate-source leakage current ($I_{LK,GS}$)
- Floating section quiescent current of the driver ($I_{QBS}$)
- Floating section leakage current of the driver ($I_{LK}$)
- Charge required by the internal level shifters of the driver ($Q_{LS}$)
- Bootstrap diode leakage current ($I_{LK,DIODE}$)
- Bootstrap capacitor leakage current ($I_{LK,CAP}$)
- High side on time ($T_{HON}$)

$I_{LK,CAP}$ is however only relevant if the bootstrap capacitor used is a electrolytic one and can be ignored if another type of capacitor is used. Using these we can calculate the total charge:

$$Q_{TOT} = Q_G + Q_{LS} + (I_{LK,GS} + I_{QBS} + I_{LK} + I_{LK,DIODE} + I_{LK,CAP}) \cdot T_{HON} \quad (3.3)$$

Using equation 3.1 and 3.3 we can calculate the minimum bootstrap capacitance:

$$C_{BOOT\text{min}} = \frac{Q_{TOT}}{\Delta V_{BS}} \quad (3.4)$$

Parameters for calculating bootstrap capacitance for IRFP4310Z\cite{6} and IR2010\cite{8} with the diode STTH1R02\cite{10} from ST as a bootstrap diode and a non electrolytic capacitor:

- $V_F \approx 1V$
3.2. Design 1

- $V_{GS_{min}} = 10V$
- $V_{DS_{on}} \approx 1.5V$
- $V_{CC} = 15V$
- $Q_G = 170nC$
- $I_{LK,GS} = 100nA$
- $I_{QBS} = 210\mu A$
- $I_{LK} = 50\mu A$
- $Q_{LS} = 5nC$
- $I_{LK,DIODE} = 20\mu A$
- $I_{LK,CAP} = 0$
- $T_{HON} = 100\mu s$

Inserting these values in equation 3.4 gives $C_{BOOT_{min}} = 81nF$ But this is a minimum value so a general rule of thumb is to multiply this value with 15 in order to be on the safe side. So the actual value used for the bootstrap capacitor $C_{BOOT}$ is $1\mu F$.

**Other parts**

As seen in figure 3.5 which shows the driver circuit there is a also three different types of resistances; R-BOOT, RG-OFF and RG-ON, and also a diode connected from the gate of the each MOSFET to the RG-OFF resistance. The purpose of the R-BOOT resistance is to limit the current going from the supply to the bootstrap capacitor. The purpose of RG-ON, RG-OFF and the extra diode is to provide one resistance at turn on, RG-ON, and another smaller one at turn off, RG-OFF. This to have faster turn off than turn on and also to make sure that there exists a low resistance path between the gate and the source when the MOSFET is supposed to be off. Because if a voltage spike with large $dv/dt$ occur on the drain of a MOSFET for example the low side MOSFET when the high side turns on. Then the voltage can travel through the internal $C_{GD}$ capacitance of the low side MOSFET from the drain to the gate and if the path between the gate and the source has a too high of a resistance the voltage at the gate can start to rise and cause a accidental turn on of the low side MOSFET.
3.2.4 Interface between microcontroller and H-Bridge

The driver IFR2010 that was chosen can actually be interfaced directly with a microcontroller or any type of logic that that uses a voltage from 3.3V to 20V. But since the H-bridge will operate at relatively high voltages and and currents compared to the microcontroller, a good isolation between the logical part and the H-bridge is desired. This in order to protect the microcontroller from any possible voltages or currents that can be so high that they cause permanent damage to it. The driver IFR2010 provides some isolation, but what is wanted is true galvanic isolation. For example an opto-coupler.

![Diagram](image)

**Figure 3.6: Isolation between half-bridge driver and microcontroller.**

**Device**

What was decided to be used is something that provides the same functionality as a opto-coupler but instead of isolating the signal optically it is isolates it magnetically. The fact that the signal is transferred magnetically instead of optically makes it a lot faster, because in a opto-coupler it takes time to turn on the light source and it also takes time for the optical sensor to react to the incoming light. This problem doesn’t exist in a magnetically coupled device since the output signal basically will follow the input signal instantaneously. The device chosen for isolating each drivers high and low input was a ADuM1210 from Analog Devices which has two channels. Other than one ADuM1210 for each driver an extra ADuM1100 was included in order to isolate the SD(Shut
3.2. Design 1

Down) signal going to both of the drivers. The ADuM1100 is similar to the ADuM1210 but has just one channel instead of two and it also has the functionality that the output goes high instead of low when there is no power on the input side. So accidental loss of power at the input shuts down the drivers, which is a good thing.

3.2.5 Supply for drivers and isolation devices

IR2010, ADuM1210 and ADuM1100 all need voltage supplies in order to work. The IR2010 needs one supply between 10-20V for being able to drive the MOSFETs connected on the output and one logical supply between 3.3-20V depending on the type of logic connected on the input.

[Image: Supply for the drivers]

Figure 3.7: Supply for the drivers.

Devices

The L78XX type voltage regulator is a common voltage regulator that is manufactured by many different companies and exist in different packages and output voltages. The decision was made to use a L7815ABV to get a regulated 15V voltage for the gate drive supply of the drivers and a L78M05ABV to get a voltage of 5V to use as a logical voltage to both the drivers and the isolators.

3.2.6 Microcontroller

By designing the H-bridge as a separate unit it will give the advantage of interfacing it with which ever microcontroller that is chosen. The idea was to use a existing development board from Atmel® called MC310 with a 8-bit ATmega32M1 AVR® microcontroller. This microcontroller is similar to a normal ATmega32 microcontroller but it has a special Power Stage Controller(PSC) which can output none overlapping inverted PWM signals
with controllable dead-time.[11] Which means that it can output a PWM signal on two different output pins at the same time, one is the normal PWM signal and the other is the inverted one. This means that when one output is high the other one is low. The controller makes sure that the signals on the output never are high at the same time. The dead-time between the signals can be controlled, dead-time means the time between one signal going low until the other signal going high. This is useful due to the time it takes from the signal going low on the input of a MOSFET until the MOSFET is actually turned off. If the high side MOSFET is on at the same time as the low side MOSFET in one of the legs of the H-bridge you will get a short circuit between the power supply and ground. This will cause a shoot through of current going through the MOSFETs in the bridge and the current could actually be so large that it damages the MOSFETs.

### 3.2.7 Summary

This design would probably have worked but due to reasons discussed in the section Design 2, it was never build and tested.

### 3.3 Design 2

![Diagram](image)

*Figure 3.8: Basic overview of design 2 of the test-bench.*

A couple of months into the project our advisor told us about this other project that another student of the university had worked on. His name is Fredrik Häggström and he had made a converter board that was planned to be used to control three-phase motors.
3.3. Design 2

As it happened to be, he had PCB boards and almost enough parts left over from that project to build a complete device, so our advisor said that we should save a lot of time and some money by using his leftover parts. Also since his converter board actually is an H-bridge with three legs instead of two, we would have the ability to use that extra leg as a controlled way of connecting a load and in that way eliminating the need for an expensive voltage source that can sink current. The board also had functionalities like the ability to measure the current through the legs, the voltage over the bridge and the temperature of the board. The big difference from design 1 is that this design have the microcontroller mounted on the same board as all the other parts. However the microcontroller used is a quite powerful one and the need to replace it later might not be an issue. Figure 3.8 shows an basic overview of design number 2.

3.3.1 Converter

In figure 3.9 an overview of the design of the converter with its three legs, consisting of MOSFETs and drivers for those, can be seen. It also shows the four small resistors of 0.5mΩ that is mounted before each connection out from the converter. The function of these resistors is to create a small voltage drop that can be measured and used to calculate the current going through them. I figure 3.10 the design of one of the legs can be seen.

Each of the legs consists of; four MOSFETs, two freewheeling diodes, four MOSFET drivers, one high and low side driver with galvanic isolation that drives the MOSFET drivers, a couple of capacitors and resistors and a bootstrap diode.

![Figure 3.9: Overview of the three legs of the converter.](image-url)
The first thing that had to be done was to check if the MOSFETs used would be able to keep the current that is required for the intended application. This design uses two parallel couple MOSFETs instead of just one, for both the high side and the low side. The ability to easily do this is one of the good things about using MOSFETs as switches. By connecting them in parallel the MOSFETs pretty much share the current going through the leg equally and in that way the power that each device has to dissipate is also cut in half.

The MOSFET that was used was an IRFB3306 HEXFET® power MOSFET from IRF. It has quite similar specifications as the MOSFET, IRFP4310Z, used in design 1, and the most significant difference between them is that IRFB3306 has a lower breakdown voltage between drain and source, only 60V instead of 100V.[12] This is within the range of the intended application and should not be a problem as long as the device is protected from voltage spikes. Another difference is that IRFB3306 has a lower on resistance between drain and source, only a maximum of 4.2mΩ and can therefore handle higher currents. So this MOSFET is definitely usable.

Freewheeling diode

The freewheeling diode used in this design is also a Schottky diode, it’s a STPS20H100C from STMicroelectronics. This one is like the MOSFETs also quite similar to the
device used in design 1. The biggest difference between them is that the STPS20H100C isn’t able to handle quite as much continuous current.\[13\] But this isn’t a problem since it only should handle the currents until the MOSFETs turns on.

**MOSFET drivers**

This design uses one separate driver for each MOSFET, a ZXGD3002 gate driver from Zetex, which has a good current capability with the ability of up to 9A peak currents at the output if supplied with 1A at the input and about 2A continuously if supplied with 10mA at the input.\[14\] These drivers are easy to use on the low side, but requires some extra components in order to function on the high side. So the way this is solved in this design is to include a high side low side driver, in form of a ADuM1230 from Analog Devices, that drives the gate drivers. The ADuM1230 also provides galvanic isolation and a great way of interfacing the microcontroller with the converter leg. The reason to not just use the ADuM1230 to drive the MOSFETs is that its current capability is much lower, with a peak current of only 100mA\[15\], and that would slow down the switching time of the MOSFETs.

**Bootstrap capacitor and gate resistance**

No new calculations are made since this is a working design, nothing has been change in the driver circuit and the bootstrap capacitor used, C18 in figure 3.10, is as high as 100uF. Actually one thing has been changed in the driver circuit, the resistors R14, R15, R16 and R17 that is put in to act as a pull-down resistor to the gate making sure that the MOSFET stays turned off if no signal is supplied from the driver, has been changed to 100KΩ instead of 1KΩ. This is done to not have a current leakage of 1mA going through them and draining the power from the bootstrap capacitor when the MOSFET is supposed to be on. But this will only affect the bootstrap capacitor in a positive way because less current leakage only means that a smaller capacitor value is needed. Because it is a tested and working design and because the gate resistances, R39, R41, R43 and R45, are fairly small already, nothing is done to change the values of them.

**Voltage supply**

In the top part of figure 3.11 the supply for the MOSFET drivers can be seen. It consists of a LM317HVT adjustable voltage regulator which output is setup with the resistors R10 and R11 and two capacitors\[16\], one at the input to filter the input voltage and one at the output to improve the transient response. A diode, D15, is also connected from output to input in order to protect the regulator against large currents being supplied into the output terminal by the output capacitor if the input terminals for some reason are shorted together. The input also has some protection, a diode, D20, is in place in order to protect the circuit against a wrong polarity connection at the input and a
62 Hardware

Transient Voltage Suppression (TVS) diode, D14, that is in place in order to protect the circuit from overvoltage at the input.

![Diagram showing TVS diode D14 and connections](image)

**Figure 3.11: Voltage sources for the converter.**

### 3.3.2 Measurement circuits

The circuit board includes measurement circuits for voltage measurement, current measurement and temperature measurement.

#### Voltage measurement

The voltage measurement is done between the positive and the negative input terminal of the converter circuit. In figure 3.9 these are named V+ and GND1 and in figure 3.12 and figure 3.13 the same connections are named 48V and GND1. The original design can be seen in figure 3.12 where the positive input of the LM358 is centered around $\frac{3.3}{2}$V which means that the output also is centered around approximately $\frac{3.3}{2}$V since the LM358 is configured to have a gain of 1.056. This will give the ability to measure both positive and negative voltages between the two input terminals at the cost of decreased positive range. However since this application doesn’t need to measure negative voltages and because it is more important to be able to measure a higher voltage, this design is modified by removing the resistance, R55, between the 3.3V source and the positive input terminal. The modified circuit can be seen in figure 3.13. The output signal from the LM358 is then fed through a low-pass filter, R37 together with C51, to the AD-converter of the microcontroller.
3.3. Design 2

Figure 3.12: Voltage measurement.

Current measurement

The circuit seen in figure 3.14 shows the current measurement circuit for the U connection of the converter board. The part of the circuit inside the dashed lines also exist for the V and the GND connection, has the exact same values and are connected to the DISABLE network in the same way, so therefore only the U version is described. Current measurement is done with a device called INA201 from Texas Instruments, which is a “High-Side Measurement Current-Shunt Monitor with Open-Drain Comparator and Reference[17].” It consist of a differential voltage amplifier, with a gain of 50V/V and a common mode rejection of 100dB, and a comparator with an internal 0.6V reference. This can be seen in figure 3.15. The differential voltage amplifier amplifies the small voltage drop that appear over the current shunt resistor of 0.5mΩ, seen in figure 3.9, when current is flowing through it. The amplified voltage can then be fed through the comparator. When the input voltage to the comparator goes above 0.6V the output goes high and if the reset pin of the comparator is high when this happens the output latches and will stay high until the reset pin is pulled low. The schematic in figure 3.14 shows that one INA201 is used to measure the current in one direction and another INA201 for the current in the other direction. This is done by flipping the voltages at the input of the second INA201 compared to the first one. The reason for doing this is that the range of the output from the differential amplifier goes from 0V to 3.3V and a negative difference at the input would result in 0V out. By using two this problem is solved.
The output voltage from the differential amplifier of each INA201 is fed both to the AD-converter of the microcontroller and to the comparator. But the voltage going to the comparator is divided by using two resistors, in figure 3.14 these resistors are R7 and R8, and R9 and R18. The original design used two 1KΩ resistors which means that the voltage to the comparator would be half of the output voltage from the differential amplifier. This resulted in that the comparator output would go high if the current went above 48A. That would mean that the DISABLE signal would go high and result in the MOSFET drivers being shutdown. This current was a little bit low, so the resistor values of R7, R9 and the corresponding ones in the circuits for V and GND, where changed to 2.7KΩ so that less of the voltage would end up at the comparator input. In this way the current has to be 88.8A in order for the DISABLE signal to go high.

**Temperature measurement**

In figure 3.16 the simple circuit for temperature measurement is included. I consists of just a voltage division between a normal fixed resistor and a thermistor that has a resistance that depend on the temperature. The divided voltage is then fed through a low-pass filter to the AD-converter of the microcontroller.
Speed measurement

How the speed measurement is done is explained in chapter 2 section 2.10. The part used is a photo interrupter together with a couple of resistors and the signal out from it will be low as light is transmitted through the slot and falls on the photo sensor. The design of the converter board includes available inputs that are supposed to be used with hall-sensors. These inputs, seen in figure 3.17, each goes to one of the external interrupt pins on the microcontroller. Since the signal out from a hall-sensor is similar to the output from the photo interrupter these inputs will be perfect to use for the speed measurement.
3.3.3 Microcontroller

The microcontroller used in this design is a LPC1768 from NXP with a 32-bit ARM Cortex-M3 processor that can run at speeds of up to 100MHz. The LPC1768 has amongst other things a special motor control PWM, an 8 channel 12-bit AD-converter and 4 general purpose
3.3. Design 2

Figure 3.17: Hall-sensor inputs.

timers.[18] This microcontroller is good enough or even more than good enough for the intended application.

Communication

The microcontroller supports CAN communication and the design includes a CAN transceiver chip that makes it possible to use CAN communication with the microcontroller. However the CAN-bus will not be used, since the original design of the test-bench uses normal serial communication from the serial port of the computer to the microcontroller and the fact that there are RX(receive) and TX(transmit) pins from one UART(Universal Asynchronous Receiver/Transmitter) easily accessible on the board. However to be able to communicate straight with the computer a level shifter has to be installed between the low level TTL(Transistor Transistor Logic) signals of the microcontroller and the high level RS-232 signals of the computer. There are many chips available for this type of translation but since the board is already made there’s no possibility to just add one to the design. Luckily since this is a normal problem there exist many small and cheap pre-made circuitboards with these kind of chips. A kit called Pololu 23201a, with a
Figure 3.18: CAN circuit.

A pre-made circuitboard and a DB-9 connector was found and purchased.

Figure 3.19: Pololu 23201a connected to converter board.
3.3. Design 2

Programming

The design also has the JTAG (Joint Test Action Group) interface of the microcontroller pulled out to a connector and this will be used to program it.

3.3.4 Voltage supply for logics

The voltage supply for the microcontroller and the other logic chips on the board can be seen in the lower part of figure 3.11. First is a LM317HV voltage regulator circuit just as the one for the MOSFET drivers, but this has an output voltage of 5V and includes C9 and D21 to have improved ripple rejection. The voltage VDD(5V) is used for some logics including the logical side of the ADuM1230. The VDD voltage of 5V is also fed to the LM3940, which is a 5V to 3.3V voltage regulator.[19] The 3.3V, VDD(3V3), output from the LM3940 is used as supply for the microcontroller. As seen in right part of figure 3.11 this voltage is then filter before it is used as a 3.3V reference voltage for the AD-converter of the microcontroller or as a supply for sensors like the INA201 which has its output fed to the AD-converter.

3.3.5 Voltage source

The voltage source consist of three 12V lead-acid batteries, normally used in cars. The reason for this is explained in chapter 2 section 2.5.

3.3.6 Load

A large power resistor, TE1000B1R0J from TYCO ELECTRONICS, was bought to be used as a load. It’s a resistor of 1Ω that can handle 1000W.[20]

3.3.7 Filter capacitor

As we explained before, we will need a capacitor in every moment, when the DC machine is running like motor and like generator. For calculating this capacitor, we will take in account the generator and the motoring mode of the DC machine, calculating the correct value of capacitance for each mode, and putting a capacitor with the biggest value or even bigger.

We will calculate the capacitor with the generator mode conditions because these conditions are more demanding. The stray inductance of wires is not so big and the internal resistor of Pb-Acid batteries is quite low too. If we have a capacitor able to work in the generating mode, it will work too in the motoring mode.

First of all we will calculate the capacitor which is able to filter the high frequency part of the current signal that goes from the H-Bridge. After that we will calculate another capacitor able to obtain a correct current signal in the battery, taking a constant current from the H-bridge because of the capacitor calculated at the beginning.
Instead of putting these two capacitors, we will put a single capacitor in parallel with the battery and also with the energy absorption leg. In figure 3.20 we can see a graphical representation of this explication, where we can see the capacitors which we have to calculate ($C_1$ and $C_2$) and the single capacitor which we will put finally. This capacitor will be the same or bigger than the addition of $C_1$ and $C_2$.

![Figure 3.20: Imaginary circuit for knowing the position of the imaginary capacitor $C_1$ and $C_2$ (top) for knowing the value of the capacitor that will be put in the real circuit (bottom).](image)

For doing this calculation, we will use the circuit of figure 3.21. This circuit is a part of the complete circuit of the system, and it goes from the DC machine until to the input of the leg with the power resistor. In addition, we only will think in one sense of rotation ($T_{B+}$ is always turned off and $T_{B-}$ is always turned off).
We will take $i_o$ as a completely square wave. Furthermore, the goal of $C_1$ is to get that $i_d$ would be the medium value of current of $i_o$. In figure 3.22, the different current waves are shown. $D_{T_{A+}}$ is the duty cycle of the transistor $T_{A+}$.

$$i_{C_1} = C \cdot \frac{dV_0}{dt} = i_d - i_o \approx I_a D_{T_{A+}} - i_o$$ \hspace{1cm} (3.5)$$

$$\Delta V_0 = \frac{1}{C_1} \cdot \int_{t_1}^{t_2} f(t) \, dt$$ \hspace{1cm} (3.6)$$

Because of the properties of the capacitor in DC circuits, the medium current in the
capacitor will be zero. For this reason, $\Delta Q$ is the same in both cycles of operation, thus doesn’t matter if we do the calculation in one cycle or in the other.

$$\Delta V_0 = \frac{1}{C_1} \cdot \int_0^{t_{on}} f(t) \, dt = \Delta V_0 = \frac{1}{C_1} \cdot \int_{t_{on}}^{t_{on}+t_{off}} f(t) \, dt$$  \hspace{1cm} (3.7)$$

$$\Delta V_0 \approx \frac{1}{C_1} \cdot (I_a - i_o) \cdot t_{on} \approx \frac{1}{C_1} \cdot (I_a - D.I_a) \cdot t_{onT_{a+}} = \frac{1}{C_1} \cdot (I_a - D.I_a) \cdot D T_{a+} \cdot T_s \hspace{1cm} (3.8)$$

$$\Delta V_0 \approx \frac{1}{C_1} \cdot (1 - D T_{a+}) \cdot D T_{a+} \cdot I_a \cdot T_s \hspace{1cm} (3.9)$$

For be safer, we will do the calculation with the maximum $\Delta V_0$ possible. The duty that maximizes $\Delta V_0$ in $D = 0.5$. About the maximum current $I_a$, we can think that it will be near to 30A as we saw in the theoretical chapter. If we accept a $\Delta V_0$ equal to 0.1V, then the capacitance of $C_1$ is shown in the expression 3.10.

$$C_1 = \frac{(1 - 0.5) \cdot 0.5 \cdot 30 \cdot 50 \cdot 10^{-6}}{0.1} = 3750 \mu F \hspace{1cm} (3.10)$$

The equivalent circuit for calculating the new capacitor $C_2$ is shown in figure 3.23.

**Figure 3.23: Part of the circuit for the calculation of $C_2$.**

If we have 1Ω in the power resistor, the current on the resistor when $T_R$ is turned on will be:

$$I_R = \frac{V_{battery}}{R} = \frac{41}{1} = 41A \hspace{1cm} (3.11)$$
3.3. Design 2

However, the maximum power dissipation of the resistance is 1000W. Hence, the maximum medium current in the resistor will be lower than 41A because the maximum duty cycle on the leg of the power resistor \((D_R)\) will be limited by \(D_{RMAX}\).

\[
P_R = R.I_R^2 \tag{3.12}
\]

\[
I_{RMAX} = \sqrt{\frac{P_{max}}{R}} = \sqrt{1000} = 31.6A \tag{3.13}
\]

\[
D_{RMAX} = \frac{P_{max} \text{ in } R}{P_{with D=1}} = \frac{1000}{1 \cdot 41^2} = 0.593 \tag{3.14}
\]

Knowing that in this occasion, the goal of C2 is to get a \(i_b\) equal to the medium value of \(i_e\), and the properties of the capacitor in DC circuits, we can calculate an appropriate value in the same way than in the C1 calculation. We can see the different current waves in figure 3.24.

\[
i_e = i_a - i_R \tag{3.15}
\]

\[
I_b \approx i_b \approx I_d - I_R = I_e = (D_{TA+I_a}) - (D_R I_R) \tag{3.16}
\]

\[
i_{c2} = C \cdot \frac{dV_0}{dt} = i_b - i_e \tag{3.17}
\]

\[
T_{RON} \Rightarrow i_{c2} = (D_{TA+I_a}) - (D_R \cdot 41A) - (D_{TA+I_a}) + 41A \tag{3.18}
\]

\[
T_{ROFF} \Rightarrow i_{c2} = (D_{TA+I_a}) - (D_R \cdot 41A) - (D_{TA+I_a}) \tag{3.19}
\]

\[
T_{ROFF} \Rightarrow i_{c2} = (D_{TA+I_a}) - (D_R \cdot 41A) - (D_{TA+I_a}) \tag{3.20}
\]
\( \Delta Q \) will be the same in both cycles again.

\[
\Delta V_0 = \frac{1}{C_2} \cdot \int_{t_0}^{t_{\text{on}}} f(t) \, dt = \Delta V_0 = \frac{1}{C_2} \cdot \int_{t_{\text{on}}}^{t_{\text{on}}+t_{\text{off}}} f(t) \, dt
\]

\( \Delta V_0 \approx \frac{1}{C_2} \cdot D_{TA+} \cdot (I_a - (D_R \cdot 41A)) - (D_{T,A+}I_a + 41A))T_S D_R \)  

Taking in account that \( \Delta V_0 \) will be maximum when \( D_R \) is equal to 0.5, and taking a maximum variation of \( \Delta V_0 \) of 0.1V, we can know the appropriate value of \( C_2 \). We can see this value in the expression 3.23.

\[
C_2 = \frac{(-D_R \cdot 41A + 41A)T_S D_R}{\Delta V_0} = \frac{(1 - 0.5) \cdot 0.5 \cdot 41 \cdot 50 \cdot 10^{-6}}{0.1} = 5125 \mu F
\]

Once we know the value of both capacitors, the capacitor that we have to put will be the same or bigger capacitor to the addition of \( C_1 \) and \( C_2 \).

\[
C \geq C_1 + C_2 = 3750 \mu F + 4625 \mu F = 8875 \mu F
\]

For building this capacitor, we will put 4 capacitors in parallel of 2200 \( \mu F \) each one. The voltage limit of these capacitors will be 63V.

### 3.3.8 Heat sink

We have to calculate the heat sink for the element that have to keep more current, the power MOSFET. The thermal resistance values that we can find in the datasheet of the
MOSFET[12] selected in the design 2 are the following:

\[ R_{\theta jc} = 0.65 ^\circ C/W \quad (3.25) \]

\[ R_{\theta cs} = 0.5 ^\circ C/W \quad (3.26) \]

\[ R_{\theta jA} = 62 ^\circ C/W \quad (3.27) \]

\[ R_{\theta jA} = 40 ^\circ C/W \text{(PCB mount)} \quad (3.28) \]

For calculating the kind of heat sink that we need, we need to know the maximum values of current and voltage in the circuit. The level of voltage is stabilized to 37V. About the current, with a current between 0A and 30A, we would be able of controlling the speed of the motor. However, the current control couldn’t be perfect at all and we could find situations where the current is bigger.

If the control is wrong, the worst situation would take place when for a big speed of the combustion engine, we brake too much hard with a very big duty in the down-side transistors and very small in the high side. In this situation the current would be the biggest as is possible.

For example, for 7000RPM, the \( V_{EMF} \) would be 38.85V(\( V_{EMF} = 733 \text{rad/s} \cdot 0.053 \frac{V}{\text{rad/s}} \)). If we have a maximum duty of 0.01 in the high-side transistors, in the down-side the duty would be 0.99. We can know the current in steady state if the motor would be able to keep this speed enough time. This situation is not possible because when the current was bigger than 30A, the motor would brake, the \( V_{EMF} \) would get smaller and current couldn’t reach this value.

But for being conservatives, we are going to calculate the heat sink for that current. The reason for doing it is the setting of the PID control is going to be experimental, and we could have a not good control in the first test. According with the section “Burning energy” in the theory chapter, the current in the coil of the motor for this situation would be the calculated in the equation 3.29 in steady state.

\[ I = \frac{V_{EMF} - 41DC_{High-side}}{R_{Motor} + R_{ON Transistor}} = \frac{38.85 - (41 \cdot 0.01)}{0.14 + 2 \cdot 0.0042} = 259A(I_{max}) \quad (3.29) \]

In the final design, we have 2 transistors in each leg. It means that we will have 130A in each transistor for this hypothetical situation, being safe that we won’t reach this current continuously in any moment. Now we are going to see if we need a heat sink. First, we have to know the power dissipation that occurs in the transistor in the normal working. For that we will see looses in the switching (\( P_s \)), and after, looses in ON estate (\( P_{on} \)).

\[ P_s = P_{on} + P_{off} \quad (3.30) \]
\[ P_{\text{on}} = \frac{1}{2} \cdot V_{\text{change off to on}} \cdot I_{\text{change off to on}} \cdot \frac{t_{\text{change off to on}}}{T_S} \] (3.31)

\[ P_{\text{off}} = \frac{1}{2} \cdot V_{\text{change on to off}} \cdot I_{\text{change on to off}} \cdot \frac{t_{\text{change on to off}}}{T_S} \] (3.32)

\[ V_{\text{change off to on}} \approx V_{\text{change on to off}} \approx 37V \] (3.33)

\[ I_{\text{change off to on}} \approx I_{\text{change on to off}} \approx 135A \] (3.34)

\[ P_{\text{on}} \approx P_{\text{off}} = 41 \cdot 135 \cdot \frac{77 \cdot 10^{-9}}{50 \cdot 10^{-6}} = 8.52W \] (3.35)

\[ P_{\text{on}} = V_{\text{ON}} I_{\text{ON}} \cdot \frac{t_{\text{on}}}{T_S} = R_{\text{on}} I_{\text{on}}^2 \cdot \frac{t_{\text{on}}}{T_S} = 4.2 \cdot 10^{-3} \cdot 135^2 = 76.5W \] (3.36)

\[ P_{\text{tot}} = 8.52 + 75.85 = 84.37W \] (3.37)

Knowing this power dissipation, and the maximum temperature in the junction (175°C), we can find out if we have to put a heat sink.

\[ T_j = P_{\text{tot}} \cdot R_{\theta} + T_{\text{ambient}} \leq T_{j\text{max}} = 175°C \] (3.38)

\[ R_{\theta} \leq \frac{T_{j\text{max}} - T_{\text{ambient}}}{P_{\text{tot}}} = \frac{175 - 30}{84.37} = 1.78°C/W \] (3.39)

\[ R_{\thetajc} + R_{\thetacs} + R_{\thetaSA} \leq 1.78°C/W \] (3.40)

\[ R_{\thetaSA} \leq 0.64°C/W \] (3.41)

For that reason, we will take a heat sink with a \( R_{\thetaSA} \) around this value, although we won’t need so small value of resistance because the calculation is too much conservative. The heat sink chosen is HS Marston150 CN of 200mm with \( R_{\thetaSA} = 0.65°C/W \).

### 3.3.9 Snubber nets

Once we have the completed model for simulating all design in Pspice, we did some test for knowing the behavior of the circuit. With these simulations we were aware of the problem of don’t put any protection circuit. Having a stray inductance of only 20nH between the capacitor of 8800µF and each leg, we got very big voltage peaks that were very dangerous for the transistor because the voltage limit of their was overtaken. In figure 3.25 we can see the voltage in the transistor terminals.
If we put a turn-off snubber in each transistor attending to the theory chapter, the capacitor and resistance values would be like the expression 3.42 and 3.43 is indicating.

\[
C = \frac{I_L t_f}{2V_D} = \frac{30 \cdot 117 \cdot 10^{-9}}{2 \cdot 36} = 48.75\text{nF} \approx 50\text{nF} \quad (3.42)
\]

\[
t_{ON} \geq 5RC \rightarrow I_f t_{ON_{max}} = 2\mu s \rightarrow R \leq 8\Omega \quad (3.43)
\]

The diode that we put in this simulation for the different turn-off snubber nets was an ultra-fast diode.

In the Appendix C we can see how the model looks with this snubber net, and also with the overvoltage snubber that we will discuss in this section.

About the results that we got, we saw two main differences. In one hand, the power dissipation because of the switching is smaller with this snubber net than before. In figure 3.26 and 3.27 we can see the difference. For the same situation, with turn off snubber the power dissipation in the transistor is smaller. It’s because the resistor is burning energy that before was dissipated in the transistor.
But on the other hand, we have seen that now we have very big current peaks in the
turn-on of the transistor, much more high than before. We can see the comparison of
both cases in figures 3.28 and 3.29.
It means that reverse recovery current is not the reason of the high peaks of current in the transistors when they are turning on, because they are higher than before, without turn off snubber nets. The problem is because the turn-off snubber is adding one way to the current when a transistor is in OFF state while its turn-off snubber capacitor is
being charged. Because of this, the turn-on of the other transistor in the same leg will have an extra current just in a very inappropriate moment. In figure 3.30 we can see the sense of current when we turn off the high-side transistor, and we turn on the down-side transistor.

Furthermore, the dangerous voltage peaks in the transistor terminals are present yet in the same way as before. We can handle the power dissipation in the transistor with the heat sink as we can see in the heat sink section. In addition, the high current peaks that we have now are really dangerous. For that reason we decided don’t put the turn-off snubber nets in our design.

For solving the overvoltage problem, we will try to put an overvoltage snubber. The problem is that we have to figure out the real stray inductance which we have between the big capacitor of 8800\( \mu \text{F} \) and the drain of the high-side transistor of each leg.

We will do the inverse process. We have available electrolytic capacitors of 2200\( \mu \text{F} \). If we put this capacitor, we can know how the maximum stray inductance that we can handle is. With the formula 2.7 which we explained in the theory section, putting a limit of 0.1V of maximum variation of voltage and 31A the maximum current, we can know the maximum stray inductance that we can have. This calculation is shown in the expression 3.44 and 3.45.

\[
\frac{C_{OV} \Delta V_{CE,MAX}}{2} = \frac{L_{\sigma} I_{L_{\sigma}}^2}{2} \tag{3.44}
\]

\[
\frac{2200 \mu \text{F} \cdot 0.1^2}{2} = \frac{L_{\sigma} \cdot 30^2}{2} \rightarrow L_{\sigma} = 24.4 \text{nH} \tag{3.45}
\]
Taking in account that the only element which creates inductance in this part of the bridge will be the current sensor (2· 5nH in each leg) and the conductor, the total stray inductance will be smaller than 24.4nH. Otherwise, if we accept bigger voltage peaks, the capacitor which we have available of 2200µF is more than enough. The maximum peak aloud will not reach the 60V, limit of the power MOSFET. In addition, we can put a smaller ceramic capacitor in parallel with the electrolytic of the overvoltage snubber for getting a faster answer.

Putting an ultra fast diode, and the same resistor that we calculated for the turn-off snubber net, we can simulate the new system with the overvoltage snubber net. As a result, we obtain a system with a very small voltage peaks. Furthermore, current peaks didn’t increase because of the overvoltage snubber net, but they still exist. In figure 3.31 we can see the voltage between drain and source in a transistor that is being switched. The difference with figure 3.25 where we didn’t have any overvoltage snubber net is quite big attending to the voltage peaks.

![Figure 3.31: Voltage in the transistor terminals because of the switching with overvoltage snubber nets.](image)

About the current peaks, maybe we could decrease it with a turn-on snubber net. The reason of having these current peaks is the reverse recovery current that all diodes of the system has. The problem of putting this snubber net is, we have to add inductances in the circuit and maybe it is not a good idea because we already have stray inductances. To put more inductance could create problems with voltage peaks, much more dangerous than current peaks.

The capacitor that we have chosen for the overvoltage snubber net is similar to the
capacitor that we have used for building the big capacitor of 8800 µF, with 2200 µF and a voltage limit of 63V.

About the diode of the snubber net, it has to be an ultra-fast diode. We have selected the part STTHH10RFP, which is able of keeping high currents with a small recovery time.

For knowing the power dissipation that the resistance needs, we know from the theory chapter that power dissipation in the resistor of the overvoltage snubber net is the same order as in the resistor of the hypothetical turn-off snubber net which we didn’t put finally. In the expression 3.46 and 3.47 we show the calculation of this value.

\[
\frac{1}{2} \cdot C_{\text{turn-off}} \cdot V_{\text{turn-off capacitor}}^2 = \frac{1}{2} \cdot 50 \cdot 10^9 \cdot 41^2 = 4.2025 \cdot 10^5 \rightarrow P = \frac{E}{t} \tag{3.46}
\]

\[
E = \frac{E}{R_{OV} \cdot C} = \frac{4.2025 \cdot 10^5}{4 \cdot 10^{-6}} = 10W \rightarrow \frac{P_{AVG}}{t_{\text{cycle}}} = \frac{10W \cdot t_{\text{discharge}}}{50 \cdot 10^6} = 0.8W \tag{3.47}
\]

We have chosen a resistor of 8.2 Ω and a maximum power dissipation of 3W (ER748R2JT).

Figure 3.32: Overview of the converter with snubber nets and filter capacitor added.
Software

The software for the testbench will be divided into two different types. The software that runs on the microcontroller and handles the hardware that control the DC motor/generator. And the software that runs on a normal computer that has LABview installed, which collect measurement data, communicates with the microcontroller and provides a graphical way of controlling the testbench.

4.1 Microcontroller

The software for the microcontroller is written in C and uses the Tiny Timber kernel developed at Luleå University of Technology, which is a small real-time kernel for task scheduling. The decision to use Tiny Timber was mainly done because Fredrik Häggström had done some code development for his converter using the Tiny Timber kernel, and some of his code could maybe be reused, but also because it would give the possibility to use the Tiny Timber kernel as an easy way of scheduling of some of the tasks. However not much of the existing code could be reused straight away and in order to make sure that the already existing code did exactly what was desired, the code was analyzed and somewhat rewritten. The parts of the existing code that could be reused only dealt with setting up the motor control PWM function, the AD-converter and the integration with Tiny Timber. In figure 4.1 a basic overview of the software can be seen. For simplicity it will be looked upon as a number of objects that each handles different functions, even if C in reality is not an objective language.

4.1.1 UART - Serial communication

The purpose of the UART is to communicated with the outside world, in this case the computer running LabVIEW™. It means that the microcontroller and the computer has to be set up so they speak the same language. This is what the UART object does. It sets up the serial communication for the microcontroller, takes care of transmitting,
receiving and translating information and makes sure that the commands sent from the computer reaches the correct destination object. For example if it’s the desired speed that is sent from the computer then the UART object will pass this information to the speed controller. In table 4.1 the parameters for the serial communication can be seen.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baudrate</td>
<td>57600</td>
</tr>
<tr>
<td>Data bits</td>
<td>8</td>
</tr>
<tr>
<td>Stop bits</td>
<td>1</td>
</tr>
<tr>
<td>Parity</td>
<td>None</td>
</tr>
</tbody>
</table>

*Table 4.1: Serial parameters.*
4.1.2 Motor Control PWM

The motor control PWM object uses the built-in motor control PWM function of the microcontroller to generate the PWM signals that are used to control the electrical motor. But since the motor control PWM function in the microcontroller is built for three-phase motors, which need three channels, and the motor used is just a normal DC motor, that needs two channels, one extra channel is available and will be used for the load control. What this object does is that it sets up the motor control PWM function of the microcontroller, all the channels for it and all the specifications for the channels, including dead-times, period and pulse-widths. It also takes care of any changes that need to be done, like changing the direction of the motor or changing the pulse-width or the dead-time to a desired value, as long as the value is within the allowed range. The allowed range is specified by the pulse period, the dead-time and time required to charge up the boot-strap capacitor. This because the low side MOSFET always has to be on for a small amount of time in order to charge the capacitor used as a boot-strap in order to be able to turn on the high side MOSFET. For normal operations this object should not be accessed other than by the speed control or load control objects, but for debugging there is a way of sending commands straight from the UART object to the motor control PWM object. The motor control PWM is setup to output PWM signals with a pulse period of 50s, which means a pulse frequency of 20kHz. The smallest change in pulse-width that is possible with this setup is 10ns which is 0.02% of the total pulse period.

4.1.3 Speed control

The speed control object has two important tasks, one is to measure the current speed and the other is to regulate the speed. In order to regulate the speed the speed control object has a PID-regulator object that does regulation of the pulse-width sent to the motor control object based on the current speed and the desired speed. The speed measurement comes in to the microcontroller as a pulse train and the frequency of this pulse train varies with the speed. So in order to measure the speed the time between pulses are measured and used to calculated the frequency, which then can be used to calculate the speed. The regulations are done each time a new measurement of speed is acquired, since there is no point in doing regulation based on a old value. This is done by inserting the current speed together with the current sampling time, time between speed updates, into the PID-regulator. In this way the PID-regulator will behave in a correct way even if there isn’t a fixed time between regulations. This due to the fact that the PID-regulator calculates the integral and derivative error based on the sample time. So even if the sample time varies, the calculations will be correct.
4.1.4 Load control

The load control object also includes a PID-regulator object that is used in order to regulate the pulse-width sent to the leg of the converter that has the load connected. This is regulated based on the current voltage over the converter and the desired voltage. These regulations are done at a fixed time interval and is controlled by the status monitor object.

4.1.5 AD-converter

The purpose of the AD-converter object is to set up the AD-converter to collect information from all of its 8 channels and store the most recent information. This collection is set up to run at a 32kHz interval.

4.1.6 Status monitor

The status monitor object runs at a specified time interval and collects and monitors; the voltage over the converter, the currents through the U, V and GND connection of the converter, the temperature of the board and the speed of the motor. This object can be used to perform different tasks depending on the status of the bridge, for example every time it runs it sends the voltage over the converter to the load control object and tells it to make regulations based on that.

4.1.7 PID

The PID object is an implementation of the PID algorithm explained in chapter 2 section 2.11. You setup the object with a proportional constant $K_p$, a integral constant, $K_i$, a derivative constant, $K_d$, a sampling period, $T_m$, and a high- and low-limit for the output of the controller. The derivative constant, $K_d$, can and will be set to zero, resulting in a PI controller which is simpler and easier to calibrate than a PID controller. The reason to limit the output is that the output should be sent to the motor control object as a pulse-width and the pulse-width that is allowed has certain limits. It also helps to prevent wind-up of the integral part of the PID. Because the integral error should not increase if the limit of the output is reached. By being able to send the sampling period, $T_m$, to the PI controller each time a sample is taken, it is possible to have correct calculations of the integral error even though the sampling period isn’t fixed.

4.2 LabVIEW software

LabVIEW™ is a software by National Instruments® that is designed to provide a graphical programming environment that can be used to develop advanced measurement,
test and control systems in an intuitive way, using graphical icons and wires to make the program resemble a flow chart.

Since most of the work done on the test-bench was to redesign the hardware, the decision was made to use the same implementation in LabVIEW™ as for the old test-bench[2], only making minor modifications if needed in order to have a working test-bench.
5.1 The board

5.1.1 Assembly

The board took quite some time to build since it was soldered by hand and consisted of almost 300 parts, most of them surface mounted. In figures 5.1, 5.2 and 5.3 the final board can be seen. Figure 5.1 shows the bottom side of the board where the MOSFETs of the three legs of the bridge are clearly visible at the top. Figure 5.2 shows the top side of the...
board where for example the large decoupling capacitors and the microcontroller (large black square) can be seen. The board is mounted on a large heat sink which is mounted on a modified lid of a metal box. In this way the board and all of its components will end up on the inside of the metal box and the heat sink on the outside.

Figure 5.2: Top view of the converter board, mounted on the heatsink together with the lid of the box.

In figure 5.4 the front view of the box is shown. As seen the box has two switches, one to turn on the supply for the microcontroller and other logics, and one to turn on the supply for the bridge side of the MOSFET drivers. In this way you can easily turn off just the bridge that is controlling the motor, but still be able to communicate with the microcontroller. Also visible in the same figure is the 12–48V supply connections for the MOSFET drivers (left side) and the 5–48V supply connection for the microcontroller and other logics (right side). The reason why there’s only one ground connection (GND) is that this connection is used as a separate ground for the microcontroller and the other logics. While the supply for the MOSFET drivers share the same ground as the normal voltage source connected over the bridge, in this case the batteries.
Figure 5.3: Side view of the converter board, mounted on the heatsink together with the lid of the box.

Figure 5.5 shows a side view of the box. The connections that are visible are the output of VDD(5V) and the connection from the outside to the EINT1 of the microcontroller. These two connections are used for the optical sensor in place in order to measure the speed. The VDD connection acts as the supply for the optical sensor and the EINT1 is connected to the output of the sensor. The speed sensors ground on the other hand has to be connected to the same ground connection as the microcontroller, the GND connection seen in figure 5.4. The connections to the bridge part of the board are on top of the heat sink as can be seen in figure 5.6 and figure 5.7.
Figure 5.4: Front view of the box for the converter board, showing power connections and switches for turning the microcontroller and the bridge on/off.

Figure 5.5: Side view of the box for the converter board, showing connections for the speed sensor and VDD output.
5.1. The board

Figure 5.6: View of the connections to the bridge.

Figure 5.7: Cables connected to the bridge.
5.1.2 Testing

Everything was soldered on to the board and then the testing started.

PWM signal problem

The first thing that was tested was the PWM functionality of the board in order to make sure that the PWM signal goes through the drivers and reaches the U, V and W outputs of the bridge. Right from the start there were problems with this. Only the W channel had a good output and the two other channels U and V had a really distorted signal on the output. After intensive troubleshooting, measuring the signal at different points on the board on its way to the output, it was found that the distortion was added somewhere close to the output. Analyzing the circuit the source of the problem was found after a while. Not mentioned earlier the board also included a high speed sigma-delta converter for doing high speed AD-conversion, in order to do faster measurements of the currents at the output of the U and V leg of the converter. The schematic for these can be seen in appendix D. When building the board these part were included even if there existed no plan to use them. However during testing the above problems were noticed and the source was after intensive troubleshooting found to be the high speed AD circuit. The reason for the problem was not found but since there existed no plan to use that circuit, the decision was made to remove some of its parts in order to shut it down. This was done mainly in order to save time and not get stuck searching for a problem that wasn’t going to effect the actual application.

Voltage measurement problem

When testing the voltage measurement circuit it was noticed that the modifications made to it was not enough and the circuit was not able to measure voltages above 36V. This happened because when the modifications were made it was not taken into consideration that the LM358D operational amplifier will saturate and not be to utilize the full voltage range of 3.3V. This meant that the operational amplifier would be saturated well before an input of 41V, which was needed to be measured. Considering this and since everything was already mounted, an easy solution was needed for this problem. The best solution found was to solder on an extra 56kΩ resistance in parallel with the existing 56kΩ resistance R36, can be seen in figure 5.8. This will create a combined resistance of 28kΩ instead of 56kΩ, which result in less of the voltage being measured ending up at the positive input of operational amplifier and in that way a wider range can be measured before the operational amplifier saturates. However this also means that the precision in the measurement goes down since small changes in the voltage to be measured will be even smaller at the input now than before. But this is a necessary modification since there is a need to be able to measure voltages of 41V and above.
5.1. The board

Figure 5.8: Modified voltage measurement.

**Speed sensor problem**

The speed measurement should not have been a problem, but when the testing of the motor started it was noticed that the optical sensor installed was broken and had to be replaced. Luckily a new sensor was found and the small circuit needed for its operation can be seen in figure 5.9. Notice that this circuit is designed so that the output will be high if light hits the sensor and low if it doesn’t. The sensor installed on the test-bench can be seen in figure 5.10.

Figure 5.9: Optical sensor circuit for Speed measurement.
Figure 5.10: The speed sensor installed on the test-bench.

Figure 5.11: The speed sensor connection to the box.
5.2 The test-bench

5.2.1 Assembly

First the three 12V batteries were connected in series in order to provide the correct voltage. Also a circuit breaker was installed so that the batteries can be disconnected without having to remove a connector from one of the terminals of the batteries. This setup can be seen in figure 5.12. The circuit breaker is installed at the positive terminal of the circuit and the red cable seen leaving the negative terminal, the terminal which has a black cable connected to it, is in place in order to provide a ground connection for the load.

![Figure 5.12: Batteries connected together in series and with an installed circuit breaker.](image)

Then the load, the DC motor and the batteries were connected to the bridge as seen in figure 5.13 and figure 5.7.
The internal combustion engine was connected to the DC motor with the use of a special joint. This can be seen in figures 5.14 and 5.15.

Figure 5.14: The joint between the DC motor and the internal combustion engine.
5.2. The test-bench

In figures 5.16 and 5.17 the complete test-bench can be seen.

Figure 5.15: The DC motor connected to the internal combustion engine.

Figure 5.16: Rear view of the test-bench.
5.2.2 Testing

For the test of the test-bench the boards voltage for the MOSFET drivers and the microcontroller and other logics was supplied with a separate voltage supply. This in order to not have distortion from the motor side of the circuit at the control side and also to be able to limit the current just in case something goes wrong. The motor however was supplied from the batteries. The LabVIEW software was not used for the tests, since we wanted to have more control and the software written in LabVIEW hadn’t been modified for our hardware. But any computer running a serial terminal program, for example Hyperterm for Windows®, could be used. What was used was a laptop running a terminal program called Realterm, this because this laptop also had the necessary software needed in order to compile code and program the microcontroller. The complete setup can be seen in figure 5.18.

The main tests that were done consisted of trying to start the internal combustion engine with the DC motor and also to test if the DC motor is able to regulate the speed of the internal combustion engine even if the internal combustion engine is trying to accelerate. The internal combustion engine started without any problem and the DC motor was able to keep the desired speed even if the internal combustion engine was trying to accelerate. The DC motor was even so strong that the internal combustion engine stopped if it was trying to accelerate too much. Also measurements were done at the connection going from the bridge to the DC motor and comparing these measurements to the simulated ones they look very much alike. In figure 5.19 a picture of one of the measurements can be seen and in figure 5.20 the simulated version.

Figure 5.17: Front view of the test-bench.
5.2. The test-bench

Figure 5.18: The test-bench.

Figure 5.19: The signal at the output of one of the connections from the bridge to the DC motor.
Figure 5.20: The simulated signal at the output of one of the connections from the bridge to the DC motor.

Problem

During the first tests a fairly low speed was used, 1500RPM, and there was no problem. But when the speed to keep was increased to 1800RPM and the internal combustion engine was trying to accelerate, the joint between the two motors was damaged. This joint simply wasn’t strong enough to handle the force or the vibrations that was put on it. In figure 5.21 the damaged joint can be seen. The rubber placed between the metal parts of the joint actually got so hot that it melted a little bit.
Figure 5.21: The damaged joint between the DC motor and the internal combustion engine.
Now that we have finished the task, we have to see if the initial purpose has been achieved. The work specification said that we should build new control and power electronics for the test-bench. We made this new control and we can say that power electronics didn’t fail in our test. We did measurements of voltage and current in the board and we can say that it was very similar to the values predicted in our simulations.

The experimental PID control worked in a correct way. The answer of the system was fast enough and we could only see some small oscillation in the speed value. We think that the discontinuous movement of the internal combustion engine produced this phenomenon.

We could control the speed of the DC machine acting as a motor and for this reason; we could start the internal combustion engine. Once the ICE was started the DC machine could brake by acting as a generator. Furthermore, when we accelerated the ICE, the DC motor was able to increase the breaking torque in order to keep the reference speed. Consequently, we can say that the work specification was completed overall.

But if we look at the general purpose, we should have been able to measure the efficiency of the combustion engine. But we didn’t have time to integrate every measurement systems in LabVIEW™ and therefore we didn’t complete this task. However, maybe the program used in the old project would be enough, and maybe it would go fast and be very easy for someone familiar with LabVIEW™ to complete this last task.

6.1 Future work

For this reason we have to speak about the future work that has to be done in order to have a complete and useful test-bench. In addition to the LabVIEW™ program and maybe some small modification to the code on the microcontroller, it would be necessary to change the joint that was broken in the tests. It would be good to look for another type of joint, in order to not have the same problem again. Also it would be very helpful to
try to align the axis of the DC motor and the internal combustion engine. If both axes are aligned, the joint will suffer less heat dissipation and the specifications for it will have fewer restrictions. Misalignment of the axises might be the reason why the joint broke in the first place.

Finally, more tests should be done in order to verify that the test-bench is working in a correct way. We only reached 1800 RPM in our tests, but the test-bench should be able to handle speeds near to 7000 RPM.
APPENDIX A

Measurement of motor capacitance

The inside of a DC motor can be considered as an RLC-circuit just as the one seen in figure A.1.

Equation A.2 gives the resonance frequency of an RLC-circuit. By rewriting A.2 to A.3 the capacitance can be found if the resonance frequency, the inductance and the resistance is known.

\[ \omega = 2\pi f \]  
\[ \omega_0 = \sqrt{\frac{1}{LC} - \frac{R^2}{L^2}} \]

Figure A.1: RLC.
A small DC motor was setup and measurements was made on it. Figure A.1 shows the test-circuit for the first measurement. This measurement doesn’t include the capacitance that exists between the coil and the armature.

\[ C = \frac{1}{L\omega_0^2 + \frac{R^2}{L}} \]  \hspace{1cm} (A.3)

Figure A.2: First measurement.

The setup for measurement 2 can be seen in figure A.2 and includes the capacitance between the motor coil and the motor armature. A simplified circuit can be seen in figure A.4.
By measuring the voltage drop over the resistor R, the current can be calculated. The current is then used together with the voltage drop over the terminals to calculate the impedance of the RLC-circuit. This is done for a number of different frequencies in order to get the shape of the impedance curve. These measurement points are then used to make an approximation of the function that matches the curve. The function is then used to find out at which frequency the impedance is the highest. The point with the highest impedance is the resonance frequency. A plot of the impedance of measurement 1 can be seen in figure A.5 and a plot of the impedance of measurement
2 can be seen in figure A.6. Another way of finding the resonance frequency is to use an oscilloscope and look at the signal at the input of the motor. The voltage of this signal will vary with the impedance, higher impedance means higher voltage. The resonance frequency can be found by observing where the voltage is the highest.

Figure A.5: Impedance versus frequency of measurement 1.

Figure A.6: Impedance versus frequency of measurement 2.
The capacitance is then calculated by using equation A.3. $C_1$ is calculated from the resonance frequency found in measurement 1. $C_2$ is equal to $C_3$ and the capacitance calculated in measurement 2 gives the capacitance of $C_1$ in parallel with $C_2$ which means that $C = C_1 + C_2$. Since $C_1$ already is known $C_2$ can be found and $C_2$ is equal to $C_3$. The tables A.1 and A.2 shows the result of the measurements.

<table>
<thead>
<tr>
<th>Measurement 1</th>
<th>Observed</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance frequency</td>
<td>545.7kHz</td>
<td>537.2kHz</td>
</tr>
<tr>
<td>$C_1$</td>
<td>25.1pF</td>
<td>25.89pF</td>
</tr>
</tbody>
</table>

*Table A.1: Measurement 1.*

<table>
<thead>
<tr>
<th>Measurement 2</th>
<th>Observed</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance frequency</td>
<td>477kHz</td>
<td>475.2kHz</td>
</tr>
<tr>
<td>$C$</td>
<td>32.7pF</td>
<td>32.7pF</td>
</tr>
<tr>
<td>$C_1$</td>
<td>25.1pF</td>
<td>25.89pF</td>
</tr>
<tr>
<td>$C_2$</td>
<td>7.6pF</td>
<td>6.81pF</td>
</tr>
<tr>
<td>$C_3$</td>
<td>7.6pF</td>
<td>6.81pF</td>
</tr>
</tbody>
</table>

*Table A.2: Measurement 2.*
APPENDIX B

DC motor specifications

We will use the same DC motor than in the project "Fördjupningskurs i mekatronik - E7019E". In the figure B.1 we show the different characteristics of this motor.

Figure B.1: DC motor specifications.
With these data we can obtain the parameters that definite the model of the DC motor.

\[ R_a = \frac{24V}{175A} = 0.14\Omega \]  
\[ K_T = \frac{11Nm}{175A} = 0.063Nm/A \]  
\[ K_E \approx \frac{24V - 5A \cdot 0.14\Omega}{4200RPM \cdot \frac{2\pi}{60}} = 0.053 \frac{V}{\text{rad/s}} \]

For estimating the damping coefficient we can see in the characteristic curve of the figure B.1 that when the motor is running to 4200 RPM, all electrical torque is spending in overcoming the friction losses.

\[ K_T I = B \cdot w \Rightarrow B = \frac{5A \cdot 0.063Nm/A}{4200RPM \cdot \frac{2\pi}{60}} = 722\mu\text{Nm} \cdot \text{s} \]

The moment of inertia has been estimated to 135\(\mu\text{Kg cm}^2\), taking values of other similar motors. About the inductance, the DC motor has 2 ferrite cores in series with the motor for adding inductance to the DC motor. Putting these inductors into the circuit we will get a small current variation between PWM cycles. The unity Ferrite-DC motor has an inductance of 10mH. For getting this value we made a test where we applied a step of voltage to this body, putting a resistance in series with it for limiting the current. Measuring the time that the current needs for reaching the steady state, we can know the value of inductance because in a coil we know that \(\frac{dI}{dt} \cdot L = V\). According with the project ”Fördjupningskurs i mekanik - E7019E”, 6,1 mH of the total correspond to the ferrite cores.
APPENDIX C

Completed model for simulations

In this appendix we are going to show the simulation of the completed model that we have used for taken different decisions while we designed the circuit. In the figure C.1 we can see the schematic of Pspice-model. Only one sense of rotation was simulated, and for this reason, we only used a half-bridge for getting faster results.

We have got a lot of models of different parts that we have used in the real circuit, like MOSFETS, schottky diodes or the ultra-fast diode of the snubber net. By contrast, the model of the activation circuit of drivers was very slow and problematic due to convergence problems. For that reason, we used normal pulse voltage sources and a brake switch in the high-side with the same ON resistor as the MOSFET.

About the control of current, in this simulation the duty cycle have to keep the same value all time, while in the real design it can change thanks to the PID control. The only control that we could put in the simulation was the voltage control, with an OPAMP working as a comparator. When the voltage was bigger to 41 V, the OPAMP activated the transistor in the power resistor leg, which had a fixed duty cycle too. About the results, when the current is negative it means that the element is sending energy to the circuit, while if it´s positive the element is receiving energy from the circuit.
Figure C.1: Schematic of the design.
Figure C.2: Speed in radians per second with a duty of 0.35 in the high-side transistor.

Figure C.3: Current in the DC motor (Duty of 0.35 in the high-side transistor).
In figure C.5 we can see a sudden torque rise which is produced by the combustion engine start-up.

Figure C.4: Current in the Battery (Duty of 0.35 in the high-side transistor).

Figure C.5: Total torque in the axis (Duty of 0.35 in the high-side transistor).
Figure C.6: Schematic of the design with turn-off snubber (Finally not implemented).
Appendix D

High speed AD-converter

Figure D.1: High speed AD circuit.

The high speed AD-converter circuit consists of two AD7401 sigma-delta converters from...
Analog Devices and a quad 2-input NAND gate called MC74AC00. These can be seen in figure D.1. There is also two special voltage regulators named HT7550 from HOLTEK, one for each AD7401, that supplies them with a very stable supply voltage of 5V. These can be seen in figure D.2.
REFERENCES


