

Master Thesis



Czech  
Technical  
University  
in Prague

**F3**

Faculty of Electrical Engineering  
Department of Cybernetics

## Development of a Hybrid Power Unit for Unmanned Aerial Vehicles

Bc. Štěpán Riss

Supervisor: Ing. Jiří Zemánek  
May 2017



## DIPLOMA THESIS ASSIGNMENT

**Student:** Bc. Štěpán R i s s

**Study programme:** Cybernetics and Robotics

**Specialisation:** Robotics

**Title of Diploma Thesis:** Development of a Hybrid Power Unit for Unmanned Aerial Vehicles

### Guidelines:

The goal of this thesis is to develop, build, and test a control system for a hybrid power unit (consisting of internal combustion engine, generator, and battery) for unmanned aerial vehicles.

- Review solutions reported in the literature or available on the market.
- Analyze requirements for the system - consider time evolution of power consumption, the behavior of the battery, etc.
- Design and build an embedded system for power management that will be compatible with onboard equipment.
- Create a basic mathematical model of the power system.
- Design and validate a control algorithm that will meet the set requirements.

### Bibliography/Sources:

- [1] P. Antsaklis, Anthony N. Michel: A Linear Systems Primer, Springer Science & Business Media - 2007
- [2] Geoffrey Brown: Discovering the STM32 Microcontroller, 2016
- [3] Joachim Schömann: Hybrid-Electric Propulsion Systems for Small Unmanned Aircraft, 2014

**Diploma Thesis Supervisor:** Ing. Jiří Zemánek

**Valid until:** the end of the summer semester of academic year 2017/2018

L.S.

prof. Dr. Ing. Jan Kybic  
**Head of Department**

prof. Ing. Pavel Ripka, CSc.  
**Dean**

Prague, February 17, 2017



## Acknowledgements

I would like to thank my thesis supervisor Ing. Jiří Zemánek for his professional leadership, advice on my work and for his patience with me. I would also like to thank Ing. Lukáš Kostka for his pleasant co-operation on this project. Finally, I must express my very profound gratitude to my parents and my family for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of writing this thesis.

## Declaration

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instructions for observing the ethical principles in the preparation of university theses.

In Prague, 26. May 2017

## Abstract

This work deals with the development of an control embedded system for hybrid-electric power unit for UAVs. This control embedded system is compatible with the onboard system of Flydeo UAVs. The embedded system controls the power flow within the hybrid unit and ensures sufficient power output. As a part of the thesis a mathematic model of the proposed hybrid-electric system has been created and based on this model a controller has been designed. This work presents the manufactured embedded system and experiments that have been performed with this device.

**Keywords:** hybrid-electric, UAVs, control, model, development, manufacture

**Supervisor:** Ing. Jiří Zemánek

## Abstrakt

Práce se zabývá vývojem vestavěného systému, který slouží k řízení hybridní pohonné jednotky pro bezpilotní prostředky. Tento vestavěný systém je kompatibilní se systémem, které používá firma Flydeo ve svých bezpilotních letounech. Součástí této práce je také vytvoření matematické modelu představené hybridní jednoty a na základě tohoto modelu navržení řídicí systém. Tato práce představuje vyrobené zařízení a experimenty, které byly pomocí tohoto zařízení provedeny.

**Klíčová slova:** hybridní, bezpilotí prostředek, řízení, model, vývoj, výroba

**Překlad názvu:** Vývoj hybridní pohonné jednotky pro bezpilotní jednotky

# Contents

<b>1 Introduction</b>	<b>1</b>	<b>6 Conclusion</b>	<b>41</b>
<b>2 Hybrid systems for UAVs</b>	<b>3</b>	<b>Bibliography</b>	<b>43</b>
2.1 Electric propulsion system . . . . .	3	<b>A Scheme of the embedded system</b>	<b>45</b>
2.2 Fuel propulsion system . . . . .	3	<b>B Layout of the embedded system</b>	<b>47</b>
2.3 Hybrid-electric propulsion system	4	<b>C CD content</b>	<b>51</b>
2.4 Existing solutions . . . . .	4		
Hybrix . . . . .	4		
Airborg™ H8 10K . . . . .	5		
B32i UAV EFI Engine . . . . .	6		
<b>3 Proposed hybrid system</b>	<b>7</b>		
Internal combustion engine . . . . .	7		
Lambda sensor . . . . .	8		
Generator . . . . .	9		
Regulator and rectifier . . . . .	9		
Ignition . . . . .	10		
Battery managment . . . . .	10		
Battery . . . . .	10		
Control system . . . . .	11		
<b>4 Power management system</b>	<b>13</b>		
4.1 Requirements . . . . .	13		
Measure and switch high current . .	13		
Switch ignition . . . . .	14		
Measuring revolutions of the combustion engine . . . . .	14		
Control servo of engine throttle . .	14		
Communication - CAN, UART . . .	14		
4.2 Hardware . . . . .	14		
4.2.1 CPU . . . . .	14		
4.2.2 Communication . . . . .	15		
4.2.3 Measuring and switching . . .	16		
4.2.4 Ignition . . . . .	17		
4.2.5 Engine throttle . . . . .	17		
4.2.6 Power supply . . . . .	17		
4.2.7 Realization . . . . .	19		
4.3 Software . . . . .	19		
4.3.1 Configuration peripherals . . .	21		
4.3.2 Software functions . . . . .	21		
4.4 Communication . . . . .	24		
<b>5 Control</b>	<b>29</b>		
5.1 Modelling of the controlled system	29		
Full hybrid system model . . . . .	34		
5.2 Controlling . . . . .	36		

## Figures

<p>2.1 Configuration on hybrid-electric system [9]: a) Series b) Parallel c) Serial-parallel ..... 4</p> <p>3.1 Simplified scheme of the hybrid-electric system ..... 7</p> <p>3.2 Development apparatus of the hybrid system ..... 8</p> <p>3.3 Full H-bridge ..... 10</p> <p>4.1 Basic hardware scheme ..... 15</p> <p>4.2 Scheme of measuring and switching of current from generator and battery 16</p> <p>4.3 Scheme for level shift from 3.3V to 5V ..... 18</p> <p>4.4 Scheme of power subsystem .... 18</p> <p>4.5 The basic layout of the device .. 19</p> <p>4.6 Front view of the embedded system ..... 20</p> <p>4.7 Back view of the embedded system ..... 21</p> <p>4.8 Pinout of the processor ..... 22</p> <p>4.9 Flowchart of software for processor ..... 23</p> <p>4.10 Simulink CAN-Bus implementation ..... 25</p> <p>4.11 Screenshot of the application for UART communication ..... 26</p> <p>5.1 Scheme of the model ..... 30</p> <p>5.2 Measured data and fitted line .. 31</p> <p>5.3 Expected dependency of RPM on the applied momentum ..... 32</p> <p>5.4 Measured and fitted data ..... 33</p> <p>5.5 Dependency of the speed of the engine and the brake momentum for each throttle ..... 33</p> <p>5.6 Fitted real momentum for 20% of the throttle ..... 34</p> <p>5.7 Dependency of output momentum and the brake momentum for each throttle ..... 35</p> <p>5.8 Fourier transform on the measured signal ..... 35</p> <p>5.9 Full hybrid system model ..... 36</p> <p>5.10 Comparison between the modelled and measured signal ..... 36</p>	<p>5.11 Implemented controller for speed regulation ..... 37</p> <p>5.12 Control system ..... 38</p> <p>5.13 Current consumption during the flight ..... 39</p> <p>A.1 The first sheet of the scheme... 45</p> <p>A.2 The second sheet of the scheme 46</p> <p>B.1 Top layer ..... 47</p> <p>B.2 Second layer ..... 48</p> <p>B.3 Third layer ..... 48</p> <p>B.4 Bottom layer ..... 49</p>
--	---



## Tables

4.1 List of CAN messages . . . . .	26
4.2 List of UART commands . . . . .	27



# Chapter 1

## Introduction

The unmanned aerial vehicle (UAV) is an aircraft without a human pilot aboard. There are many types and forms of UAVs, but this work is primarily about UAV quadcopter. Quadcopters are commonly used for a variety of applications. From military purposes such as surveillance, monitoring or mapping to recreation purposes like taking aerial video and photography or quadcopter racing. There are plenty of advantages and reasons why quadcopters are used so commonly. First of all, they are relatively cheap and due to their simple mechanical design, they can be built by amateurs. The next advantage is that, since they have begun to be popular, platforms for developing quadcopters have started to expand.

Quadcopters, like others UAVs, have several drawbacks. Apart from the noise from the propellers, there is a critical problem with the energy storage onboard. The general majority of quadcopters uses the battery as their power supply. The better quality class of the quadcopters with a battery source of energy can last in the air for half an hour, the best ones up to 60 minutes. This fact drastically decreases their value and their usability. Because of this problem, an alternative power source needs to be found.

Using gasoline as the primary energy source seems the best way to replace the batteries. Gasoline has an energy density of 12 kWh/Kg and the li-ion battery has between 160-230 Wh/kg [9]. To compute a rough estimation of electrical energy that can be converted from the gasoline, the following equation is used.

$$D = D_{\text{gasoline}} \cdot e_{\text{IC}} \cdot e_{\text{gen}} \quad (1.1)$$

Where  $D_{\text{gasoline}}$  is the energy density of gasoline,  $e_{\text{IC}}$  is the efficiency of the internal combustion engine and  $e_{\text{gen}}$  is the efficiency of the generator. Constants for estimation were used from current combustion engine and generator technologies. The parameters that are used for estimation [6] [4]:

$$D_{\text{gasoline}} = 12 \text{ kWh/Kg}, \quad e_{\text{IC}} = 0.25, \quad e_{\text{gen}} = 0.90 \quad (1.2)$$

$$D_{\text{gasoline}} = 2.7 \text{ kWh/Kg} \quad (1.3)$$

After reducing the energy density of gasoline by thermal and mechanical losses, the calculated energy density overcomes the battery many times.

The weight of the unit that transforms gasoline into electric energy has to be taken in a consideration. This weight always depends on the combustion engine and generator technologies used.

The assignment of this thesis came from company the Flydeo<sup>1</sup>. Flydeo is a small Czech company, which focuses on the development and manufacturing of UAVs. The final hybrid unit should be installed in the one of the quadcopters that Flydeo produces. The photo in Figure 1.1 shows the X8 drone. This model is focused on long time flight and after being developed should be equipped with the hybrid power unit.



**Figure 1.1:** Photo of the Flydeo X8 drone <sup>2</sup>

The first part of the text presents existing hybrid power units and the proposed hybrid system. For the controlling of the proposed hybrid unit, an embedded system needs to be developed. This embedded system is required for testing and measuring the power capabilities of the hybrid system as well. The design and manufacture of this device constitutes the second part of this thesis. The last part of this work is to create a basic mathematical model of the power system and design a control algorithm that will meet the set of requirements.

Following this introduction, Chapter 2 summarizes state-of-the-art hybrid power units. Furthermore, the benefits and drawbacks of existing solutions are discussed in Chapter 2. Chapter 3 presents the proposed hybrid system and its components. Chapter 4 describes the design and manufacture of the embedded control system. The modeling of the hybrid system and proposed control system is developed in Chapter 5.

---

<sup>1</sup><http://flydeo.com/>

## Chapter 2

### Hybrid systems for UAVs

The electric propulsion system and propulsion system with a combustion engine for UAVs are presented in this chapter, then a basic idea of combining these two systems in the hybrid-electric propulsion system and its possible configurations. The advantages and drawbacks of the different solution are discussed. At the end of this chapter, the existing solutions of hybrid-electric systems are presented.

#### 2.1 Electric propulsion system

This system is based on batteries and electric motors. Batteries are used to store energy, and electric motors drive propellers. A form of a flight controller and electronic speed controller are placed on the vehicle if needed. The main advantage of this system is very fast response time for throttle input and very precise thrust control. Another benefit is that the electric propulsion system is quiet and clean. The propulsion does not produce noise emissions, except for propeller noise. The electronic components of this system are not complex, in the sense of mechanical construction, thus more reliable. The main drawback of the electric propulsion system is the energy density of the batteries, which limits flight time. Another disadvantage of the batteries is that batteries require an amount of time to recharge when drained. Nevertheless, the main benefit of this is system is the efficiency of electro motors. Because of the prevailing advantages, electric propulsion is commonly used for small UAVs.

#### 2.2 Fuel propulsion system

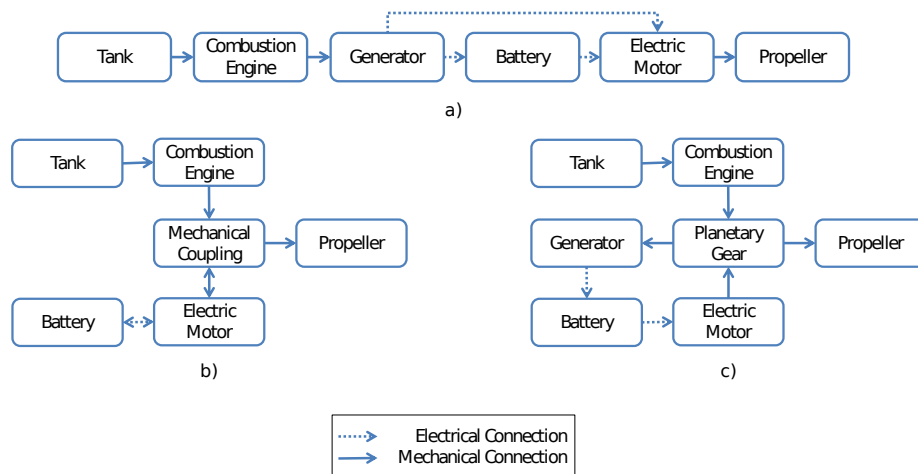
The power source of the fuel propulsion system is liquid, which holds a significant amount of energy. In most cases, petrol or diesel is used for energy storage. Energy from the fuel is released through an internal combustion engine (ICE). The combustion engine is directly attached to the propellers and drive the vehicle. The main disadvantage of a combustion engine is poor thermal efficiency, because the engine have to operate outside its optimal operation range and the response time for the throttle input of combustion engines is poor compared to electric motors. ICE is difficult to setup due to its

mechanical complexity and therefore managing this system gets complicated.

## 2.3 Hybrid-electric propulsion system

This system is a combination of the electric propulsion system and the propulsion system with a combustion engine. The hybrid-electric system suppresses the drawbacks of the above-listed systems by using fuel as the main power source, but an electric motor as a propeller driver. Power density of the gasoline is much higher than the battery and control strategy can keep the internal combustion engine (ICE) within an optimal fuel efficiency operating region [10].

The basic three configurations are presented and discussed in [9]. Each arrangement has its specification and is suitable for different applications.



**Figure 2.1:** Configuration on hybrid-electric system [9]: a) Series b) Parallel c) Serial-parallel

## 2.4 Existing solutions

There are only a few solutions of this hybrid-electric unit for UAVs. They are presented in this section with their benefits and their drawbacks.

### Hybrix

Hybrix is a project of the Spanish company Quaternium<sup>1</sup>. Hybrix is the first hybrid-electric multirotor UAV. This vehicle can stand in the air for two hours with maximum takeoff weight of 20 kg.

That long flight time is excellent, but this device has two main drawbacks. First of all, the device has only four propellers. That means that if one of these propellers does not work, the whole vehicle will crash almost uncontrolled.

<sup>1</sup><http://www.quaternium.com/portfolio/hybrix-uav/>



**Figure 2.2:** Hybrix quadcopter by Quaternium<sup>1</sup>

Secondly, in the footage of Hybrix it is clear that the combustion engine in the device does not have any intelligent control of the throttle. When there are peaks in power consumption, the throttle of the engine is very quickly changed. That leads to wasteful fuel consumption and decreases the engine lifespan.

### ■ Airborg™ H8 10K

This device comes from the US company Top Flight<sup>2</sup>. The parameters of this vehicle look very good; 3 hours with up to a 4 kg payload, 1 hour with up to a 15 kg payload.



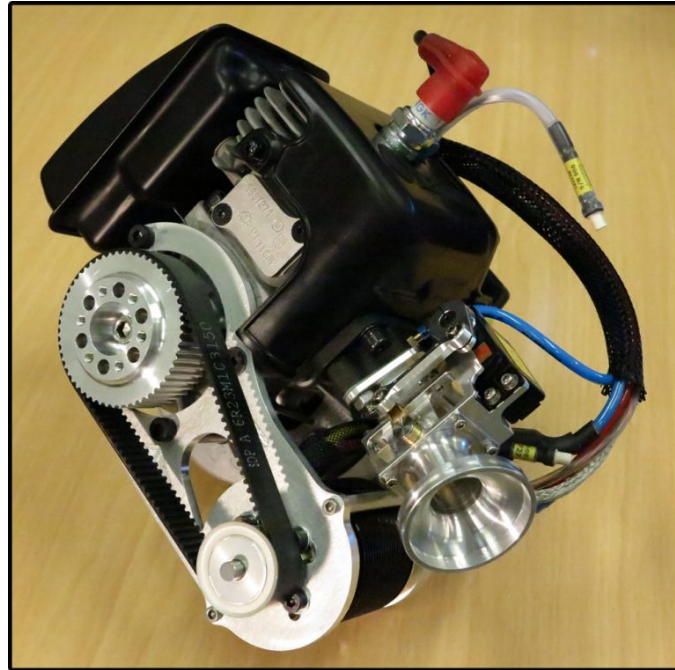
**Figure 2.3:** Airborg™ H8 10K with Top Flight Hybrid-Power System<sup>2</sup>

Unfortunately, the only source of information about this device comes from the Top Flight website and there is no other evidence that the mentioned parameters are real. There is only footage from the Top Flight, which does not prove anything. Probably this device is made up and serves only to draw attention to the company.

<sup>2</sup><http://www.tflighttech.com/products/airborg-h8-10k-with-top-flight-hybrid-power-system.html>

### ■ B32i UAV EFI Engine

The B32i is a 2-stroke industrial engine fitted with a 2 kW generator for use in hybrid electric vehicle applications. This unit comes from the US company Power4Flight<sup>3</sup>.



**Figure 2.4:** B32i Electronic Fuel Injected UAV Engine <sup>3</sup>

The main advantage of this system is a highly efficient generator and electric fuel injection. On the other hand, the energy yield from the gasoline is not high. With this unit, gasoline has electric energy density of 1818.18 kW h/kg. In the introduction, I have shown that the electric energy density should go up to 2700 kW h/kg. This unit also does not include any form of power control and two-stroke engine causes a great vibration.

---

<sup>3</sup><http://power4flight.com/>

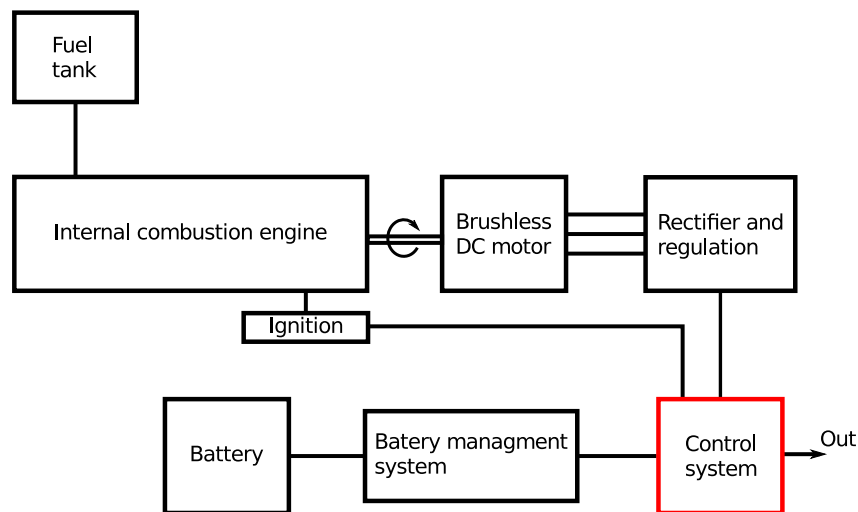


## Chapter 3

### Proposed hybrid system

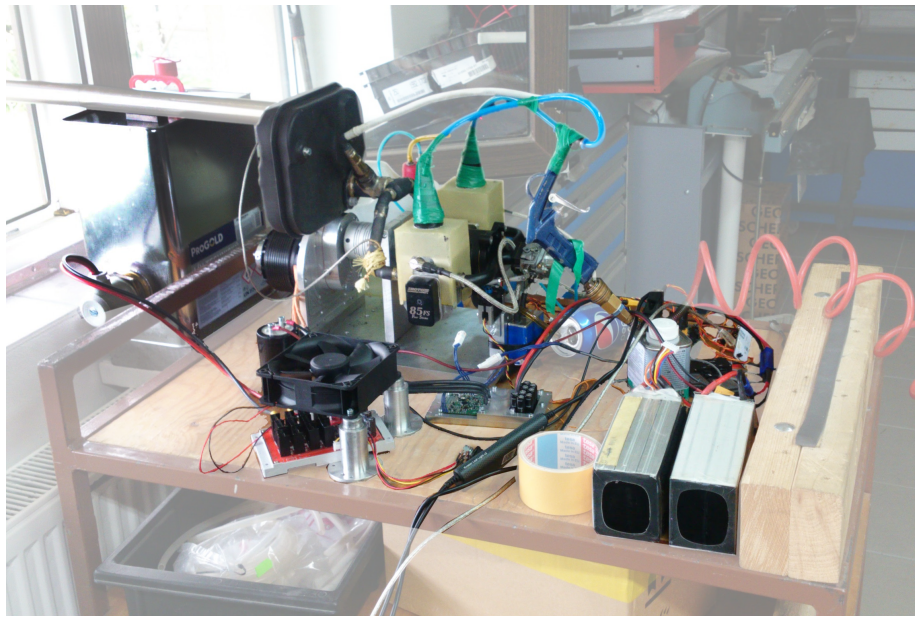
This chapter describes the proposed hybrid system and its components. The proposed hybrid system should be a full replacement of the battery for the UAV. The new system should significantly increase flight time and instead of time consuming charging of the battery, energy would be added only by refueling the tank.

The scheme in Figure 3.1 shows the basic the components of hybrid-electric system and the relations between them.



**Figure 3.1:** Simplified scheme of the hybrid-electric system

The basic idea of this hybrid-electric solution is to generate electric power by the generator and rectifier to the specified voltage level value. The battery is connected to the generator in parallel. The battery covers power peaks, that can not be handled by the power generated from the generator.



**Figure 3.2:** Development apparatus of the hybrid system

## Internal combustion engine

The internal combustion engine is a critical component of the hybrid-electric unit. The combustion engine converts the chemical energy of gasoline into mechanical energy and thermal energy. The usual efficiency of internal combustion engines is about 25% [6].

Two types of combustion engine were tested. First, a smaller single piston, two-stroke engine and then a two piston, four-stroke boxer engine [3]. The single piston engine was shown not to be a good candidate for the core component of the unit. This engine provided permanent electric power of 900 W with 5200 RPM, and fuel consumption was 15 g/min. That gives only 1 kWh/kg. In addition to the poor efficiency of the engine, there was also great vibration from the engine.

The four-stroke engine test has shown much better results. The four-stroke engine was able to generate 2 kW of electric power. The fuel consumption with 2 kW generated power was 17 g/min. That gives 1.96 kWh/kg, which is a much better result than by a two-stroke engine. After setting up a lambda sensor and calibration of a carburettor, output energy efficiency climbed to 2.1 kWh/kg due to more balanced fuel mixture. The four-stroke boxer engine also does not generate such strong vibration as the two-stroke engine. The designation *boxer* indicates that pistons go directly into each other and thereby this eliminates most of the vibrations. This four-stroke engine can run with speed from 1500 RPM to 6000 RPM.

## Lambda sensor

The lambda sensor measures the proportion of oxygen in the gas or liquid. In our case, the output gases from the engine. By the readings from the sensor, we can tune the carburettor to an ideal mixture of air and fuel. A lean fuel mixture can cause an engine to have a surge or miss at idle, and part throttle stumble on acceleration, leading to engine overheating and lack of power. A rich fuel mixture can cause an engine to foul the spark plugs, and also lack power or run sluggishly. For our purposes we use lambda sensor Bosch LSU4.9<sup>1</sup> with ALM (Accurate Lambda Meter) from the company Ecotrons<sup>2</sup>. ALM communicates via a CAN-Bus, so there is no need for a special form of access to data from the sensor.

## Generator

The generator of the hybrid-electric unit transforms mechanical energy into electric energy. Also, it is used as a starter of the combustion engine. The generator is a brushless DC electric motor [1]. The primary requirements of the generator are that it has a compatible KV parameter with optimal revolutions of the combustion engine (optimal KV parameter means, that generator will generate desired voltage in the optimal operation range of the engine); the KV parameter indicates how many revolutions per minute will generate one volt on the output. For reason of stability and vibration suppression of the hybrid unit, the generator is connected to the engine via transmission that has a ratio of 1:2 and changes the direction of the rotation. That means that the generator speed is two times higher than the engine speed and axis of rotation of the generator and the engine are opposite, and shocks should cancel out.

## Regulator and rectifier

This embedded system manages the generator. The main purpose of this device is to start up the combustion engine and then rectify the generated voltage. Then, it can use an electric brake to generate an electric current with a voltage which is lower than the voltage on the battery. This device is composed of full H-bridge and a CPU. The H-bridge is an electronic circuit that enables switching voltage on phases of the generator to start the combustion engine.

Figure 3.3 shows a scheme of H-bridge. If the voltage is generated on the phases and rises above the voltage of the battery, the body diodes of the MOSFETs rectify the generated voltage, and a current starts to flow.

<sup>1</sup>[http://www.ecotrons.com/technology/bosch\\_lsu\\_49\\_is\\_superior\\_to\\_lsu\\_42\\_sensors/](http://www.ecotrons.com/technology/bosch_lsu_49_is_superior_to_lsu_42_sensors/)

<sup>2</sup><http://www.ecotrons.com/products/wideband-controller-alm-can/>

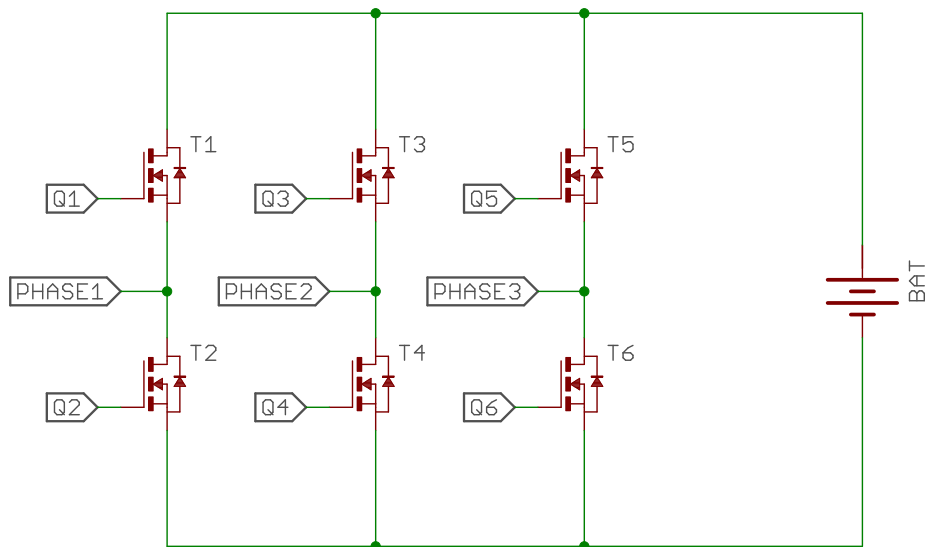


Figure 3.3: Full H-bridge

## Ignition

The ignition device is a built-in system, which generates a spark on the spark plug in the combustion engine. This system requires 5V for correct functionality. A signal will also go from this system to indicate rotation of the engine. This signal will be used for measuring RPM of the engine later on.

## Battery management

The battery management is important for this unit. The battery frequently discharges and charges, while the hybrid unit operates. Therefore, some form of battery cells monitoring has to be implemented. The battery cell monitoring system can provide protection from overcharging or over discharging. For the purposes of monitoring and balancing, a BQ76PL455A<sup>3</sup> device has been chosen. The BQ76PL455A is an integrated 16-cell battery monitoring and protection device. For development purposes the evaluation module BQ76PL455EVM<sup>4</sup> was used.

## Battery

The primary purpose of the battery in the hybrid-electric unit is to cover high current peaks [8]. The voltage on the battery also defines the maximal revolutions that the generator can achieve. When the generator generates a voltage higher than the voltage on the battery, the current starts to flow

<sup>3</sup><http://www.ti.com/product/BQ76PL455A>

<sup>4</sup><http://www.ti.com/tool/bq76pl455evm>

to the battery, and this current generates momentum and decelerates the generator (the engine).

## ■ Control system

The control system device should control the process and the connect all components. The main purpose is to control the throttle of the combustion engine based on the power consumption of the output system. This system should be able to measure the current flowing from the generator and the battery; then it should be able to communicate with all the other components of the hybrid unit and collect all information. The control system should send the measured data (generated current, current from the battery, speed of engine, voltage of the battery) to the onboard output system.



## Chapter 4

### Power management system

The process of designing and manufacturing is described in this chapter - from the list of operational requirements to the first functional prototype of hardware and software. The primary purpose and requirements for the embedded system are presented.

#### 4.1 Requirements

A list of requirements of the embedded system is presented. Most of the requirements are based on an onboard system of the company Flydeo. The primary purpose of this embedded system is to control and measure the power flow from the generator and battery. Therefore, the basic requirement of the system is to have some component for measuring the electric current and a possibility of controlling the power flow.

Other requirements of the system are:

- Switch ignition
- Measure revolutions of the combustion engine
- Control servo of engine throttle
- Communication - CAN, UART

All the requirements are described in detail below.

#### Measure and switch high current

The operation of the input voltage is between 30 V - 60 V and the embedded system has to be able to measure and switch up to a 45 A permanent load (100 A peaks). The embedded system should connect the output of the rectifier and battery and merge them into one output.





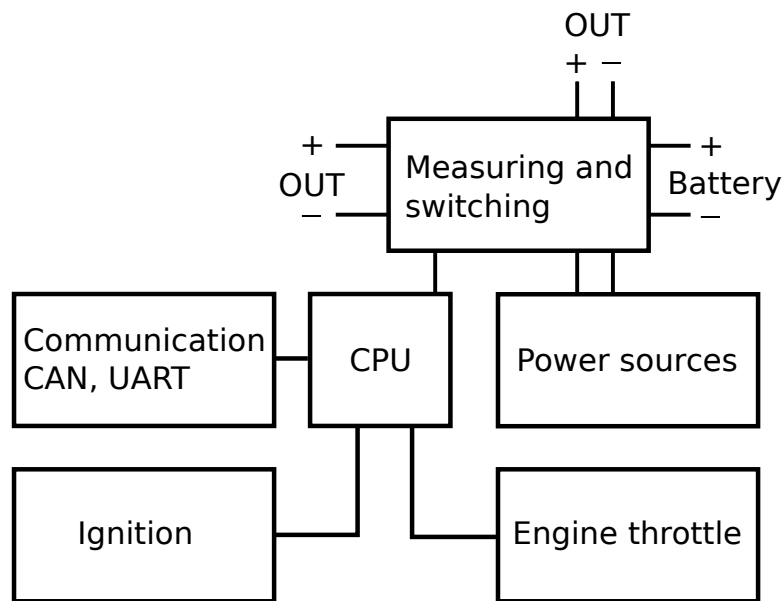


Figure 4.1: Basic hardware scheme

supply of 3.3 V is needed for this microprocessor.

#### 4.2.2 Communication

Communication is a crucial part of the device. Firstly, the embedded system communicates with other devices in the onboard system by the CAN-Bus, and secondly, it communicates with a PC by UART (universal asynchronous receiver/transmitter). Although the microprocessor STM32F303 has a special CAN periphery, I chose a stand-alone CAN controller MCP2515<sup>2</sup> for CAN communication. This controller is capable of transmitting and receiving CAN data frames. The main advantage is that the MCP2515 has two acceptance masks and six acceptance filters that are used to filter out unwanted messages, and thereby reduce the host MCU's overhead. The MCP2515 interfaces with microcontrollers via an industry standard Serial Peripheral Interface (SPI). Like a physical layer of the CAN-Bus periphery on the device is the SN65HVD230D<sup>3</sup>. This device meets all parameters (size, speed, operating supply).

For communication with the processor via UART I used the UART periphery of the processor, so I led wires from the processor to pinhead. The pinout of the UART is in an arrangement to be compatible with the FTDI cable.

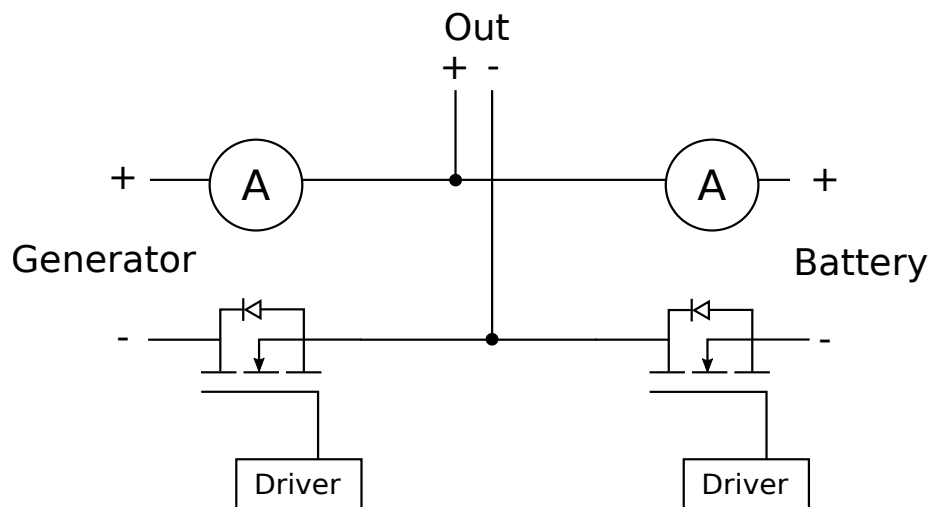
<sup>2</sup><http://www.microchip.com/wwwproducts/en/en010406>

<sup>3</sup><http://www.ti.com/lit/ds/symlink/sn65hvd232.pdf>

### 4.2.3 Measuring and switching

This subsystem is responsible for measuring and switching the current from generator and battery. The first task was to figure out measuring device. Because of its zero resistance and power loss, the hall sensor is the best way to measure high current. It is not as precise as measuring the current with a shunt resistor, but for current up to 100 A, the precision of hall sensor is satisfactory. Besides, measuring high current with shunt resistors is very inefficient. A device called ACS758ECB<sup>4</sup> meets the required parameters perfectly. The applied current flowing through its copper conduction path generates a magnetic field which the Hall IC converts into a proportional voltage. It means that from the measured voltage we can easily calculate the current flowing through the sensor.

N-channels MOSFETs provide switching of the generator and battery to output. After consultation with experts from our university, I decided to use Opti-MOS Power Transistors<sup>5</sup> on low-side switching. Low-side switching should minimize the risk of damaging the MOSFETs due to slow switching. To switch MOSFETs I used drivers<sup>6</sup>. This MOSFET driver requires at least 10 V to turn the MOSFET on. I have decided to drive them with 12 V for assurance.



**Figure 4.2:** Scheme of measuring and switching of current from generator and battery

<sup>4</sup><http://www.allegromicro.com/~media/Files/Datasheets/ACS758-Datasheet.ashx>

<sup>5</sup>[http://www.infineon.com/dgdl/Infineon-BSC014N06NS-DS-v02\\_01-en.pdf?fileId=db3a3043382e837301386ab95a521dcd](http://www.infineon.com/dgdl/Infineon-BSC014N06NS-DS-v02_01-en.pdf?fileId=db3a3043382e837301386ab95a521dcd)

<sup>6</sup><http://www.ti.com/product/UCC27512>

#### ■ 4.2.4 Ignition

The next periphery that has to be controlled by this device is the ignition of the combustion engine. The ignition requires 5 V for its operation. The ignition provides a spark in the combustion chamber, which ignites the fuel. To create this spark, high voltage has to be generated by the ignition. Because of this high voltage, I have decided to supply the ignition with galvanically separated voltage. High voltage generates electromagnetic noise and thanks to galvanic separation this noise will not pass to the device. Galvanic isolation serves as safety element as well. The ignition device mounted onto the combustion engine provides a signal, which gives a rising edge when the crank of the engine reaches the dead centre. This signal needs to be processed by the CPU and revolutions of the engine are computed. Due to the galvanic separation between the ignition and embedded system some optocoupler needs to be used for this signal. I have chosen ACPL-217<sup>7</sup> for this purpose.

The TPS2032<sup>8</sup> power distribution switch is connected in series with the isolated power source. This integrated circuit provides overcurrent protection for the ignition. When the output load exceeds the current-limit threshold a short is present, the TPS2032 limits the output current. TPS2032 has a pin with an overcurrent signal. This signal must pass through the ACPL-217 optocoupler before it proceeds to the CPU. If processor detects an overcurrent signal, the processor will disable the pin of the isolated power source.

#### ■ 4.2.5 Engine throttle

The throttle of the combustion engine is controlled by a servo motor. This servo motor is directly linked to the lever, which controls the volume of fuel injected into the engine. The servo motor requires 5 V for power supply and a control signal. This signal defines an angle of rotation of the shaft. Servo is controlled by standard PWM signal for servo motors. The signal is defined with 50 Hz and an impulse length from 1 ms (minimal angle of rotation) to 2 ms (maximum angle of rotation). The servo needs a different voltage level than used by the CPU. The signal for servo needs 5 V level while the CPU uses only 3.3 V level. Therefore, some scheme for level shifting needs to be used. The scheme for level shifting is presented in Figure 4.3.

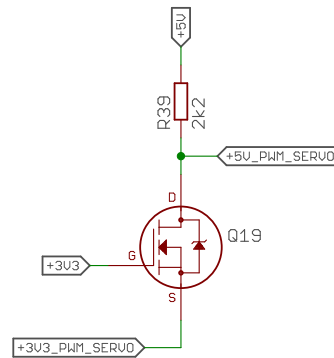
TPS2032 power distribution switch provides overcurrent protection for the servo power supply. Apart from overcurrent protection, the TPS2032 has an external pin for switching the device on and off. Both signals, overcurrent and enable, are at 5 V level. The circuit for voltage level shifting needs to be used to ensure voltage compatibility with the CPU.

#### ■ 4.2.6 Power supply

This subsystem manages the power supply for the device. The input voltage can be between 30 V - 60 V from the generator and the battery. The highest

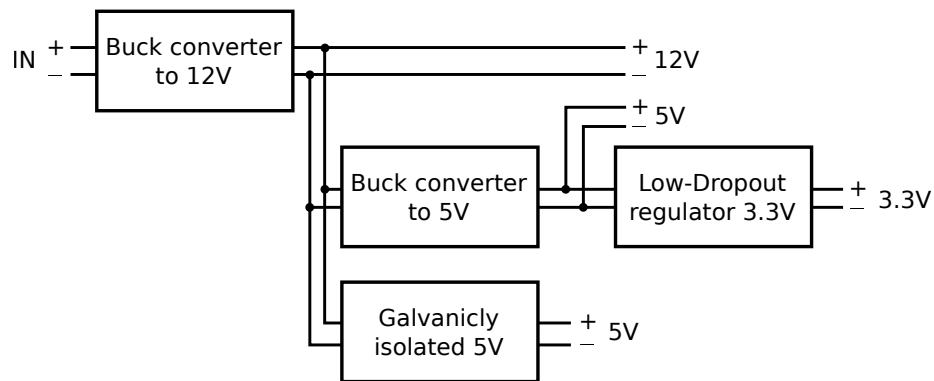
<sup>7</sup><http://terzo.acmesystems.it/download/datasheets/ACPL-217.pdf>

<sup>8</sup><http://www.ti.com/lit/ds/symlink/tps2032-q1.pdf>



**Figure 4.3:** Scheme for level shift form 3.3V to 5V

voltage required by the device is 12 V. This voltage is needed for MOSFETs driving. I have decided to use buck converter (step-down converter) for dropping down the input voltage to 12 V level. Then the device needs 5 V to operate with the servo motor. This voltage level is provided by the buck converter as well, but as input for this converter, the 12 V level is used. Another voltage level is 5 V but galvanically isolated. For galvanic separation I have chosen a TDN-5-0911WI<sup>9</sup> power source. This DC/DC converter takes voltage 12 V as input and generates 5 V at the output. One primary requirement was placed on this voltage source; it has to have an external pin for switching off and switching on the output. The last voltage used on the device is 3.3 V. 3.3 V is the voltage level of all logic units on the device. This level voltage is achieved by a TLV1117-33<sup>10</sup> low-dropout voltage regulator. These power supplies cover all the device's requirements. Figure 4.4 shows arrangement of the power supplies.



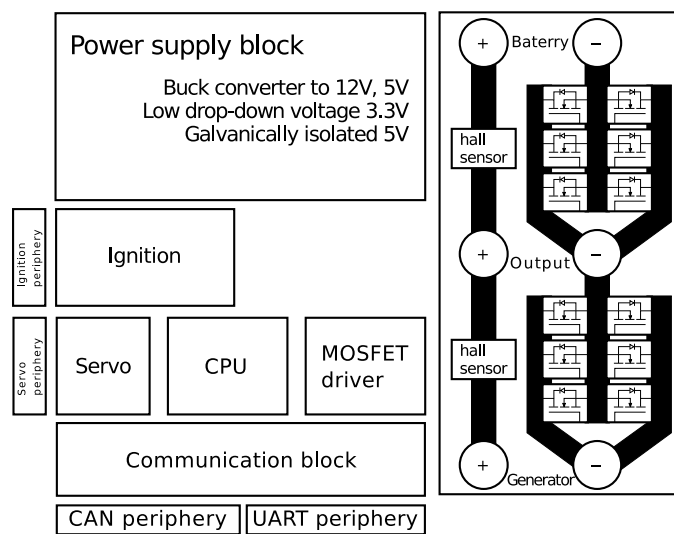
**Figure 4.4:** Scheme of power subsystem

<sup>9</sup><http://www.mouser.com/ds/2/687/tdn5wi-908534.pdf>

<sup>10</sup><http://www.ti.com/lit/ds/symlink/tlv1117-33.pdf>

## 4.2.7 Realization

Through the device can flow in a large current peak up to 100 A. This condition sets a particular requirement for the PCB (printed circuit board), and multiple problems have to be figured out. First of all, provide sufficient copper area to conduct permanently a current of 45 A. Next, ensure that electromagnetic interference is not transmitted to the logical part of the embedded system. The last problem in the context of high current is the cooling of the device, especially the cooling of the MOSFETs, which switch the generator and the battery. The MOSFETs can never have zero resistance between the drain and source. Therefore a negligible amount of heat is emitted when the high current passes.



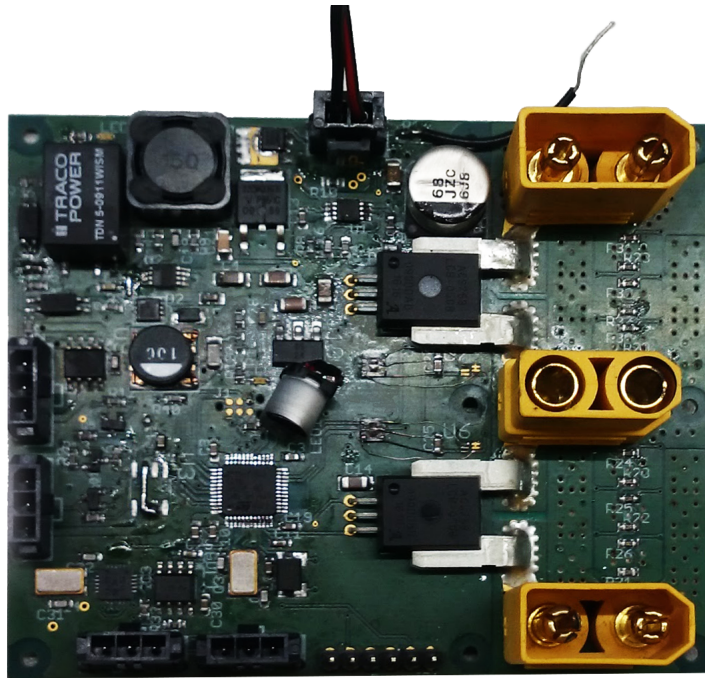
**Figure 4.5:** The basic layout of the device

Figure 4.5 shows the basic arrangement of the function block on the PCB. The four-layer PCB is used for the embedded system. A count of layers is derived from the balance of power demands, complexity and price. The designed layouts can be seen in Appendix B. I used the Eagle CadSoft<sup>11</sup> for the PCB design. The manufactured embedded system is shown in Figures 4.6 and 4.7.

## 4.3 Software

The embedded system is controlled by the STM32 microprocessor [2]. The primary purpose of this processor is to manage peripherals and run a control loop for controlling power generation. Another issue the processor must take care of is communication and transmitting telemetric data for another part of the onboard system. Because of the slow dynamics of the combustion engine, the processor does not have high demands on computing speeds. Nevertheless,

<sup>11</sup><https://www.autodesk.com/products/eagle/overview>



**Figure 4.6:** Front view of the embedded system

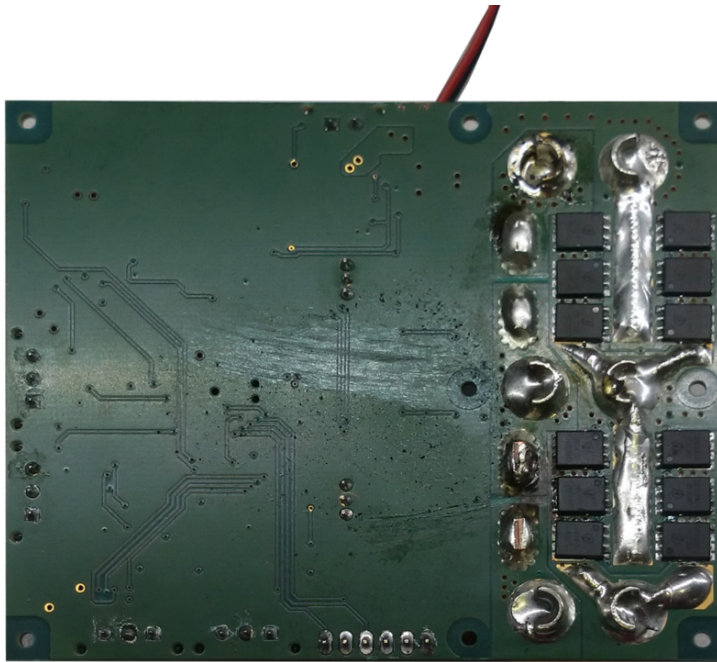
this device is designed for aerial vehicles; therefore the software needs to be robust and well tested.

I used programming language C, which is the standard programming language for ARM processors. A System Workbench for STM32<sup>12</sup> is used as an integrated development environment (IDE). The System Workbench toolchain, called SW4STM32, is a free multi-OS software development environment based on Eclipse, which supports the full range of STM32 microcontrollers and associated boards. The key Features of this IDE for this application is GCC C/C++ compiler, GDB-based debugger, ST-LINK support and Linux support.

For loading software into the microprocessor, a tool called ST-LINK<sup>13</sup> is used. The ST-LINK is an in-circuit debugger and programmer for the STM8 and STM32 microcontroller families. This tool allows real-time debugging and exploration of processor memory, which is very useful for programming and development.

<sup>12</sup><http://www.st.com/en/development-tools/sw4stm32.html>

<sup>13</sup><http://www.st.com/en/development-tools/st-link-v2.html>



**Figure 4.7:** Back view of the embedded system

### ■ 4.3.1 Configuration peripherals

The configuration of peripherals was done with the use of software STM-CubeMX<sup>14</sup>. STM32CubeMX is a graphical tool that allows configuring STM32 microcontrollers very easily and generating the corresponding initialization C code through a step-by-step process. To generate the code I used HAL (Hardware Abstraction Layer) drivers provided by STM.

Figure 4.8 shows pinout of the microprocessor captured from the STM-CubeMX software.

### ■ 4.3.2 Software functions

This section describes important segments of software and its functionality. The main loop of the program is very simple. Figure 4.9 shows a flowchart of program for the microprocessor. In the first version, the processor only measures required data and sends it to the computer via the CAN-bus. The computer processes this data and sends a response. Then the device reacts to the message from the computer.

---

<sup>14</sup><http://www.st.com/en/development-tools/stm32cubemx.html>

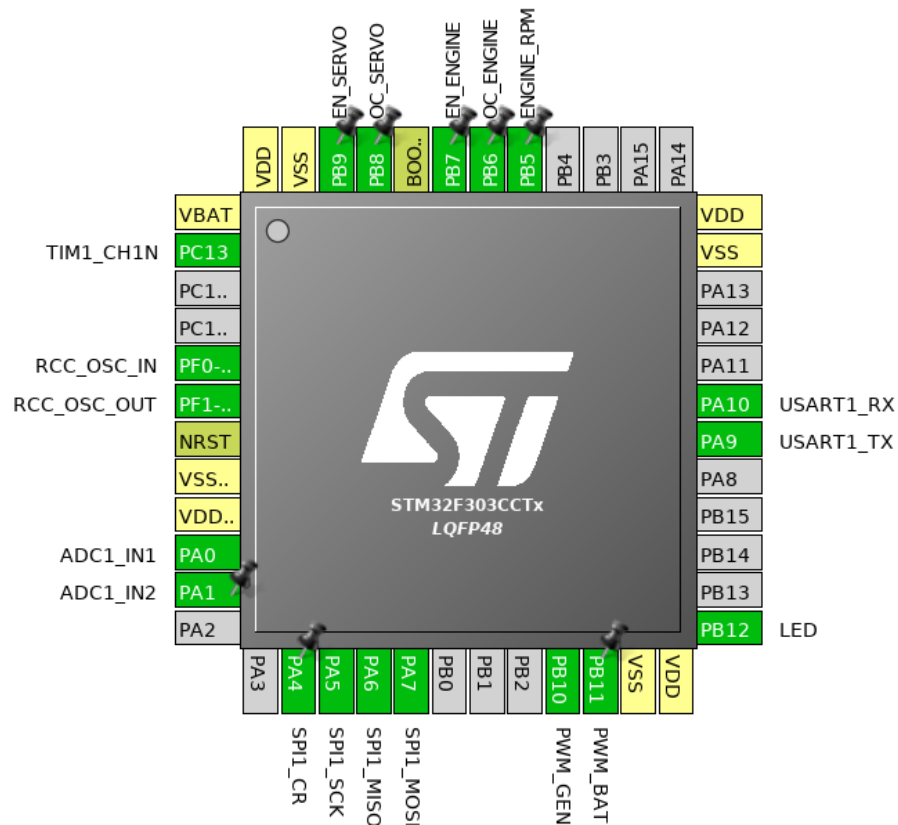


Figure 4.8: Pinout of the processor

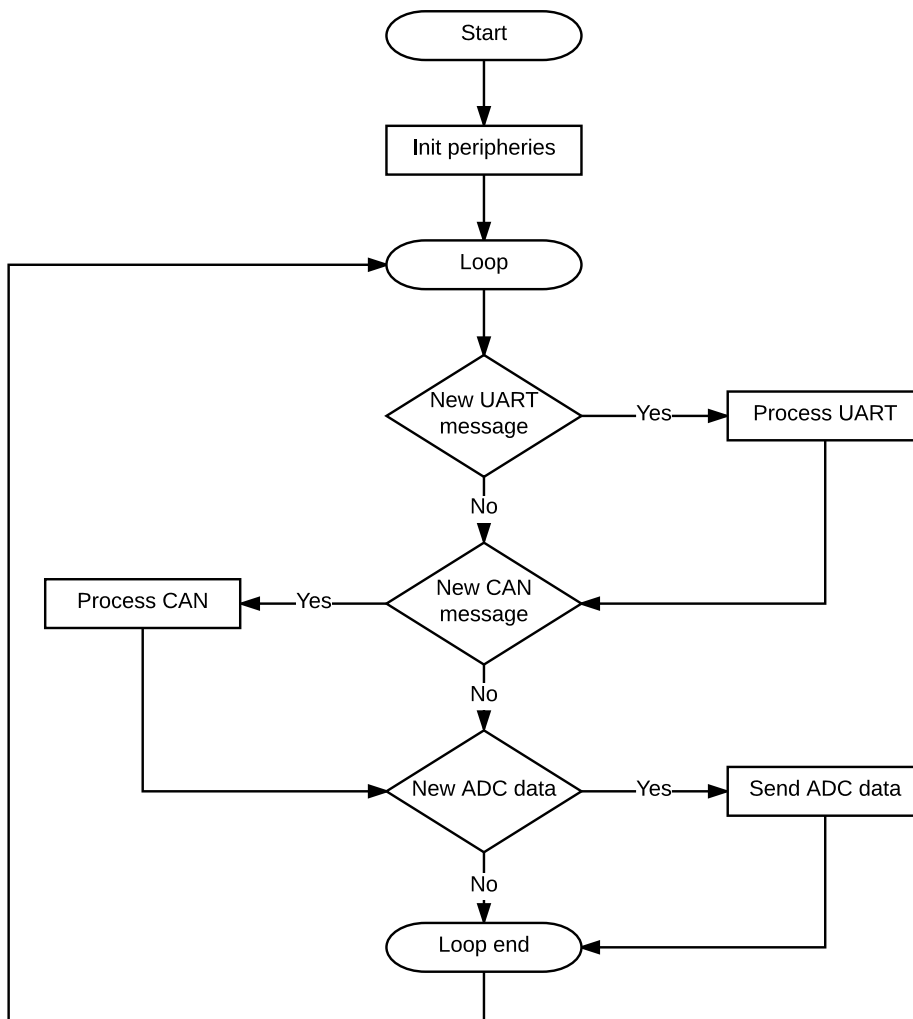
### CAN communication

The microchip MCP2515 manages CAN-Bus communication. The processor is connected to the device MPC2515 via the SPI. The function for SPI communication is provided by HAL drivers. The main difficulty was to understand how to communicate with the MPC2515 and write a library for communication with the processor. The CAN-bus is set to 500 kbs and the MCP2515 needs to be initialized to this speed. Time quanta and bit timing have to be computed based on crystal speed.

### ADC

The Analog-to-digital converter (ADC) is a built-in component of the microprocessor. Two channels of ADC are used (for the generator current and the battery current). For reading data from ADC, I used a Direct Memory Access (DMA) unit. The DMA does data transfers between memory locations without the need of the CPU. That means that I can set memory space to where AD converter store data after conversion and processor do not lose a significant amount of processing time. Then, there are a interruptions of DMA called *CpltCallback* and *HalfCpltCallback*. *CpltCallback* is called whenever the





**Figure 4.9:** Flowchart of software for processor

memory assign to DMA is filled and *HalfCpltCallback* is called whenever that memory is half full. *HalfCpltCallback* is beneficial for use there where is a high speed of writing to assign memory. With this interruption, the processor can start processing data earlier, and the chance of rewriting memory is minimized.

As the test has shown, raw data from ADC are noisy, and the application of some basic filter is required. The program assigns memory of 128 elements(64 for each channel) in size to the DMA, and instead of sending every sample, the program takes 64 last samples and computes the arithmetic mean value. Size of 64 samples for one measurement is compromise between frequency of computing the new measurement, between the smoothness of the measured signal and information loss by the arithmetic mean.

## ■ UART

Serial communication is primarily used for the development and configuration of the device (manual switching of the generator and the battery, set servo position, etc.). The functions for transmitting UART messages are provided by the HAL drivers, but the receiving message is not that trivial.

I again used direct memory access to receive a string. This time, the DMA got available memory with only one byte. So after receiving one byte, interruption *CpltCallback* is called, the program saves this byte to the array and continues stocking received bytes there until `\n` (newline) or `\r` (carriage return) is received. After receiving a new line character, the flag is raised and the program will read received a message in the main loop. This method has shown to be efficient and reliable.

## ■ Speed of engine measurement

The speed of the combustion engine can be measured from the signal, which goes from the ignition. This signal gives rising edge whenever the crank of the engine enters the dead centre. The signal is connected to the processor's pin, which allows external interruption. This means that this pin can be set to call interruption when it reads rising/falling edge. In this interruption the program resets the 16-bit counter and starts counting from zero again. This counter will count until the next rising edge is detected. From the value of the counter, a period of the revolts can be calculated. The period needs to be inverted to get frequency (or RPM). Due to knowledge, that engines operates with speed from 1000 RPM to 10000 RPM; the measurement can achieve the best precision on in this interval. With 1000 RPM, the period is 0.06s. This is the longest period that can happen, and therefore the timer is set to count to circa 58000 (counter max is  $2^{16}$ ). In the case of 10000 RPM the period is 0.006s and timer count to 5800.

## ■ 4.4 Communication

The device communicates through the CAN-Bus and UART serial port. A tool called Kvaser Leaf v2 allows the computer to communicate via the CAN-Bus.

For development purposes, it is required to transmit and receive CAN messages to the Matlab Simulink. There is only one toolbox to Simulink, which should be compatible with the Kvaser tool. Nevertheless, the license for this toolbox could not be obtained despite the fact that our faculty should have it. Fortunately, a project called Lintarget<sup>15</sup> was developed on our faculty. This project allows a model to be compiled of the designed control system to the C-code and combine it with target specific support functions. The resulting executable can be run in real-time on the target Linux system.

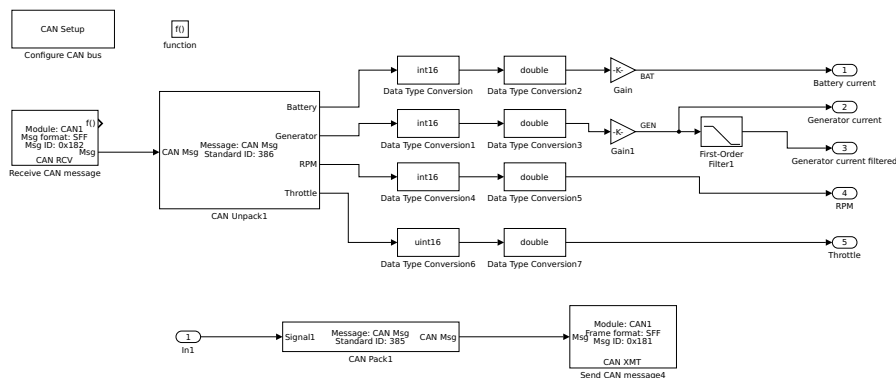
---

<sup>15</sup><http://lintarget.sourceforge.net/>

Simulink can use this executable for the external mode and can visualize data from it. That means that using this tool, a model from Simulink can be built, the resulting executable can be run on the computer (only Linux platform) and Simulink can connect to the process and communicate with it. Before using the Lintarget, a CAN interface is needed to be brought up. The following commands require administrator rights and serve to bring up the interface and set the baud rate of the bus.

```
ip link set can0 down
ip link set can0 type can bitrate 500000
ip link set can0 up
```

The toolbox Lintarget provides basic blocks for sending and receiving CAN messages for the ERT Linux Simulink<sup>16</sup> target when a mainlined socket based CAN-Bus support is used. The *cantransmit* and *canreceive* blocks support directly the encapsulation and conversion to the Simulink signals for basic data types: uint8, uint16 and uint32. Figure 4.10 shows an example of the implementation of CAN communication in Simulink.



**Figure 4.10:** Simulink CAN-Bus implementation

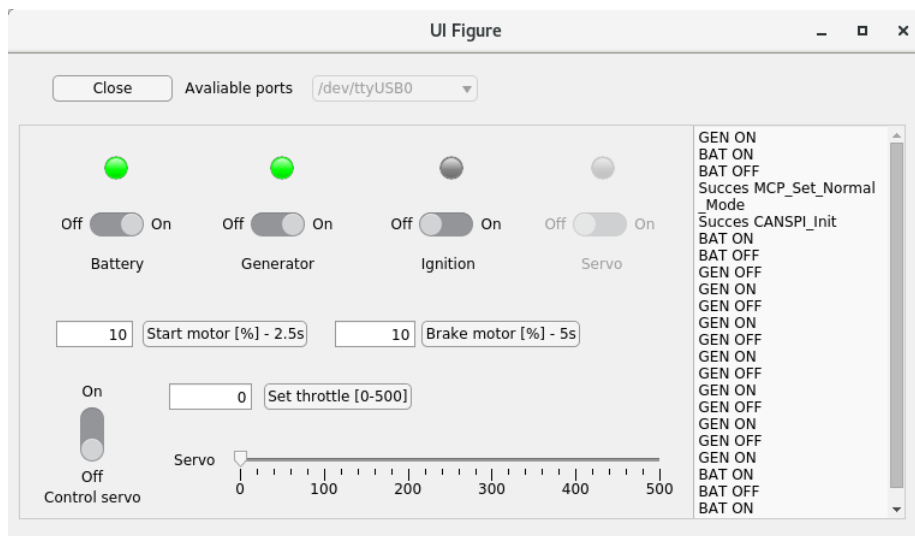
Communication with the device via UART was done using an FDTI cable, which converts USB to serial port. Because of the very frequent communication and plenty of commands I have created a desktop application. I used the Matlab App Designer to make this application. The primary motivation for using Matlab to write this program was the multi-platform

<sup>16</sup>[http://lintarget.sourceforge.net/can\\_bus/index.html](http://lintarget.sourceforge.net/can_bus/index.html)

CAN ID	Data length	Purpose
0x110	6	Communication with regulator
0x112	8	Message 1 from lambda sensor
0x113	8	Message 2 from lambda sensor
0x181	2	Data from computer to the device
0x182	8	Data from the device to computer

**Table 4.1:** List of CAN messages

demand. A screenshot of the desktop application is shown in Figure 4.11. On the right side of the application, there is a text area, where received strings are displayed.



**Figure 4.11:** Screenshot of the application for UART communication

The primary purpose of the UART interface is to configure the microprocessor and its peripherals. The commands are shown in Table 4.2. The processor has defined responses to acknowledge receiving and executing the received command. The following configuration of the UART is this project:

- Baudrate: 115200
- Flow Control: None
- Data Bits: 8
- Parity: Even
- Stopbit: 1

Command	Purpose	Response of the processor
'G'	Switch MOSFETs to the generator on	"GEN ON"
'g'	Switch MOSFETs to the generator off	"GEN OFF"
'B'	Switch MOSFETs to the battery on	"BAT ON"
'b'	Switch MOSFETs to the battery off	"BAT OFF"
'S'	Enable ignition	"IGNITION ON"
's'	Disable ignition	"IGNITION OFF"
'Ex'	Set position of the throttle <i>x</i> - parameter [0% - 100%]	"PWM SET"
'P'	Enable servo	"SERVO ON"
'p'	Disable servo	"SERVO OFF"
'C'	Enable control	"CONTROL ON"
'c'	Disable control	"CONTROL OFF"
'Mx'	Starting combustion engine <i>x</i> - parameter speed of motor [0% - 100%]	"STARTING"
'Kx'	Braking combustion engine <i>x</i> - parameter brake intensity [0% - 100%]	"BEAKING"

**Table 4.2:** List of UART commands



# Chapter 5

## Control

This chapter describes the process of designing and analyzing the control problem. The requirements for the control system are presented.

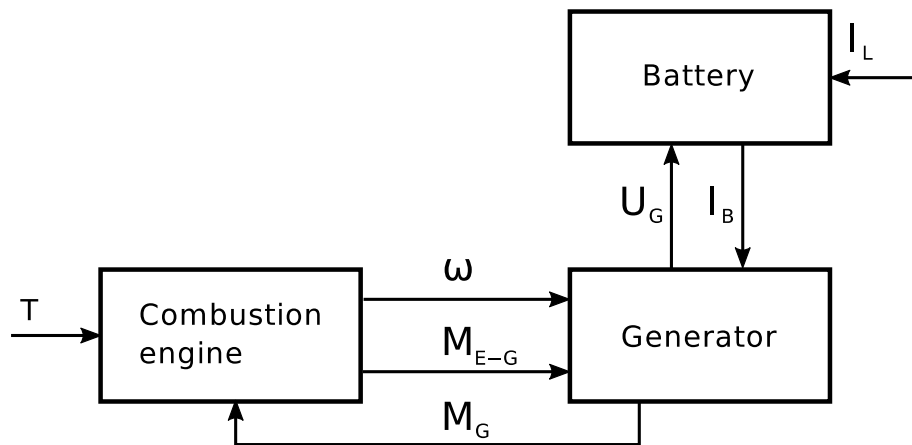
The primary purpose of the control system is to manage the power flow from the battery and the generator and secure that power on the output is available all the time. The control system should watch the current flowing from the battery and set the generator to recover that amount of power back to the battery. If the generator generates more power, than the output system needs and the battery is charged, the system should slow the engine down and saves the fuel. The power generated by the generator can be controlled by the throttle of the combustion engine. To propose and adequate control system, the modelling of the controlled system is necessary, and the following section is dedicated to that.

### 5.1 Modelling of the controlled system

The model of the system is required for the designing and testing of the proposed control system. For the designing and testing, MATLAB/Simulink software is used. MATLAB/Simulink is a powerful simulation tool for system and control designs. It provides a lot of simple, powerful and user-friendly toolboxes and simulation blocks.

The controlled system contains a combustion engine, generator, and battery. The outputs of the system are current flowing from the generator, the current flowing from the battery, revolutions of the combustion engine and the voltage of the battery. Based on this information the input of the system should be driven. The only input of the system is the throttle of the combustion engine. Figure 5.1 shows the controlled system with all relations.

The controlled system is composed of three subsystems. The subsystem of combustion engine, generator, and battery. The primary idea is to create models of these subsystems first and then connect this subsystem to create the full model of the system. Here are the listed connections between the subsystems:



**Figure 5.1:** Scheme of the model

- $T$  [%] - input throttle
- $\omega$  [rad/s] - speed of the combustion engine
- $M_G$  [Mm]- brake momentum of the generator
- $M_{E-G}$  [Mm] - difference between the momentum of the generator and the engine
- $U_G$  [V] - generated voltage
- $I_B$  [A] - current supplied to the
- $I_L$  [A] - current consumption of the output system

### ■ Battery

For our purposes, I used a simplified model of the battery, where the temperature dependency and battery age are neglected. The subsystem of the battery has two inputs and one output. The inputs are the voltage  $U_G$  and the current  $I_L$ . The only output is the current  $I_B$  which is a current, that flows into the battery.

A basic battery model is included in MATLAB/Simulink Electric Drives/Extra Sources library<sup>1</sup>. The Battery block implements a generic dynamic model parameterized to represent various types of rechargeable batteries including li-ion type.

This model takes input voltage and if the voltage exceeds the voltage on the battery, the current starts to flow to the battery. This current is then output  $I_B$  and goes to the generator subsystem. The second input  $I_L$  is current consumed by an output system.

<sup>1</sup><https://www.mathworks.com/help/physmod/sps/powersys/ref/battery.html>



## Generator

Essentially, the model of the generator only takes the speed of the engine and the momentum applied and based on it generates a corresponding voltage and current. If the generated voltage exceeds the voltage on the battery, the current starts to flow and the creates momentum which brakes the combustion engine. Therefore, the model of the generator has three inputs and three outputs. The first input for the speed of the engine  $\omega$ , the second input for the load current  $I_B$  and the third is a momentum of  $M_{E-G}$ . The outputs are the generated voltage  $U_G$  and the amount of generated brake momentum  $M_G$ .

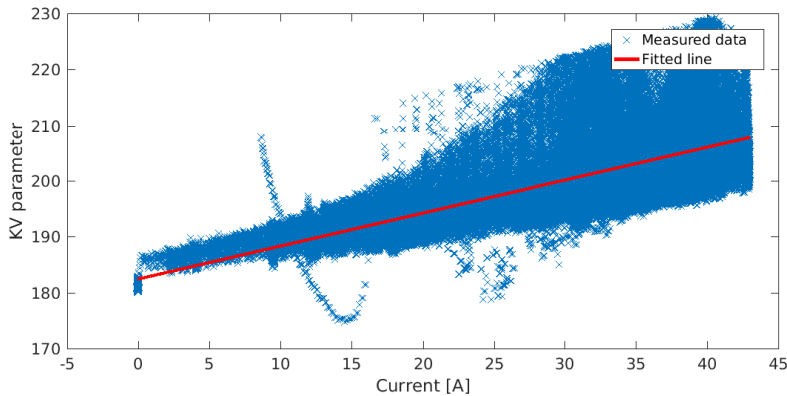
The model computes the generated voltage from the speed of the engine and the KV parameter.

$$U = \frac{R}{K} \quad (5.1)$$

Where R denotes the speed in RPM and K denotes the KV parameter. If the losses of the generator are neglected, the generated current can be calculated from the power constraint.

$$U_G \cdot I_G = M_{E-G} \cdot \omega \quad (5.2)$$

The KV parameter is dependent on the current flowing through the generator because of the back EMF. This dependency needs to be measured and defined. Figure 5.2 shows the measured data and a model created from them. The generator without load has a KV parameter 182, which corresponds with defined parameters from the manufacturer. When the generator creates about 40 A, the KV parameter is 209. That means that the generator loses 15 % of efficiency on the back EMF with a 40 A load.

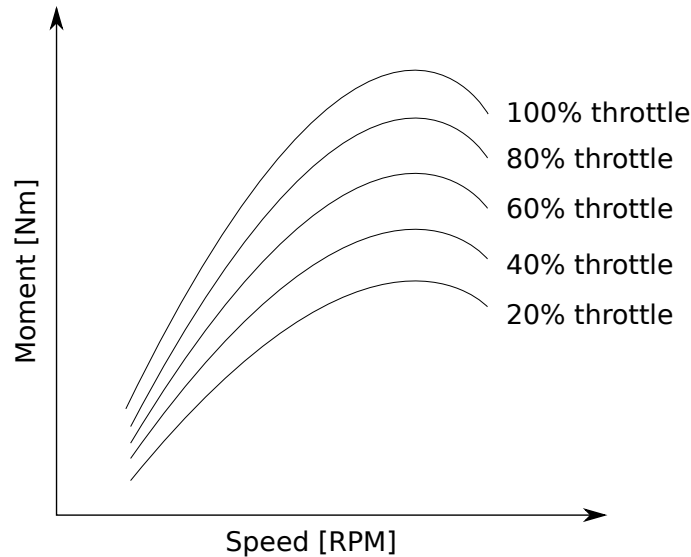


**Figure 5.2:** Measured data and fitted line

The momentum of the generator  $M_G$  is computed based on the current load input  $I_M$  and the actual KV parameter.

## ■ Combustion engine

The model of the engine should have one input for the engine throttle  $T$  and one for the momentum  $M_G$ , that brakes the engine. The outputs of the engine are the speed of the engine  $\omega$  and the difference between the momentum of the generator and the engine  $M_{E-G}$ . To create a mathematic model, relations and dependence between the inputs and output need to be measured and modeled. The idea was to open the throttle of the engine gradually from 20% to 100%. For every level of the throttle, the linear load of the brake torque would be applied to the engine and measure revolutions and output power. The electronic brake that should be activated by the regulator device and provide the brake torque. The output power is measured by the output voltage and current. Figure 5.3 shows expected dependency graph of the speed of the engine and the brake momentum [7].

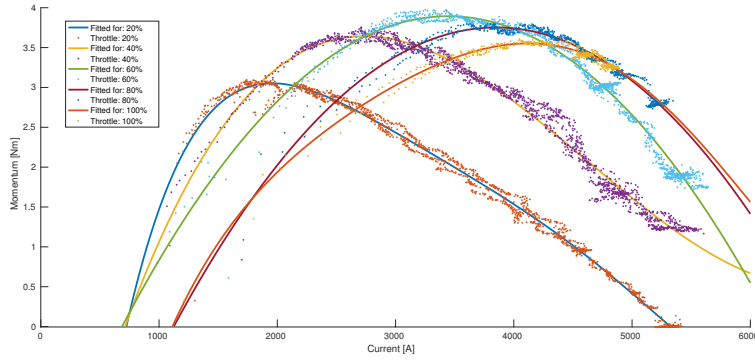


**Figure 5.3:** Expected dependency of RPM on the applied momentum

The electronic brake on the device failed to work as expected, fortunately there was a different solution. For testing purposes, a electronic load was installed in the apparatus. This electronic load could drain up to 60 A from the hybrid system. If the battery is removed from the system and an electronic load is increasing, a corresponding momentum is generated by the engine. This method can provide the needed data.

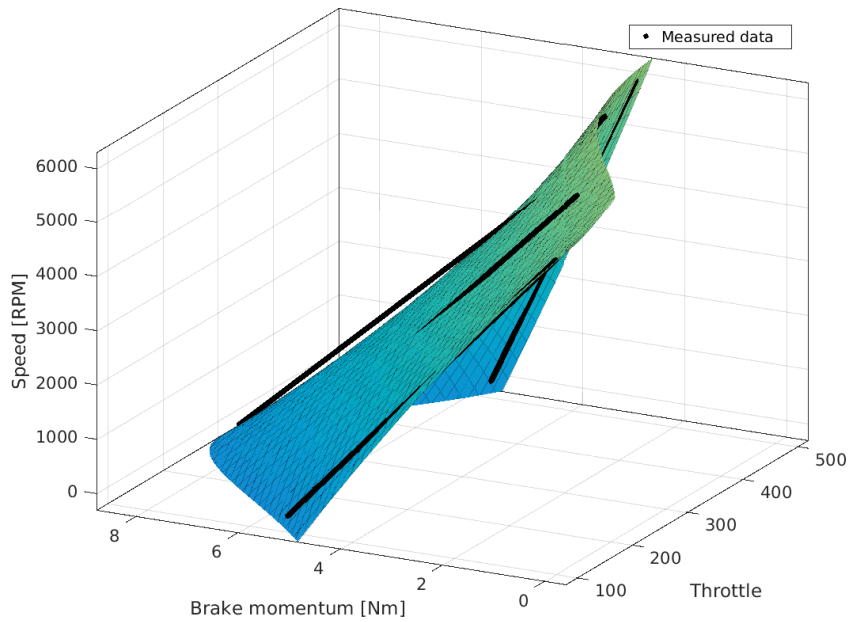
The measured data are shown in Figure 5.4. This Figure also shows the fitted functions for the measured data. The fitted functions are polynomial function with a degree from 3 to 5. The degree used was based on the smallest fitted error. From now on, these fitted functions are used instead of the measured data.

From these data, a model of the combustion engine is constructed. Because there are two outputs, two parts of the model need to be created. At first, there has to be a dependency of the speed of the engine on the brake



**Figure 5.4:** Measured and fitted data

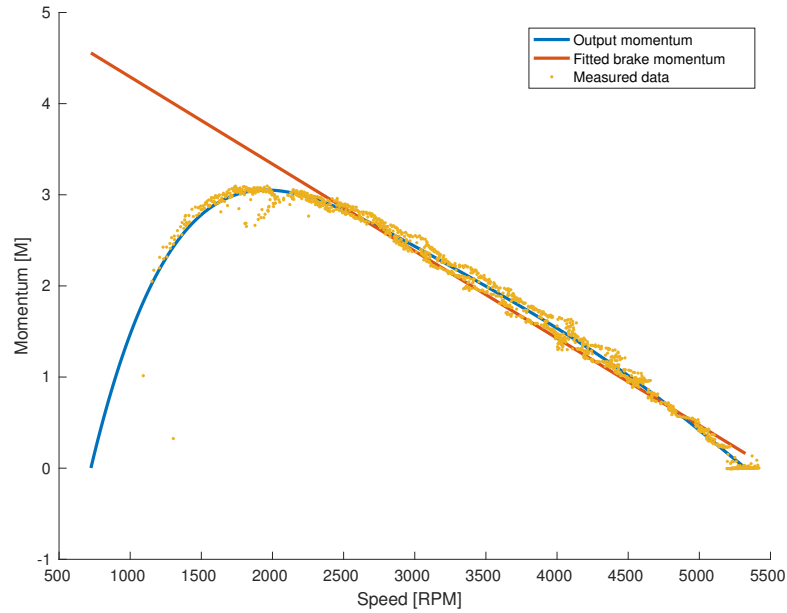
momentum. This dependency is modeled by fitting a polynomial surface of degree 3 in  $x$  and degree 3 in  $y$  on the measured data. Resulting model is shown in Figure 5.5. The throttle is defined on a scale from 0 to 500 (500 is 100% wide open throttle). This scale has a higher resolution than a percentage scale without using decimal numbers.



**Figure 5.5:** Dependency of the speed of the engine and the brake momentum for each throttle

Secondly, the dependency of the output momentum and the brake momentum. Figure 5.4 shows that until a certain speed of the engine is reached, the output momentum and the brake momentum corresponds. From that point, the real brake engine does not correspond to the measured data and needs to

be fitted. Figure 5.6 shows the estimated brake momentum.



**Figure 5.6:** Fitted real momentum for 20% of the throttle

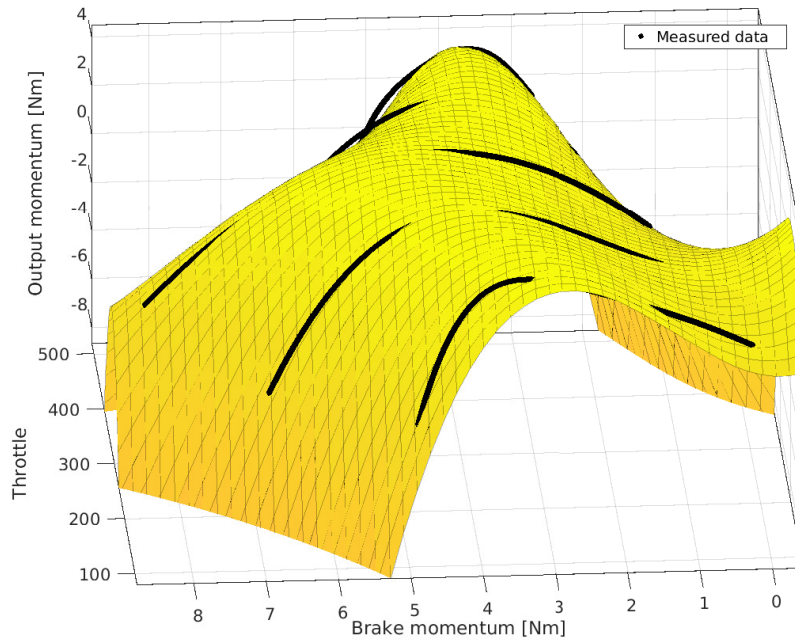
From these data, a model of dependency of the output momentum and the brake momentum for each throttle can be created. Model is a fitted polynomial surface of degree 4 in  $x$  and degree 4 in  $y$ .

Simulated signal from the model of the combustion engine have to contain noise as the original signal. After applying Fourier transform on the measured current, there can be seen harmonic wave in the frequency of the speed of the combustion engine. That means that when the engine ignites, there is a peak in the generated momentum. The result of the Fourier transform can be seen in the example in Figure 5.8. There is a harmonic wave on 80 Hz (4800 RPM) which corresponds to the speed of the engine at the moment.

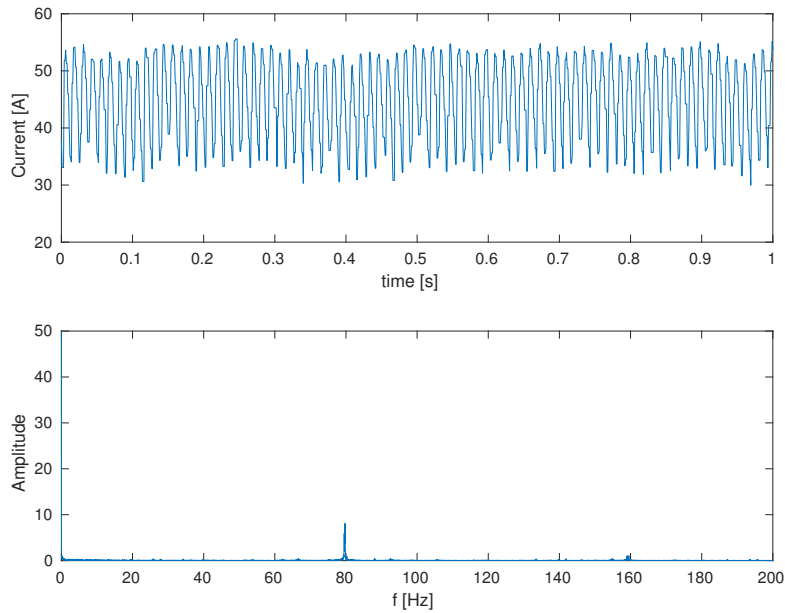
After testing and tuning, sufficient model was created. Nevertheless, the engine reacted on the input throttle very differently whether it was cold or had been running for a while. Carburettor settings also have a major influence on the engine parameters and transient response. This model can serve as a basic idea of engine properties, but to create more accurate model, more data would had to be obtained. Measuring temperature of the engine pistons and a lambda value could significantly increase credibility of the model.

## ■ Full hybrid system model

The full hybrid system model connects all subsystems. This model corresponds with the real system in the operation range. A control system is designed



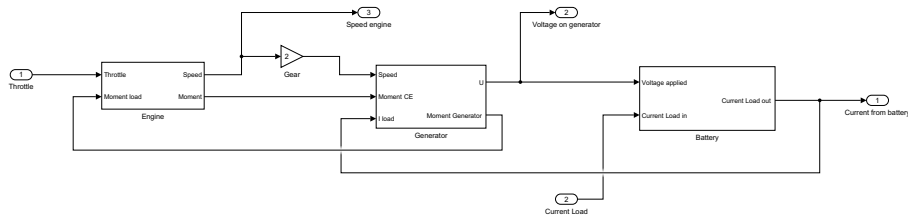
**Figure 5.7:** Dependency of output momentum and the brake momentum for each throttle



**Figure 5.8:** Fourier transform on the measured signal

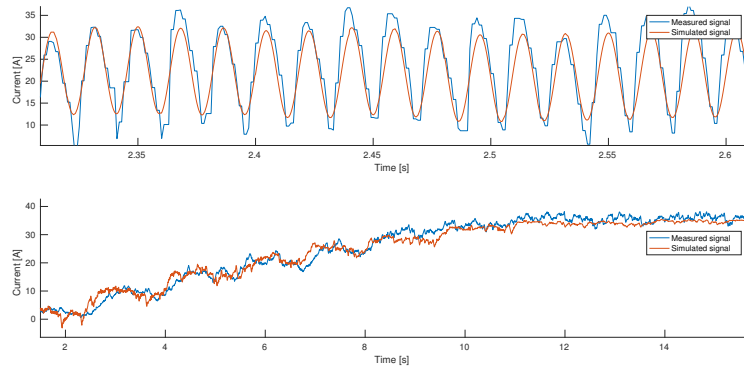
based on this model.

Figure 5.10 shows a comparison of the measured signal and signal from the



**Figure 5.9:** Full hybrid system model

model. The upper plot shows a comparison of the raw signals and has been measured and simulated with a constant throttle. The plot below shows current responses after step changes of the throttle in the range from 20 % to 80 %. Signals are filtered by a low-pass filter with a time constant  $T_s = 0.08$  s.



**Figure 5.10:** Comparison between the modelled and measured signal

## 5.2 Controlling

The control system needs to operate in two modes:

- Engine speed regulation
- Permanent power generation

In the first one the system only controls a speed of the engine without load (without power generation). The demands on this mode of the control system is to keep the constant RPM of the engine within the range where the generated voltage does not exceed the battery voltage and therefore no power is generated. This mode can be used for idling or heating up the engine.

The second mode of control is for permanent power generation. This mode should be active during the flight. The main requirement of the system is to ensure enough power to cover the demands of the load. This means, that

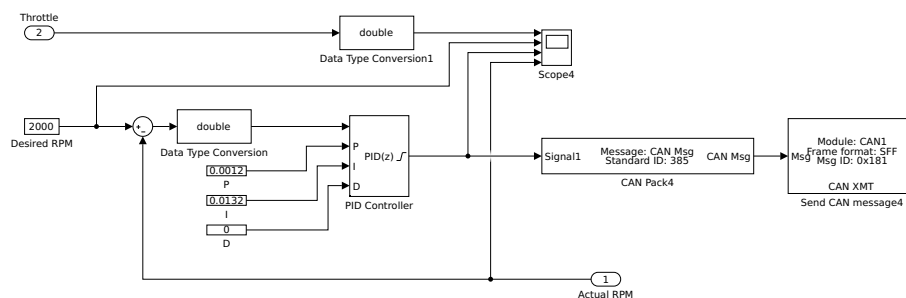
if the power is drained from the battery, the generated power needs to be increased. Ideally, the energy of the battery is used only to cover power peaks and permanent power consumption is covered by the generator. Another important requirement is to keep the battery in an optimal state of charge. The optimal state of charge of the battery is where the voltage level is at 50 V (4.15 V on the cell).

### ■ Engine speed regulation

The controller of the engine speed only watches the speed of the engine and based on this adjusts the throttle position. This mode works with the engine without any load. There are no critical requirements for this control. The system with the combustion has a slow response and the control system only needs to drive the output to the requested value.

At first, the transition characteristic of the system has to be measured. I assumed that this system is a first order system. Strejc method<sup>2</sup> was used for the identification constants of the system. After identifying the system, a simple feedback PI regulator was proposed. The parameters of the PI regulator were estimated experimentally and tuned on the real system.

Figure 5.11 shows Simulink scheme of PID controller.



**Figure 5.11:** Implemented controller for speed regulation

### ■ Permanent power generation

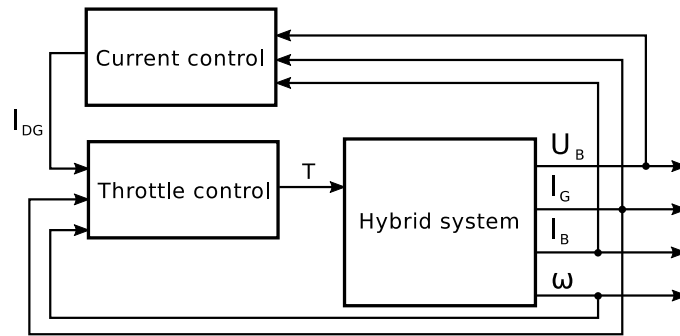
This control mode should drive the engine throttle to secure enough generated power. The amount of required power is based on the actual output power consumption and power that is needed to charge into the battery. That is the primary requirement of this control. Apart from the power requirements this control has to drive the throttle smoothly and avoid rapid changes.

The actual power consumption can be measured by a current flowing from the battery. If the generator provides sufficient energy, current flowing from

<sup>2</sup>[http://www.352.vsb.cz/uc\\_texty/Identifikace/str/metody.htm#ma3](http://www.352.vsb.cz/uc_texty/Identifikace/str/metody.htm#ma3)

the battery equals to zero. When the generated energy exceeds the output consumption, the remaining energy charges the battery.

The control of the permanent power generation can be divided into two control subsystems. The first one (Throttle control) controls only the amount of the generated power. As an input takes the desired value of generated current and drives throttle to achieve this value. The second control subsystem (Current control) surrounds the first one and controls the amount of generated power based on the output of actual and longterm power consumption and a state of charge of the battery. The full control system is shown in Figure 5.12.



**Figure 5.12:** Control system

The controlled system is known and the throttle-RPM-power dependency is well measured. Therefore, the main control element is feed-forward control. The feed-forward control is based on the static lookup table, where for every desired value a table value of the throttle is assigned. The lookup table was created using an linear interpolation of the measured data. Because the feed-forward control is not error-based, the control system is enhanced with a feedback element. The feedback controller only needs to correct the remaining deviation of the feed-forward controller [5]. PID controller is utilized as a feedback controller.

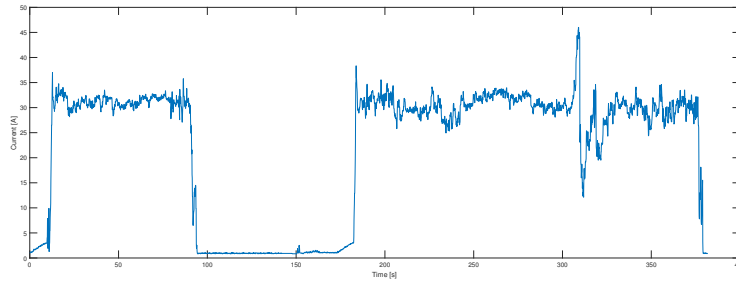
The Current control determines the amount of current generated. The basic version of this controller takes the input for current from the battery and from the generator. The controller can compute the output current consumption as the sum of input currents. Then the controller sends this consumption to output, to the Throttle controller. By that, the control system covers power the power demands as far as the generator is capable of.

The next level of the Current control is to integrate the current that can not be provided by the generator and is drained from the battery. In the time when the generator is not working on the full power, the integrated power will be charged back to the battery. The charging current has to be limited to the maximum charging current of the battery.

This controller also controls voltage level of the battery. If the battery is fully charged, the generator can not overcharge the battery.



Figure 5.13 shows the real current consumption during the flight. These data are from the target quadcopter, to which the hybrid power unit should be placed.



**Figure 5.13:** Current consumption during the flight



## Chapter 6

### Conclusion

In this work, I have presented the existing solutions for a hybrid-electric power unit for quadcopters and a proposed hybrid-electric system. Then I have described the development of the embedded system. The primary purpose of this embedded system is to control and manage the power flow from the generator and the battery. After manufacturing the embedded system, a mathematical model of the hybrid power unit had to be created. Based on this model a basic control was designed in the Simulink environment.

The crucial part of this work was to develop an embedded control system. After manufacturing and testing the first version of the embedded system, a few complications has arose. I wrote down a list of things, that will be handled differently in the second version. For example, the low-side switching of MOSFETs proved to be impractical, because of a floating ground. Then, through the physical layer of the CAN-Bus a small current flows and charges the capacitors of the other devices which should be off. This problem should be dealt with by galvanic separation of the CAN-Bus.

Despite minor complications, the embedded system worked perfectly and in combination with real-time communication in Simulink provided a powerfull platform for measurement and developing.

The basic mathematical model was created and tested in the Simulink, and the basic controllers were proposed. Unfortunately, during one measurement session, the embedded system burned out under uncertain circumstances. Therefore, model is based on limited data and after manufacturing second version of the device more measurement have to be done to complete the model. Only controller for the engine speed regulation was tested on the real setup.

The work will continue by designing a second version of the embedded system. A list of known changes to the second version of the embedded system:

- Add safety measures (zener diode against reverse polarity, fuses)





## Bibliography

- [1] P. Bogusz et al. “An analysis of properties of the BLDC motor for unmanned aerial vehicle hybrid drive”. In: *2015 International Conference on Electrical Drives and Power Electronics (EDPE)*. 2015 International Conference on Electrical Drives and Power Electronics (EDPE). Sept. 2015, pp. 458–464. DOI: 10.1109/EDPE.2015.7325338.
- [2] Geoffrey Brown. *Discovering the STM32 Microcontroller*. Indiana University, June 5, 2016.
- [3] Grutter Import B.V. *ROTO 85 FS 85cc boxer rc model gas engine (5.5hp, 2800gr)*. URL: [http://www.bigplanes.nl/contents/en-uk/p1647\\_ROT0-85-FS-gas-engine-RC-model-airplane.html](http://www.bigplanes.nl/contents/en-uk/p1647_ROT0-85-FS-gas-engine-RC-model-airplane.html) (visited on 04/04/2017).
- [4] *Energy Density of Gasoline - The Physics Factbook*. URL: <http://hypertextbook.com/facts/2003/ArthurGolnik.shtml> (visited on 04/04/2017).
- [5] Rolf Isermann. *Engine Modeling and Control: Modeling and Electronic Management of Internal Combustion Engines*. Google-Books-ID: LWY1-BAAAQBAJ. Springer, July 1, 2014. 646 pp. ISBN: 978-3-642-39934-3.
- [6] S. Kadirov and N. Paswan. *Internal combustion engines*. Google-Books-ID: 3Yd0DgAAQBAJ. Litres, Mar. 23, 2017. 475 pp. ISBN: 978-5-04-048990-9.
- [7] M. A. Kalam and H.H. Masjuki. “An experimental investigation of high performance natural gas engine with direct injection”. In: *Fuel and Energy Abstracts* 36(5) (May 2011), pp. 3563–3571.
- [8] Languang Lu et al. “A review on the key issues for lithium-ion battery management in electric vehicles”. In: *Journal of Power Sources* 226 (Mar. 15, 2013), pp. 272–288. ISSN: 0378-7753. DOI: 10.1016/j.jpowsour.2012.10.060. URL: <http://www.sciencedirect.com/science/article/pii/S0378775312016163> (visited on 05/23/2017).
- [9] Joachim Schömann. *Hybrid-Electric Propulsion Systems for Small Unmanned Aircraft*. de. Dr. Hut, 2014. ISBN: 978-3-8439-1847-3.

- [10] B. Škugor, D. Pavkovic, and J. Deur. “A series-parallel hybrid electric vehicle control strategy including instantaneous optimization of equivalent fuel consumption”. In: *2012 IEEE International Conference on Control Applications*. 2012 IEEE International Conference on Control Applications. Oct. 2012, pp. 310–316. DOI: 10.1109/CCA.2012.6402738.

# Appendix A

## Scheme of the embedded system

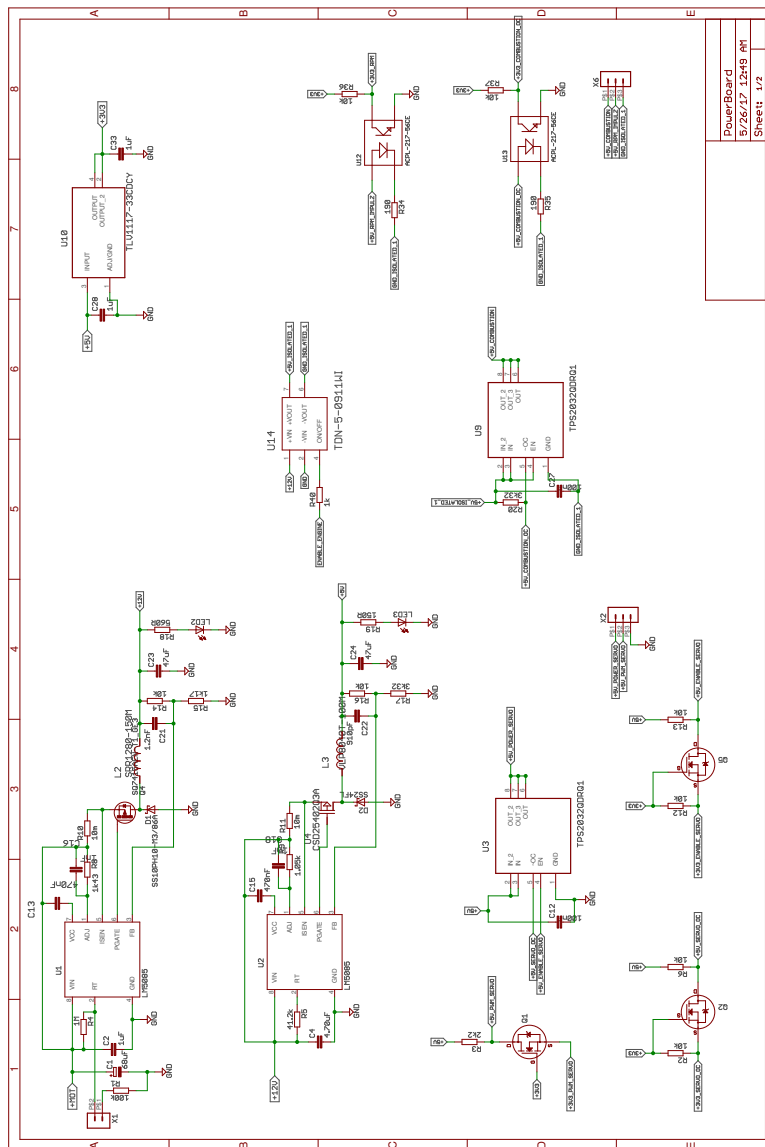


Figure A.1: The first sheet of the scheme





## Appendix B

### Layout of the embedded system

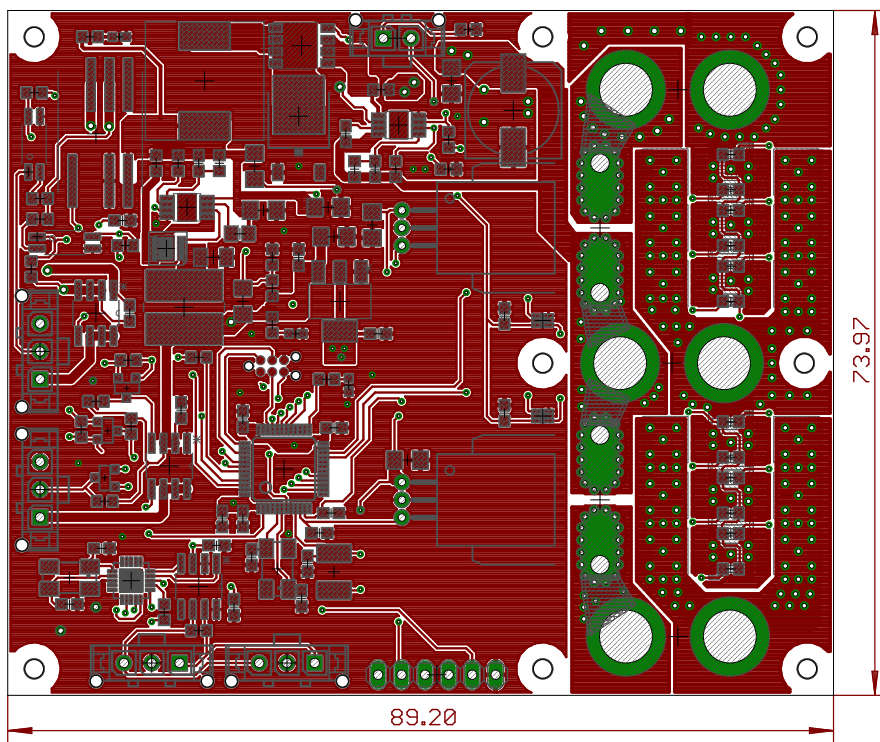


Figure B.1: Top layer

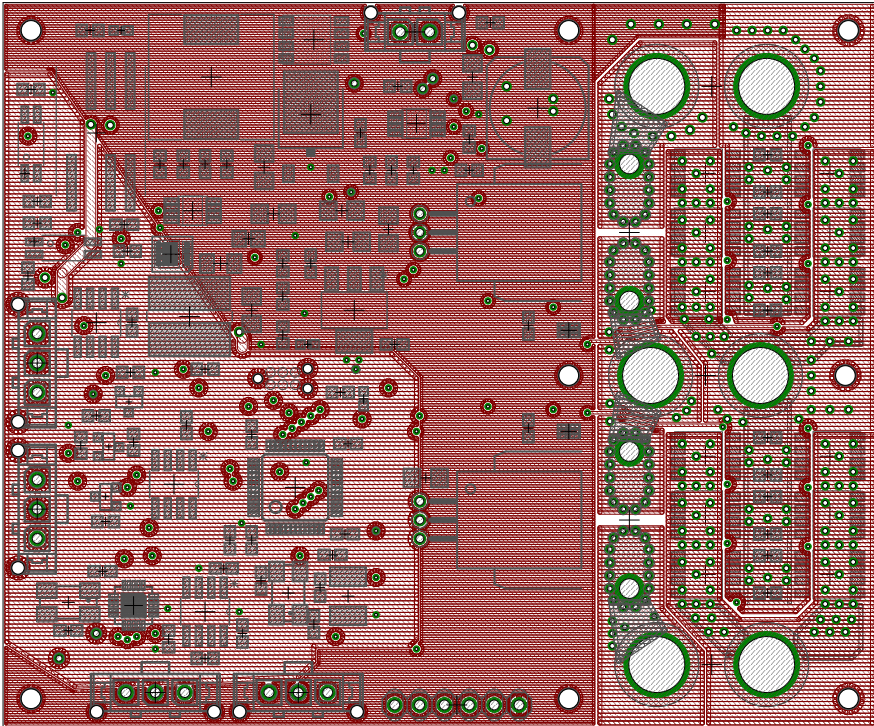


Figure B.2: Second layer

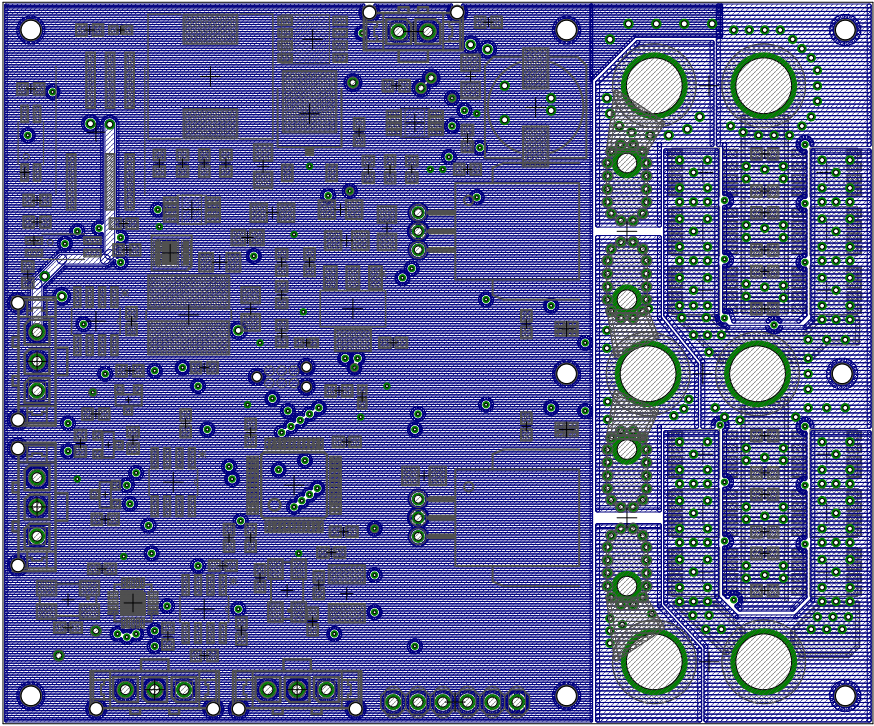
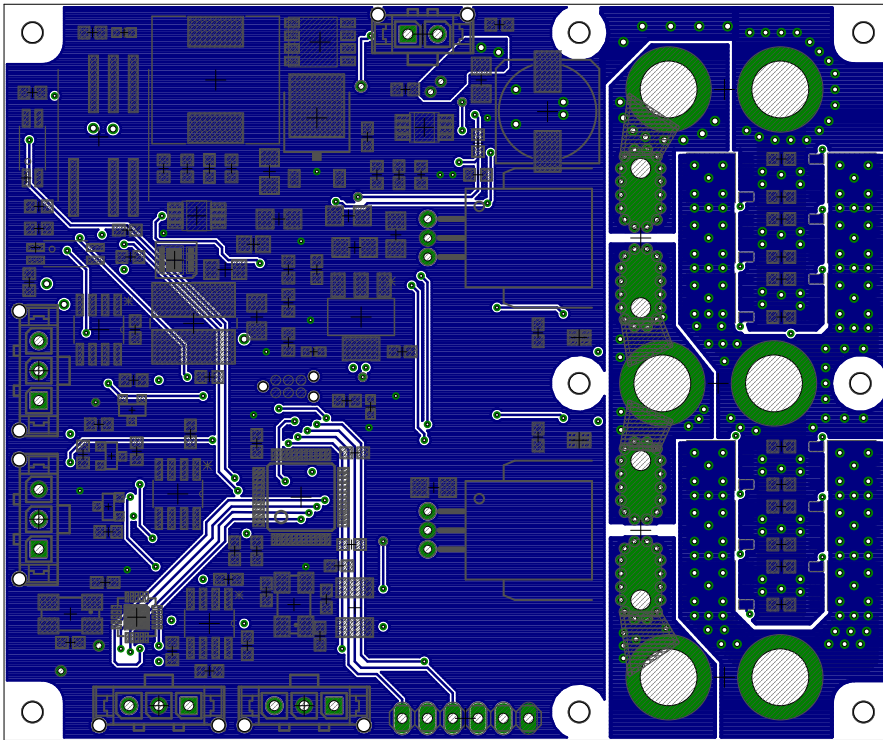


Figure B.3: Third layer



**Figure B.4:** Bottom layer



## Appendix C

### CD content

