# Controlling a Brushless DC Motor in a Shift-by-Wire System

**Master's thesis**
performed in **Vehicular Systems**

by
**Johan Wiberg**

Reg nr: LiTH-ISY-EX-3517-2003

16th December 2003

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**Master's thesis**

performed at the
**Division of Vehicular Systems**,
**Dept. of Electrical Engineering**
at **Linköpings universitet**

for **DaimlerChrysler AG**

by
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Linköping, 16th December 2003

**Avdelning, Institution**
Division, Department

Vehicular Systems,
Dept. of Electrical Engineering
581 83 Linköping

**Datum**
Date

16th December 2003

**Språk**
Language

☐ Svenska/Swedish
☒ Engelska/English
☐ ______

**Rapporttyp**
Report category

☐ Licentiatavhandling
☒ Examensarbete
☐ C-uppsats
☐ D-uppsats
☐ Övrig rapport
☐ ______

**ISBN**
—

**ISRN**
LITH-ISY-EX-3517-2003

**Serietitel och serienummer**
Title of series, numbering

**ISSN**
—

**URL för elektronisk version**

http://www.vehicular.isy.liu.se
http://www.ep.liu.se/exjobb/isy/2003/3517/

**Titel** Styrning av en borstlös DC-motor i ett Shift-by-Wire-system

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Author

**Sammanfattning**
Abstract

Shift-by-Wire is about replacing the mechanical link between the automatic transmission and the shift lever with an electromechanical system. This will make new safety functions possible and assist the driver in other ways.

To do this, an actuator with a brushless DC motor is built into the transmission. It controls the position of the shift valve, which decides the driving position.

This thesis concerns the controlling of the brushless DC motor. This is done by programming a shift control unit with a Motorola HC12 microcontroller. The performance of the motor is then tested and evaluated.

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## Acknowledgments

First of all I would like to thank my supervisor at DaimlerChrysler, Michel Willems, for having given me the chance of working with this project. I had a lot of fun both on and off work. Franz-Josef Wollscheid, Rainer Hägele and Falk Heller also helped me answering all my questions. I greatly enjoyed my time in Esslingen, mainly thanks to all the great people at REM/EP, Niclas, Johan, Zandra, Tina, Daniel, Michael and others.

I have received a lot of good input on my report from my supervisor in Linköping, Per Andersson.

My thanks also go to Fredrik Wallin for discussing, and correcting details in, my thesis.

Finally I would like to thank Karin for supporting me and for always being there for me.

Linköping, October 2003
*Johan Wiberg*

# Contents

# Chapter 1

# Introduction

As demands for driver comfort and flexibility in cars increase, many systems that historically have been pure mechanical are now controlled electromechanically. These systems are often called ”by-wire”, e.g. steer-by-wire and brake-by-wire. Shift-by-wire is an electromechanical system that replaces the mechanical link between the automatic transmission and the shift lever. The shifting between the four driving positions P(ark), R(everse), N(eutral) and D(rive) is then controlled electronically.

To do this, an actuator, consisting of a brushless DC motor, a set of gears and a manual override, is built into the transmission. The motor creates a linear movement of the shift valve which hydraulically controls the driving position. The reasons for using a brushless motor are its durability, high torque and ability to run in transmission oil.

Two prototypes have been built so far. One for a Mercedes E-Class and one for a Jeep Grand Cherokee and both use normal DC motors. The next step is to build a brushless DC motor into the Jeep.

## 1.1 Motive

What is the reason to change a system that has been used with good results since the very first car? Not all new technology is a step forward. There are however reasons to replace mechanical systems, and Shift-by-wire has several advantages.

First of all there is the possibility to remove the shift lever completely. This increases the freedom of the interior design. Earlier the shift lever was placed on the floor between the seats or, common in American


Figure 1.1: Shift control at the steering wheel. A possibility with Shift-by-Wire.

cars, by the steering wheel because a mechanical link had be connected to the transmission. Now the shifting can be done by a lever, joystick, touchscreen or buttons placed anywhere in the car.

The possibilities of implementing new functions are greatly enhanced, since it is all controlled by software. For example, the car could automatically shift to Park and engage the parking lock when the driver removes the key. These functions of automation lead to better driver comfort and safety.

The assembly of the car is easier when there is no mechanical link between the interior and the transmission. There is no adjustment needed when assembling the different parts of the car and this can save time and money. The signals to the transmission could be sent over the already existing vehicle network, for example the CAN bus, which is a commonly used communications bus.

## 1.2 Objectives

The objectives are to control a brushless DC motor with a shift control unit and to make the motor run in a Shift-by-Wire system in a Jeep Grand Cherokee. This is done to show the possibilities of Shift-by-Wire. The system will serve as basis of discussion when serial production is considered.

## 1.3 Methods and Execution

After the first few weeks of reading to get to know the project, the Simulink model of the system was examined. When the shift control unit arrived from the manufacturer, there was a week of soldering and attaching cables. Several hardware errors were corrected before the motor showed any signs of life. Then followed programming which was done in C and flashed onto the microcontroller. The performance of the motor was compared to the model and then evaluation was done at the end.

The simulations and modelling have been done in Matlab Simulink, programming in CodeWright and compilation by Cosmic Compiler. The resulting file is flashed to the microcontroller by Zap Debugger.

## 1.4 Organization

The work has been done from February to August 2003 at Daimler-Chrysler AG in Esslingen in Germany as the final part of my Master of Science education in Applied Physics and Electrical Engineering at Linköpings universitet.

## 1.5 Thesis Outline

Chapter one is an introduction to the project and it describes Shift-by-Wire and why it is developed. Chapter two describes the background from where I started working; how an automatic transmission works, what the actuator should do and some alternative solutions. In chapter three there is a description of the brushless DC motor and how to control it. Chapter four presents the Simulink model of the system and the results from a simulation. In the fifth chapter, the Shift Control Unit is described along with the operating system, the communication possibilities with a computer and the control algorithm for the motor. Chapter six is a presentation of the motor performance and how it responds to different tests. Finally, chapter seven sums up and looks into the future.

# Chapter 2

# Physical Prerequisites

## 2.1 The Automatic Transmission

The project is carried out on the Chrysler 45RFE transmission, which is a four-gear rear-wheel-drive automatic transmission in the 1999 Jeep Grand Cherokee with a 4.7-liter V8 engine. The details of an automatic transmission will not be described here since it is not necessary for the understanding of this thesis. However, some basic knowledge is nice to have for the overall picture.

A modern automatic transmission consists of a combination of mechanical, hydraulic and electrical technology that work together in a quite fascinating way. The different gear ratios depend on the design of the planetary gear system, see figure 2.1. It consists of a ring gear, a sun gear and two or more planet gears, kept together by a planet carrier. Each of these three components can be used as input, output or be held stationary. The gear ratio is determined by choosing which part plays which role.

For example, the ring gear can be connected to the input shaft coming from the engine, the planet carrier to the output and the sun locked. If the ring is turned the planets walk along the sun gear causing the planet carrier to turn the output shaft in the same direction as the input shaft but at a slower speed. By using another combination of input, output and lock other ratios can be created. By connecting several of these planetary gear systems in series very specific ratios can be created, adjusted to desired values for all forward and reverse gears.

The 45RFE uses three identical planetary gear systems to simplify manufacturing and has the ratios 3, 5/3, 1 and 3/4 for forward op-

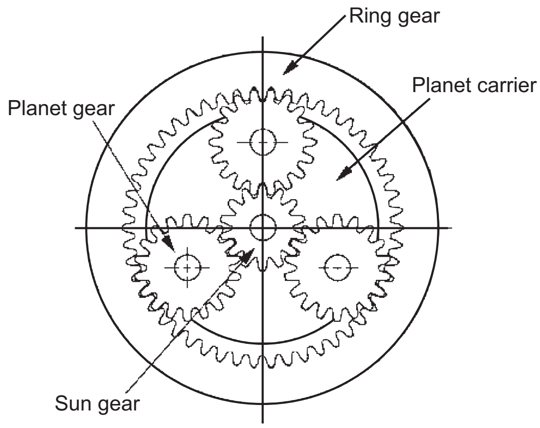


Figure 2.1: A planetary gear system.

eration and 3 in reverse. For example, this means that in reverse, the input to the transmission rotates three times as fast as the output.

The shifting procedure along with other things is controlled by hydraulics. This is done in the control valve assembly, which is a metal plate with a complex maze of passages that distribute pressurized transmission fluid to the numerous clutches and bands inside the transmission. To use a certain gear the transmission must lock some of the planetary gears and some have to be connected to the output and the input shafts. This is done by applying oil pressure at a certain combination of clutches and bands. Shifting between P, R, N and D is also controlled here by a shift valve. Depending on the position of the valve, pressure is distributed to different clutches. This shift valve is controlled mechanically by the shift lever in a normal transmission and for example by a DC motor in a shift-by-wire system. More information about the 45RFE transmission is found in [9].

## 2.2 The Actuator

Since the entire mechatronical system has to be fitted into the transmission it has to be made relatively compact, even though there is more space in a 45RFE than in many other transmissions.

Figure 2.2 shows the actuator which is added inside the normal transmission. It consists of a Brushless DC motor (BLDC motor) and a gear reduction of 1:200 to make sure the motor has enough torque to move

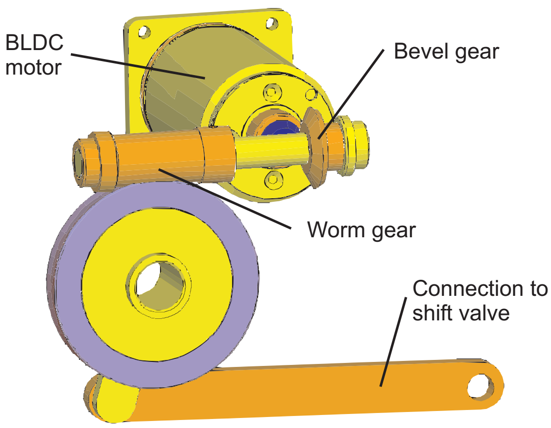


Figure 2.2: Actuator: DC motor and a gear reduction of 1:200.

the shift valve. The worm gear acts as a lock for the larger wheel so it cannot turn unless the motor is turning. This arrangement also makes sure that the shift valve is not moving out of position during driving, if there is an interruption in the control signal to the motor.

When the motor turns, the horizontal bar moves and creates a linear motion of the shift valve inside the control valve assembly. The position of the shift valve controls the hydraulics inside the transmission.

### 2.2.1 Shift Valve Positions

The distances that the shift valve has to move are P-R: 14.6 mm, R-N: 10.5 mm and N-D: 10.3 mm. That equals 14.9, 10.7 and 10.4 rotations for the motor. There is a small range of about a millimeter that is allowed at each position. This makes the system forgiving because one mm corresponds to about one rotation for the motor, so stopping inside the right range is quite easy.

During this thesis there was no time to build the entire system. The motor was not connected to the gears nor to the shift valve. Instead the motor was tested on its own and the rotations of the motor were counted when performing a shift. Later a position sensor will close the loop.

### 2.2.2 Position Sensors

To get closed loop control of the system, there is a linear position sensor for the shift valve. This is a PLCD sensor for the Mercedes and a eddy current sensor for the Jeep.

PLCD sensor stands for Permanent Magnetic Contactless Displacement sensor and it consists of a soft magnetic core surrounded by a coil, wound around the entire length. On each end of the core is a second short coil. A permanent magnet is attached to the shift valve. The magnetic flux causes localized magnetic saturation. The position of the saturated area along the sensor axis can be determined by the coil system. The output is a voltage (0 - 5V) which is sent to the A/D converter.

The reason for not using this kind of sensor in the Jeep is that it was too short for the distance, 35.4mm between P and D, so a Eddy Current sensor with maximum measuring length of 50 mm is used there. It uses Faraday's law of induction which states that an eddy current is created in a conducting material when it is placed in a changing magnetic field. The sensor consists of a cylinder with a coil inside. A metallic ring is placed around the cylinder sliding along its axis. When the coil is driven by an alternating current a changing magnetic field is created that induces eddy currents in the metallic ring. The eddy currents circulate in a direction opposite that of the coil, thus reducing the magnetic flux in the coil and thereby its inductance. The distance between the coil and the ring affects the magnitude of the influence and from there the position of the ring can be determined.

There is also a control unit driving the AC and determining the impedance of the coil. The output from the control unit is a current which goes through a resistor and the voltage from here is connected to the A/D converter. The accuracy of this sensor is extremely high, 0.15 nm. The microcontroller uses a 10 bit A/D converter which limits the accuracy to $\frac{50mm}{2^{10}} = 49\mu$m. The accuracy of the sensor is therefore excessive and a cheaper one could easily be used.

When the signal has been converted to digital values it passes through a low pass filter. This to get a less noisy signal to the controller. That is especially important when a derivative controller is used, since it is sensitive to noise. The filter is a second order Butterworth filter which creates a nice signal to the controller.

For detailed information, see [15] (the PLCD sensor), [14] (the Eddy Current sensor) and [7] (the low pass filter).

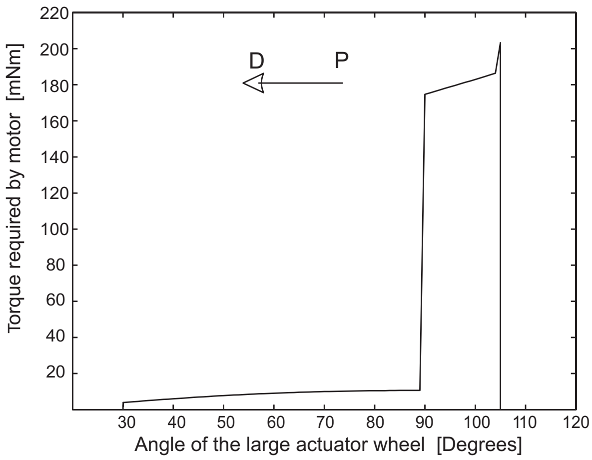


Figure 2.3: The torque characteristics when shifting from P to D. P is at 105° and D is at 20°.

### 2.2.3 Parking Lock

When the motor turns, not only the shift valve moves but also the parking lock. The critical moment is the shift to P since there in all cars with automatic transmission is a mechanical lock to make rolling impossible while in P. This is another system than the parking brake, which uses the wheel brakes to immobilize the car. The parking lock on the other hand mechanically locks the output shaft of the transmission by entering a block of metal into a wheel. This is further described in [2] and [13]. The reason for having a parking lock is a legal issue legislated by NHTSA (National Highway Traffic Safety Administration) in USA and by EU legislation. See [11] and [8].

The parking lock consists of a spring and a cone shaped cylinder that forces the block of metal into a gear inside the transmission. In an extreme case, when the car is fully loaded and parked at a steep hill, the torque on this gear can be up to 900 Nm. Then a large force is needed to pull the parking lock out of the gear and this force specifies the motor performance. The torque required by the motor is shown in figure 2.3. As seen, the torque required to move only the shift valve, between 90° and 20°, is much smaller than to remove the parking lock. If the parking brake matter was solved in another way, then a weaker/cheaper motor could be used and at the same time the system could be made faster. BMW for example solved it with hydraulics. That is not done in this project since too much of the transmission would have to be rebuilt.

Problems could occur with the parking lock if there was an error in the Shift-by-Wire system. Since the worm gear locks the position of the larger wheel, what would happen if the electronic system failed while the parking lock was in place? It would be impossible to move the car. This is not acceptable and a manual override is installed which allows the wheel to slide when a lever on the outside of the transmission is pulled. Then it is possible to drive the car to service.

These torque calculations have been made by a student in an earlier project at DaimlerChrysler [4].

## 2.3 Add-on or Integrated Shift-by-Wire

There are two separate designs that car manufacturers have used for their Shift-by-Wire systems, the integrated and the add-on system. This thesis deals with the integrated system, which means that the actuator is placed inside the transmission housing. With the add-on system the actuator is placed outside attached to the shaft that earlier was connected to the shift lever in the car interior. DaimlerChrysler is researching on both these since they have different advantages, but the integrated system will probably eventually be the more economical and practical solution.

The advantage with the add-on principle is that no alterations to the transmission itself are necessary, which means that a prototype can be built much faster. The actuator and sensor are just added on the outside of a normal transmission. One problem which arises is that the heat from the exhaust pipe, which runs close by, can disturb the system. This leads to heat insulation difficulties.

The integrated system is car model independent, meaning that when the transmission is ready it can be placed in any car model that used the transmission earlier, since no outer alterations are made. This flexibility is of course desirable. However, the system is specific to this transmission where the add-on system can easily be applied to other transmissions.

## 2.4 Shifting using Electromagnetic Valves

The shifting in automatic transmissions between the driving positions P, R, N and D has always been controlled mechanically, but the gear shifting has been done electronically. That means that it is possible to control the hydraulics in the transmission electronically, and that is done by electromagnetic valves. Could not the same method be used for the driving positions P, R, N and D?

Yes, and that would be the most elegant solution. Then the actuator would be unnecessary and the entire transmission would be controlled by the electromagnetic valves. There are two reasons why this has not been done here. The first one is that too much of the transmission would have to have been rebuilt. That could have been done but would have been a considerably larger project requiring more time. Secondly there is now the possibility to build a car in serial production with or without Shift-by-Wire with basically the same transmission. It could for example be extra equipment for a couple of years to see the public opinion.

## 2.5 Competitors

Other car manufacturers are also developing shift-by-wire systems and some already have cars in serial production. BMW has a integrated system developed by the German drive line specialist ZF and Bosch for their 7 series. It is an electrohydraulic system and a selector lever by the steering wheel lets the driver control the driving mode.

Rolls Royce uses an add-on system for their automatic transmission. Alfa Romeo, Porsche and Audi also have a system with the same function, but constructed completely different. It is a standard transmission with an automatic clutch and electronically controlled shifting by paddles at the steering wheel.

# Chapter 3

# Brushless DC Motors

## 3.1 The Principles

A normal DC motor consists of an inner rotor with a coil and an outer stator with magnets. When current is led through the coil in the rotor a magnetic field is created that interacts with the magnets in the stator. This causes a rotation of the rotor. The rotation generates a change of direction of the current through the coil, which leads to a continued rotation. The transfer of the current to and from the rotor is handled by brushes that are fastened at the stator and press against the rotor and this is the weak point of a DC motor. The friction causes wear and lowered efficiency.

A brushless DC motor is simply a normal DC motor turned inside out. That means that the coil is on the outside and the magnets are inside. See figure 3.1. The point is that there is no physical contact between the stator and rotor. The stator consists of several coils which current is lead through creating a magnetic field that makes the rotor turn. Three phases are usually used creating six different ways to let current run through the coils. A microcontroller frequently redirects the current leading to a fast-changing magnetic field turning the rotor. To be able to do this efficiently the microcontroller needs to know the position of the rotor and this information is supplied by hall sensors. To evaluate the position and redirect the current is a computational burden for the microcontroller, which is the main reason why brushless motors have not been more popular in the past. This is however not a problem today. The advantages of a BLDC motor compared to a DC motor are several.

- The friction is lower and the durability better, since there are no brushes to wear out.

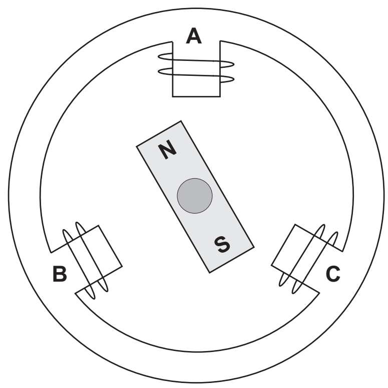


Figure 3.1: A three-phase BLDC motor.

- There is also no brush dust, which is important here where particles in the transmission oil can damage the transmission.
- A BLDC motor has a high torque/volume ratio and by the position of the coil on the outside the cooling of the motor is easy.
- Perhaps the major advantage is however that a BLDC motor can be made completely sealed off. That is important when, as in this case, the motor runs completely in transmission oil inside the transmission.

The permanent magnet usually consists of several pole pairs since that creates a larger torque than using only one pair. Naturally, the cost also increases with the number of poles. The BLDC motor used in this project consists of five pole pairs. See section 3.3.

## 3.2 Controlling a BLDC Motor

Two parameters of a normal DC motor are very easy to control, the speed and the direction. To control the speed, vary the input voltage. To change the direction, simply reverse the polarity. The speed is often controlled with pulse width modulation which is the same for normal and brushless motors. To be able to run a brushless motor, information from for example hall sensors about the angular position of the rotor is necessary. Current has to be directed through two of the three phases. The position of the rotor decides which phases should be active.

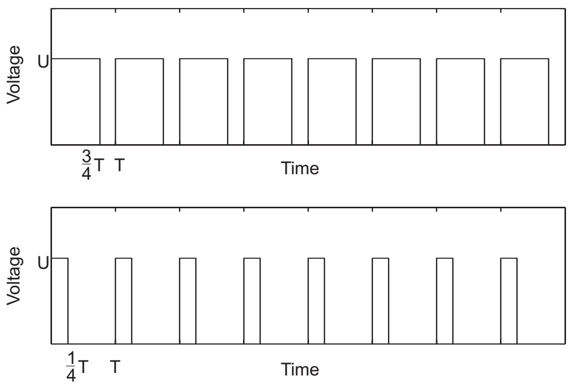


Figure 3.2: PWM signals with 75% and 25% duty cycle respectively.

### 3.2.1 Pulse Width Modulation

Pulse width modulation, PWM, is a very popular method for controlling the speed of electric motors. The principle is simple. For example, if the speed should be 50% of the maximum speed, the voltage is not turned down to 50%. Instead, the voltage is quickly turned on and off resulting in an average voltage of 50%. If 75% is required, called a duty cycle of 75%, then the voltage is kept turned off 25% of the time. See figure 3.2. If the switching frequency is high enough the motor will run at steady speed due to the inertia and inductance of the motor. This method has some nice advantages:

- It is easy to implement in a microcontroller. Only one output pin is needed to control the speed.
- No battery power is lost at low speeds. If variable voltage is used then a possibility would be to place a resistor in series that would absorb part of the voltage. However, that would mean that the battery is still supplying maximum voltage and that power would be wasted in the resistor.
- A motor controlled by PWM will generate more torque as the pulses use the full power supply in short intervals.

### 3.2.2 Hall Sensors

Knowledge of the angular position of the rotor is necessary for the microcontroller. Without this information, it does not know how to apply voltage to the three phases to create a torque. The angular position is

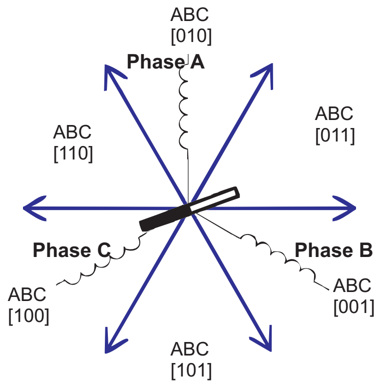


Figure 3.3: The six hall sensor states of the motor.

therefore supplied by hall sensors.

When a magnetic field is applied to a system with an electric current a hall voltage perpendicular to the field and to the current is generated. This was discovered by Edwin Hall in 1879. This principle is often used in BLDC motors to determine the position of the rotor. The sensor delivers three signals that comprise six states, described in [6] and [1]. Each state corresponds to a certain position of the rotor, which therefore can be determined with 60° accuracy. See figure 3.3. For example, at the moment the rotor is in state ABC[100].

### 3.2.3 Torque Generation

To generate maximum torque, the angle between the stator flux and the rotor flux has to be kept at 90°. There are BLDC motors using two or four phases but only three-phase systems will be discussed here. By applying voltage to two of the three phases the field can be directed in six different directions, see figure 3.3. The result is that the angle cannot be kept at 90°, instead it varies between 60° and 120°. The commutation process is illustrated in figure 3.4. The moment the rotor exits hall state ABC[110] and enters ABC[100], the current is lead through the windings in a different way resulting in a stator flux change of 60° counter clockwise. This to keep the angle between stator and rotor flux as close to 90° as possible for maximum torque. This switching of currents is called commutation.

Figure 3.5 shows how the voltage is switched for counter clockwise rotation. Exactly one phase is high and one is low at every moment

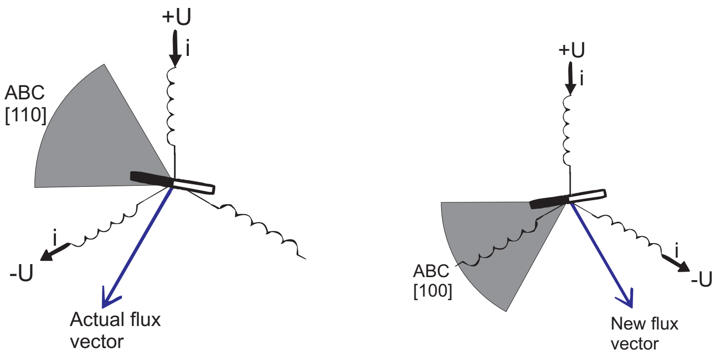


Figure 3.4: The commutation process. The left figure shows the moment prior to commutation and the right the situation afterwards for rotation counterclockwise.

| HS A | HS B | HS C | Phase A | Phase B | Phase C |
|---|---|---|---|---|---|
| 1 | 0 | 0 | $+U$ | $-U$ | $NC$ |
| 1 | 0 | 1 | $+U$ | $NC$ | $-U$ |
| 0 | 0 | 1 | $NC$ | $+U$ | $-U$ |
| 0 | 1 | 1 | $-U$ | $+U$ | $NC$ |
| 0 | 1 | 0 | $-U$ | $NC$ | $+U$ |
| 1 | 1 | 0 | $NC$ | $-U$ | $+U$ |

Table 3.1: Commutation sequence for counterclockwise rotation depending on the hall sensor output.

during a complete rotation. Table 3.1 shows the same thing again plus the states of hall sensors. The decision of how the current should be applied is made from this table, but since large currents often are needed, the decision-making and the actual power supply are separated. The last stage before the motor is a three-phase bridge gate driver which handles the high currents, see figure 3.6. It receives on or off signals to its high and low side switches which allows currents to run through the motor. Only one of the low side and one of the high side switches are allowed to be active simultaneously.

### 3.2.4 System Overview

One way to summarize how to run the brushless DC motor is shown in figure 3.7. The hall sensors constantly supply the angular position of the motor to the commutation handler. By measuring how often the hall sensors change state it is easy to calculate the speed. The digital controller uses the target speed $\omega_{ref}$ and the actual speed $\omega_{act}$ to

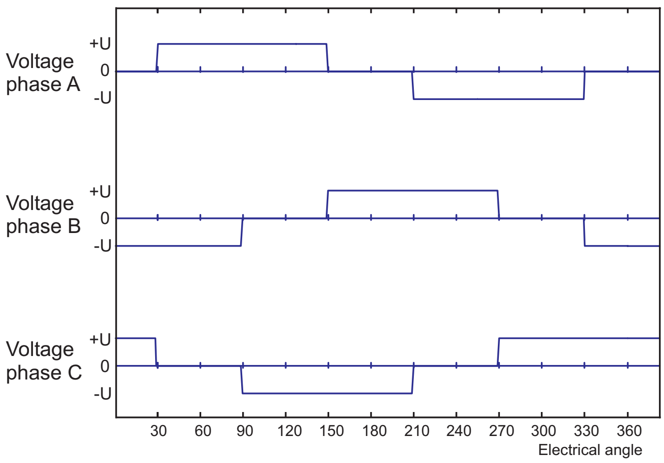


Figure 3.5: Voltage strokes applied for counterclockwise rotation.

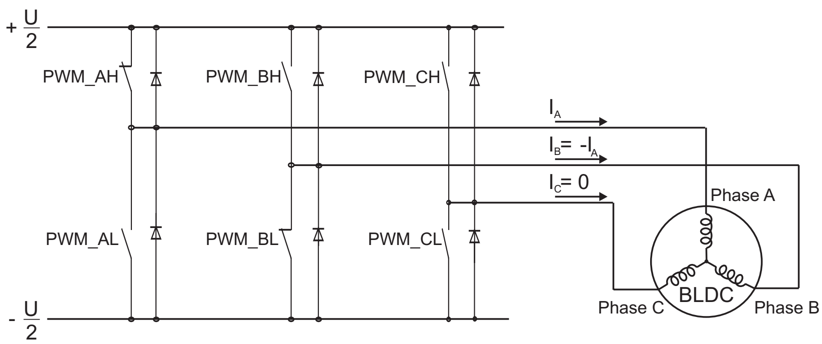


Figure 3.6: An example of a three phase bridge gate driver that handles the current supply to the motor. In this case $PWM_{AH}$ and $PWM_{BL}$ are high.

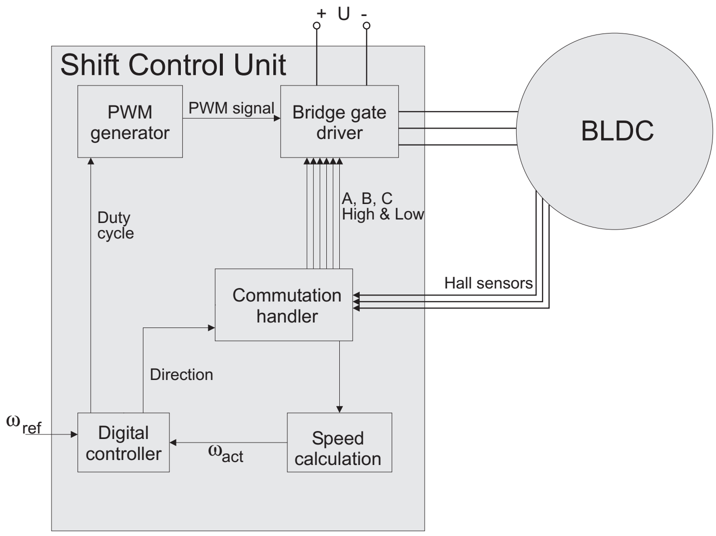


Figure 3.7: System overview.

determine the new duty cycle. It also sends the desired direction to the commutation handler. This is where the directions of the currents to the motor are decided. It uses a table like table 3.1 and sends six signal to the bridge gate driver's six switches. The PWM generator creates the appropriate signal from the duty cycle and sends it to the bridge gate driver. The switches that are set to be open are then not constantly open but instead turned on and off at the high PWM frequency. This creates the right magnitude and direction of the current. Finally the voltages over the three phases is similar to those in figure 3.8.

## 3.3 Brushless Motor MM41 35-3L

The motor used is supplied by the French company MMT, Moving Magnet Technology. It has five pole pairs which means that the rotor consists of five magnets, totally 10 poles. See figure 3.9. After one rotation each hall sensor has switched value 10 times, and no two have switched at the same time. That means that the hall state changes 30 times during one rotation. To avoid misunderstandings, two separate rotations must be defined. One mechanical rotation, 360 mechanical degrees, is one turn for the motor. But during that time 5 electrical rotations are made because it passes the north and south side of the rotor 5 times. In an example like figure 3.1 there is no difference between these two since it only has one pole pair. More pole pairs could make

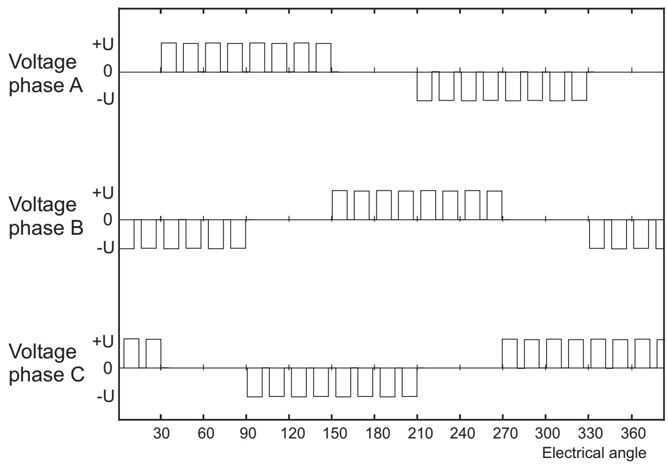


Figure 3.8: Voltages for each phase from the bridge gate driver.

the motor slower, since it has to switch current direction 30 times per rotation compared to just 6 times. The advantage with more poles is that the torque is higher.

Since the position sensor is not yet connected, these hall sensor signals are not only used to obtain the rotor position, but also to estimate the position of the shift valve, had it been connected. P is set to position 0. R is 14.9 rotations away, which equals 446 hall state changes. In the graphs in the following chapters there are steps from for example 0 to 446. This is explained further in section 5.2.2.

### 3.3.1 Specifications

The specifications of the motor which have been used during modelling of the motor are shown in table 3.2. The stall torque is well above the around 200 mNm which is the maximum in figure 2.3, which means that the motor is strong enough.

## 3.4 Sensorless Driving

The development of BLDC motors is now going in the direction of sensorless motors, which means that the hall sensors are removed. Then the rotor position has to be measured in some other way. There are at least three reasons for this progress.

- Productions costs. If a system like this would come to the point

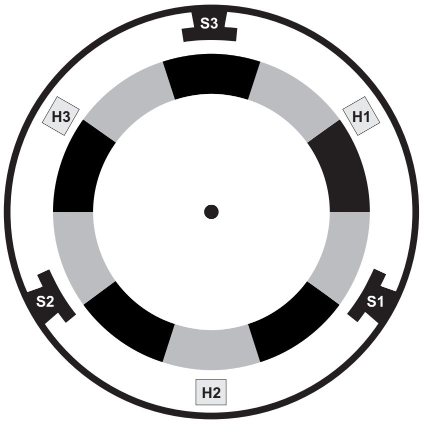


Figure 3.9: The MMT motor with five polepairs.

| MMT MM41 35-3L | | |
|---|---|---|
| Maximum speed | 6000 | rpm |
| Peak stall torque | 946 | mNm |
| Peak torque at maximum speed | 169 | mNm |
| $K_m$ | 0.018 | Nm/A |
| $K_e$ | 0.018 | V/(rad/s) |
| Inertia, J | 27 | $gcm^2$ |
| Inductance, L | 250 | $\mu$H |
| Resistance, R | 0.2 | $\Omega$ |

Table 3.2: Specifications for the BLDC motor from MMT.

of mass production, the manufacturer has to try to cut the production costs. Every euro saved on each car is important in a series of 100000 cars. The cost of the sensors and the wiring is then considerable.

- Impossibility to make additional connections between the motor and the control unit. With normal BLDC control the sensed information must be sent to the control unit using three extra cables. This is not always possible.

- Errors in systems like this often occur in cables and sockets. Fewer cables lead to fewer potential errors.

It has been shown that by sensing the voltage at the third phase, the one not connected to the power, the position of the rotor can be estimated. A method usually called back-EMF sensing will be discussed here.

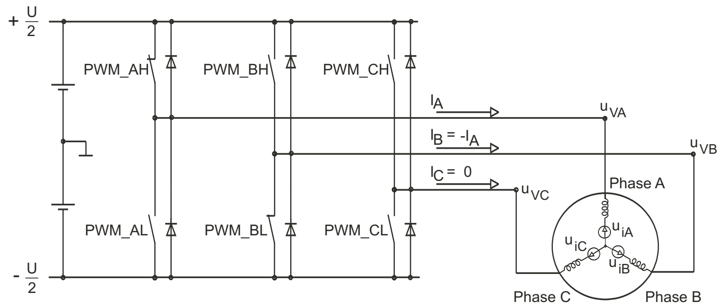


Figure 3.10: The three phase bridge driver with the back-EMF voltages $u_{iA}$, $u_{iB}$ and $u_{iC}$ shown.

### 3.4.1 Back-EMF Sensing

When the current is commutated, back-EMF voltages are induced in the stator windings. Let us assume that phases A and B are powered by the PWM signal and phase C is not connected, as in the following scenario. See also figure 3.10. $u_{VA}$, $u_{VB}$ and $u_{VC}$ are the branch potentials, i.e. the voltage between one power stage output and ground. $u_{iA}$, $u_{iB}$ and $u_{iC}$ are phase back-EMF voltages induced.

$PWM \rightarrow PWM_{AH}, PWM_{BL}$
$u_{VA} = u/2, u_{VB} = -u/2$
$i_A = -i_B, i_C = 0$

The desired variable $u_{iC}$ cannot be measured, but $u_{VC}$ can. The relationship between the two variables can be calculated from figure 3.10. How it is done is shown in [3]. The equation is only valid when phase C is not powered. Since

$$u_{VC} = \frac{3}{2} u_{iC} \tag{3.1}$$

can the induced back-EMF voltage $u_{iC}$ be calculated by measuring the voltage $u_{VC}$. The voltages for the other phases can be calculated accordingly. During one revolution, 0-360 electrical degrees, the voltage $u_{VC}$ varies according to the pattern in figure 3.11. The shaded rectangles show where equation 3.1 is valid. Those are the areas where phase C is not connected to power. Then 30 degrees after each zero-crossing point the commutation occurs and phase C becomes powered. By sensing these zero-crossing points it is possible to control the commutation without the hall sensors. One can also vary the angle from the 30 degrees after the zero-crossing point to get a better behavior.

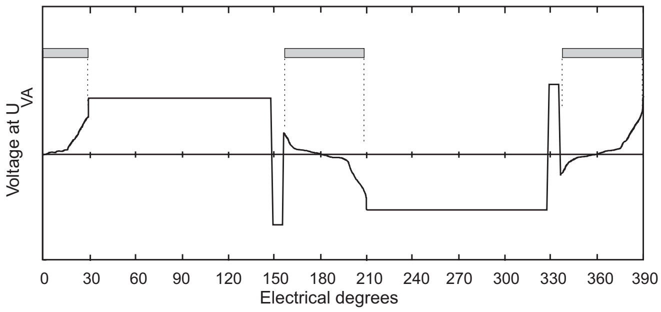


Figure 3.11: Branch voltage during one revolution. The angular position of the rotor can be estimated by sensing the zero-crossing points, here at 180° and 360°.

This deviation is called switching angle and can be adjusted to fit the load applied to the system.

# Chapter 4

# System Modelling

A Simulink model of the system has been made in two previous theses, [13] and [15]. Some small modifications were made, such as adding measuring noise. The model could be used as it was, even though it was made for a normal DC motor. The behavior seemed to fit also for this motor. Only some constants had to be calculated in another way. Figure 4.1 is the model of the entire system. It is a closed loop with the actuator, controller and position sensing.

## 4.1 Modelling a DC Motor

It is quite easy to model a normal DC motor so that the angular velocity $\omega(t)$ is controlled by the applied voltage $u_{app}(t)$. The model is entirely based on some fundamental laws of physics. Further details can be found in [10] and [16]. To start with, Kirchhoff's law can be used on the circuit in figure 4.2, resulting in equation 4.1 describing the electrical part of the motor. Newton's second law describes the mechanical part, how the torque affects the system. It states that the inertial load J times the angular acceleration is equal to the sum of all torques, equation 4.2.

$$u_{app}(t) = Ri(t) + L\frac{di(t)}{dt} + u_{emf}(t) \tag{4.1}$$

$$J\frac{d\omega(t)}{dt} = \sum \tau_i \tag{4.2}$$

Faraday's law of induction states how a change in the magnetic environment of a coil causes a voltage (electromagnetic force, emf) to be induced in the coil. This is the same principle as in the eddy current sensor, chapter 2. The back emf, $u_{emf}(t)$, is proportional to the angular velocity $\omega(t)$. Lorentz's force law describes the force upon a coil in a magnetic field. That leads to that the produced torque $\tau(t)$ is

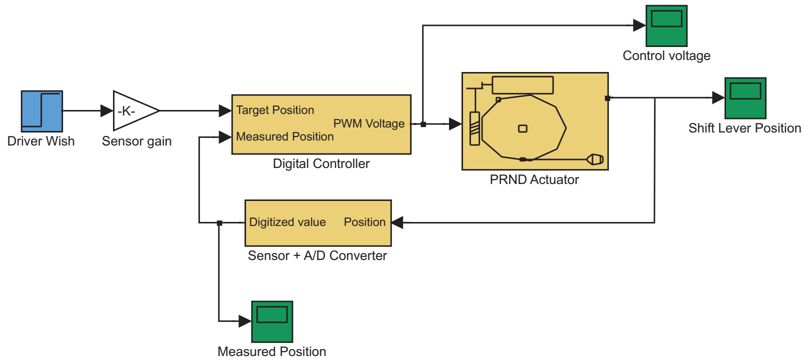


Figure 4.1: A model of the total system.

proportional to the current $i(t)$. These two laws lead to the following expressions,

$$u_{emf}(t) = K_e \ \omega(t), \tag{4.3}$$

$$\tau(t) = K_m \ i(t). \tag{4.4}$$

$K_e$ $[V/(rad/s)]$ is the emf constant and $K_m$ $[Nm/A]$ is the armature constant, which are both related to physical properties of the motor, such as magnetic field strength and number of turns of the coil. These have the same numerical value in SI units. By combining equations 4.1 and 4.3 can the electrical part of the motor be described by

$$u_{app}(t) = Ri(t) + L\frac{di(t)}{dt} + K_b \ \omega(t). \tag{4.5}$$

Equations 4.2 and 4.4 lead to the mechanical part

$$J\frac{d\omega(t)}{dt} = K_m \ i(t) - K_f \ \omega(t), \tag{4.6}$$

where $K_f \ \omega(t)$ is the result of the friction in the motor. Friction also comes from the transmission oil the motor is running in. This friction is extremely temperature dependent. This leads to two differential equations describing the system which can for example be used in a state-space representation,

$$\frac{di(t)}{dt} = -\frac{R}{L}i(t) + \frac{1}{L}u_{app}(t) - \frac{K_b}{L}\omega(t), \tag{4.7}$$

$$\frac{d\omega(t)}{dt} = \frac{K_m}{J}i(t) - \frac{K_f}{J}\omega(t). \tag{4.8}$$

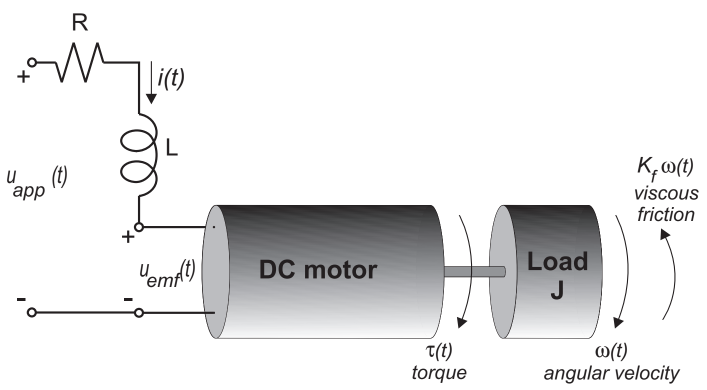


Figure 4.2: A simple model of a DC motor.

The state-space system has two states, the current $i(t)$ and the angular velocity $\omega(t)$. Input is the applied voltage $u_{app}(t)$ and output is the angular velocity $\omega(t)$,

$$
\begin{aligned}
\frac{d}{dt}\begin{bmatrix} i(t) \\ \omega(t) \end{bmatrix} &= \begin{bmatrix} -\frac{R}{L} & -\frac{K_e}{L} \\ \frac{K_m}{J} & -\frac{K_f}{J} \end{bmatrix} \begin{bmatrix} i(t) \\ \omega(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} u_{app}(t) \\
y(t) &= [0 \quad 1] \begin{bmatrix} i(t) \\ \omega(t) \end{bmatrix}.
\end{aligned}
\tag{4.9}
$$

From this representation the transfer function can be derived. Methods are described in for example [5] and lead to the transfer function from $u_{app}(t)$ to $\omega(t)$,

$$
G(s) = \frac{\omega(t)}{u_{app}(t)} = \frac{K_m}{JLs^2 + (RJ + K_f L)s + RK_f + K_e K_m}. \tag{4.10}
$$

Normally the friction $K_f$ is small, resulting in that $RJ >> K_f L$ and $K_e K_m >> RK_f$. These significantly smaller terms are neglected and the transfer function for a DC motor is often written as

$$
G(s) = \frac{K_m}{JLs^2 + RJs + K_e K_m}. \tag{4.11}
$$

By dividing both the numerator and denominator by $K_e K_m$, the time constants can be identified.

$$
G(s) = \frac{1/K_e}{\frac{RJ}{K_e K_m}\frac{L}{R}s^2 + \frac{RJ}{K_e K_m}s + 1} \tag{4.12}
$$

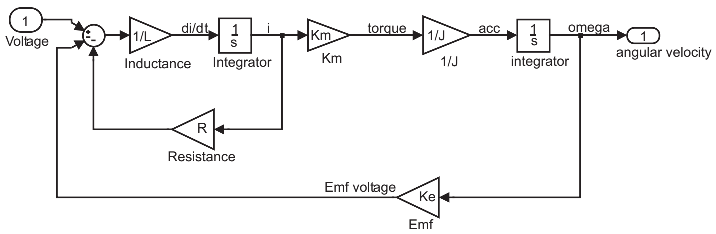


Figure 4.3: A Simulink model of a DC motor.

With the mechanical time constant $\tau_m = \frac{RJ}{K_e K_m}$ $[s]$ and the electrical time constant $\tau_e = \frac{L}{R}$ $[s]$ the expression finally looks like

$$G(s) = \frac{1/K_e}{\tau_m \tau_e s^2 + \tau_m s + 1} \tag{4.13}$$

This is also the transfer function for a BLDC motor. The only difference is the way to calculate the resistance and inductance, since the motor has three phases (see chapter 3 and especially figure 3.6). This does not affect the model. Only the way to calculate the motor constants $K_e$, $K_m$, $\tau_m$ and $\tau_e$ is changed. This is described in [16].

The resulting model of the motor in Simulink is figure 4.3. It is one part of the PRND Actuator block in figure 4.1.

## 4.2 Modelling the Gears

To be able to move the shift valve the speed needs to be reduced. This of course makes the system slower, but also allows the motor to run at high rpm. The gear ratio in this system is 1:200, which means that 200 turns for the motor equals one turn for the output. Since a DC motor is very fast this not a problem.

The gears consists of one bevel gear with the ratio 1:2 and one worm gear with ratio 1:100. See figure 2.2. The efficiency is in the model estimated to about 80% for the bevel gear and 20% for the worm gear, leading to a total efficiency of about 15%.

## 4.3 Output from Simulation

The simulink model is used to find suitable control parameters. Figure 4.4 shows the result of a simulation. The top plot shows the position and the bottom the control signal during a step from P to R.

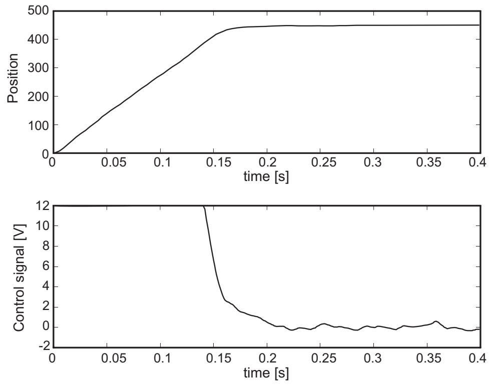


Figure 4.4: The results from a simulation with K= 0.5 and $T_d = 0.004$. The y-axis in the position plot is scaled to match the hall state changes.

The position is the output from the A/D converter in figure 4.1, called Measured Position. The The control signal is the ouput from the digital controller, called Control Voltage. Comparisons to the actual output are made in chapter 6 and they show that the model fits the measured data quite well.

The Simulink model is also used to verify that the motor is strong and fast enough. To see if the system has enough safety margin, the efficiency of the gears can be lowered and the motor torque needed can be checked. One also has to make sure that the system is fast enough and verify that the chosen gear ratio is the appropriate one. In this case is the motor very strong with a high torque. By studying the torque at different places in the model one can see that the gear ratio 1:200 is not needed. Maybe 1:100 is more appropriate.

# Chapter 5

# Software

This chapter intends to explain how the control of the motor is coded and also which programmes and standards are used. An overview of the system is seen in figure 5.1. It shows both the Shift Control Unit (SCU), which runs the motor, and the communication with a computer used during development. The programmes running on the computer handle the following.

- Let the user change the driver wish, i.e. shift driving position.
- Receive the results from a shift via a Matlab Graphical User Interface.
- Supervise the traffic on the CAN bus and adjust control parameters.
- Flash updates of the code to the SCU. This program can also handle real-time debugging of the system.

The SCU and the communication with the computer will be described in the following pages. Last is a description of the control algorithm running on the SCU.

## 5.1 Shift Control Unit

The Shift Control Unit (SCU) contains all the electronics needed for controlling the motor. The heart is a microprocessor, HC12 from Motorola, which is very commonly used in cars. Also there are chips for commutation of the BLDC motor, CAN communication, serial communication and A/D converters.

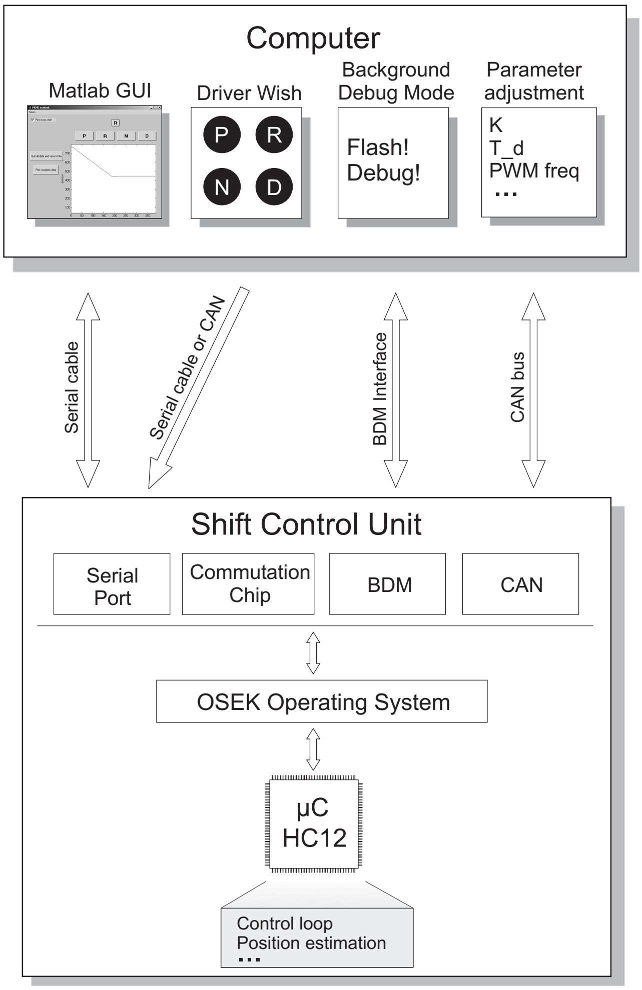


Figure 5.1: Software overview.

### 5.1.1 Microcontroller HC12

A microcontroller is a complete computer system with CPU (Central Processing Unit), memory, a clock oscillator and input/output on a single integrated circuit. In this project the HC12 microcontroller from Motorola was used which is a 16-bit device with 25 MHz maximum bus speed.

### 5.1.2 The Operating System

The operating system running on the SCU is developed by OSEK which is a joint project of the automotive industry. OSEK is an abbreviation for the German term "Offene Systeme und deren Schnittstellen für die Elektronik im Kraftfahrzeug" meaning "Open Systems and the Corresponding Interfaces for Automotive Electronics". The goal was to standardize the interfaces of control units and make them more application-independent. This to make control units from different manufacturers compatible, [12].

The OSEK operating system is designed for real-time applications and capable of multitasking. It uses tasks with different priority and a scheduler organizes the sequence of task execution. Each task has its own frequency deciding how often it should be activated. This project uses two tasks ordered after priority.

- Task 1: Motor control.
- Task 2: Driver wish

The driver wish function listens to signals from the driver. If a shift is requested, this function goes through a check list to see if a shift is allowed. With a positive result the motor control function is activated. It runs the motor to move the shift valve to the target position. During testing two more tasks are used.

- Task 3: Change control parameter via CAN (see section 5.1.4).
- Task 4: Communicate with PC. (see section 5.1.3)

How often each task should be executed is set individually and task 1 will interrupt any other task when the scheduler tells it to start.

### 5.1.3 Serial Communication

The SCU has a chip for serial communication and this is connected to the serial port of a PC. In the motor control function there is a possibility to sample a shift. For example can the position, control signal and hall state be saved in an array. When the control algorithm is finished

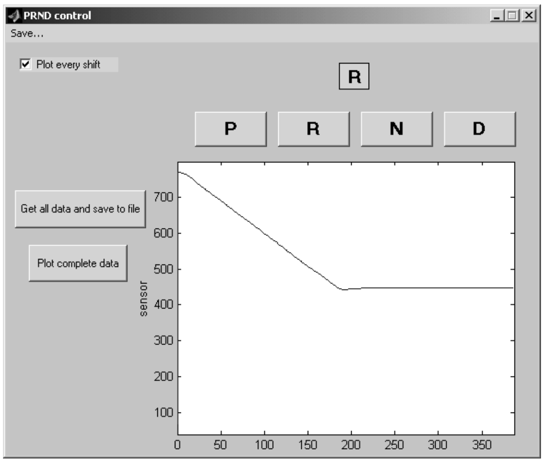


Figure 5.2: A screen shot of the Matlab Graphical User Interface that receives data from the SCU via the serial port.

and the shift valve is at the desired position, the sampled signals are sent over the serial cable along with the current control parameters. A simple GUI (Graphical User Interface) is created in Matlab which can receive signals directly from the serial port. It automatically plots available signals and saves them to a file. This makes the evaluation easier. The rise time and overshoot can be checked and the control parameters can be adjusted accordingly. There is also a possibility to change the driver wish from the GUI. The memory size of the CPU allows that around 2400 samples are saved, 800 each of position samples, control signal and for example hall state. These 800 samples are collected in about 300 ms.

### 5.1.4 Controller Area Network

Controller Area Network (CAN) is a serial communication bus for real-time control applications and was originally developed by Bosch. It is used for many time-critical applications like anti-lock braking systems, engine management and traction control. The speed is up to 1 Mbit/s and there is a good error detection. CAN is based on the so-called broadcast communication mechanism, which means that no receiving addresses exist, only messages. These messages are identified by using a message identifier. The identifier is a unique number within the network. A control unit checks the identifier of each message that passes on the bus to see if it is something of interest. In that case the entire message is read. All messages also have a priority. This is be important when several stations compete for bus access.

In this project the CAN bus is used during the development phase to send signals to the control unit. For example can the control parameters, PWM frequency and driver wish be changed via a CAN programme on the PC. This makes the work much faster since no changes in the code are necessary. The driver wish will possibly still be sent over the CAN bus in serial production. The shift control unit will listen to the bus and check all identifiers to see if the driver wish identifier shows up.

### 5.1.5 Background Debug Mode

Background Debug Mode (BDM) is a standard for debugging code running on embedded systems. A program, Zap Debugger from Cosmic Software, is running on the computer debugging the code on the SCU in real-time. The communication is done through the parallel port on the computer to a BDM interface which is connected to the SCU. The main reason for using this is its flashing capabilities. When updates in the code are done, they are flashed onto the microcontroller's flash module. Through the Zap Debugger you can halt and start execution of the code, as well as step through it.

## 5.2 Control Algorithm

The goal for the control is to switch as quickly as possible between the positions P, R, N and D without overshoot. Since the BLDC motor is running without being connected to the gears and thus without any load not too much time has been spent on trying to optimize the performance and find the optimal parameters. The dynamics will probably change too much when the system is complete. For example, the total inertia of the system will increase. The control algorithm used has been developed in an earlier thesis [7], and only some smaller modifications have been made. It is a PD controller with some modifications for the D-part. First the continuous version,

$$v(t) = K(y_{ref}(t) - y_{act}(t) + T_d \frac{d(\beta y_{ref}(t) - y_{act}(t))}{dt}) \tag{5.1}$$

where $K$ is the proportional coefficient and $T_d$ the derivative coefficient. $\beta$ is set to 0 to avoid spikes in the control signal when the reference value is changed, i.e. a shift occurs. This has not the desired effect since the steps are large and the proportional part is large enough to alone maximize the control signal. However, the overall result is better than when $\beta$ is set to one.

The discrete differential approximation is realized by the backward Euler method. It computes the difference between the current sample and an earlier sample and divides by the time between the samples. With $\beta = 0$ the control signal

$$v[n] = K(y_{ref}[n] - y_{act}[n] - T_d \frac{y_{act}[n] - y_{act}[n-N]}{T_s N}), \tag{5.2}$$

where N is the number of samples used by the Euler backward method. A larger N generates a smoother derivative which is less sensitive to noise. In this application is N=20. The derivative part is now only dependent of the actual output and not changes in the reference signal. The maximum control signal is 100% PWM so the following nonlinearity is added:

```
if v > MAX_PWM
    u = MAX_PWM
else if v < -MAX_PWM
    u = -MAX_PWM
else
    u = v
```

In task 1, where the motor control is placed, there is a loop that executes the control algorithm a number of times. How many times the loop should be iterated is a matter of adjustment. A short loop takes shorter time which means that during long time the motor is not controlled, since task 1 is not active. The position of the motor could change a lot while other tasks are active and that results in a bad controller. But the loop cannot take longer time than the period time of the task. Then the other tasks will never be active. The ratio between the length and the period time of task 1 was set to about 85-90%, which led to 40 iterations for the loop. That means that during one round of task 1 the position is checked and the control signal is updated 40 times.

### 5.2.1 Accuracy Demands

The mechanical system is forgiving in the respect that there is a small range that is allowed for the shift valve for each driving position. That means that it is not essential for the shift valve to be exactly in place, there is about half a millimeter in each direction that also is permitted. Without this safety margin there would be problems with noise. In all systems there are noise of different kinds and this will especially affect the measurements of the position sensor.

To avoid constant corrections from the motor when noise is influencing

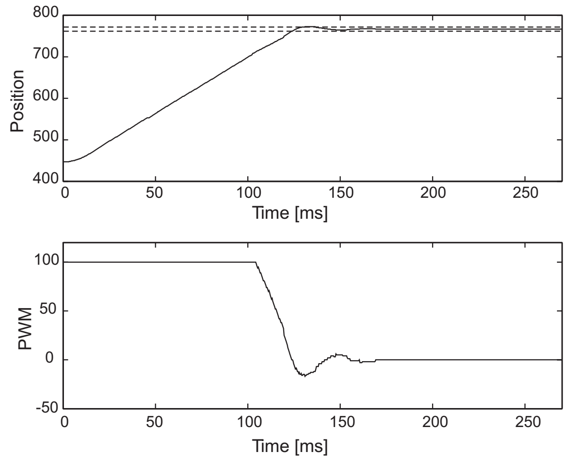


Figure 5.3: A step where the control signal is turned off after the position has been in the right area for 100 samples. The position at the y-axis is referring to the number of hall state changes.

the sensor signal when the position actually is within the permitted range, the control algorithm is designed to stop regulating when the position has been in the right area a certain time. This prevents wear to the actuator and unnecessary power consumption.

The result is shown in figure 5.3 and 5.4. The second figure is a zoom at the point where the position reaches its reference value and the x-axis is changed from milliseconds to samples. It shows how the position enters the accepted range (767 $\pm$ 5 samples) at around sample 400. It stays there for 100 samples, which is the condition to stop controlling. Therefore the PWM signal is set to 0 at around sample 500, even though the position is not exactly at the target position 767.

This way of control has been shown to work in this case where the exact position is not essential. This is also nice because the brushless DC motor has some problems with low PWM signals. There is a magnetic resistance that can be felt if the motor is rotated by hand when it is turned off. There are only a number of positions in one rotation that the motor will stop at. If it is let go at another point, it will return to one of these positions. The result is that the position could be one or two hall states from the target and the control signal is a few PWM, but it cannot move the motor. This problem is also solved with this technique of having a ”good-enough-range”.

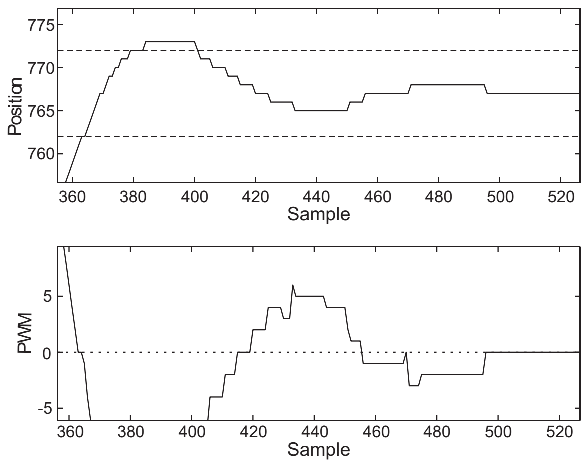


Figure 5.4: A zoom of figure 5.3.

### 5.2.2 Position Estimation

Since the BLDC motor is not yet connected to the gears and the shift valve, there is also no position sensor signal to close the control loop. Instead a function was created that checks which hall state the motor currently is in. This function does not handle the actual commutation. That is handled by hardware in the commutation chip. This software function only counts the number of hall state changes and from that it calculates the distance that amount would equal for the shift valve. The distance of 14.6 mm between P and R equals an angle change of 26.8 degrees for the large actuator wheel. That equals $200 \cdot 26.8 = 5351$ degrees for the motor, i.e. 14.87 rotations. During one rotation of the motor the hall state changes 30 times, see section 3.3. Thus, a shift from P to R equals $14.87 \cdot 30 = 446$ hall state changes. The function is illustrated in figure 5.5.

One problem that has not been dealt with is caused by the tasks of the operating system. The function counting the hall state changes is placed in task 1. That means that any hall state change occurring during another task is not registered. If task 1 is active 90% of the time then 446 registered changes is only 90% of the real amount, since the motor also is running when other tasks are active.

The result of this problem is shown in figure 5.6. The state of the hall sensors are changing in the order 1-3-2-6-4-5, which corresponds to a counterclockwise rotation in figure 5.5. When it comes to sample

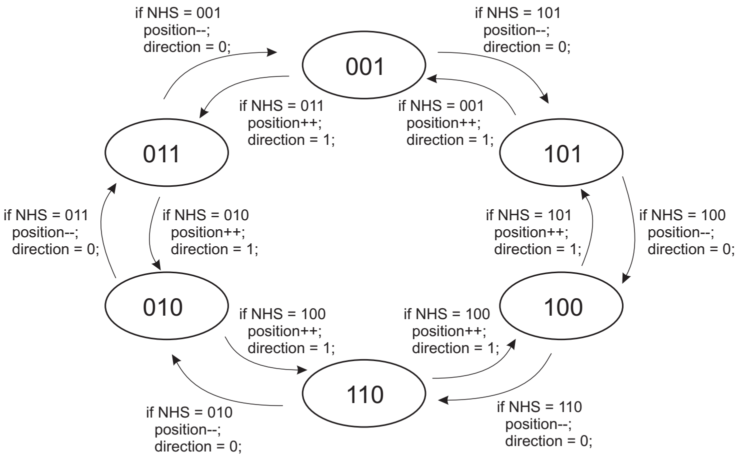


Figure 5.5: The principle for the hall state change counter function. NHS = New Hall State.

642, there is a jump in the other direction, from 2 to 3. That results in a position change in the wrong direction. This does not mean that the motor has changed direction. The reason is that sample 641 is the last sample during task 1 and 642 is the first sample when task 1 starts again. In the time in between, the motor has run, unknown how many turns, and when task 1 starts again the hall state happens to be 3 and a decrease of the position is registered. After that the correct direction is set.

Important to remember is that this does not affect the actual commutation. What happens when an error occurs is only that the distance to the target position is calculated falsely. The evaluation of the results is harder since it is not completely clear the exact distance the motor has turned.

This could be solved by creating some kind of interrupt for this function. Maybe could the control task be activated every time the hall state changes. Then no state would be missed and the control signal could be updated at every change. That was however not possible with the software and actually not really important. The problem will not appear when a signal from a real position sensor is used. This function is only used temporarily to calculate the distance the motor is turning. A signal from a sensor is updated independently of which task is active.

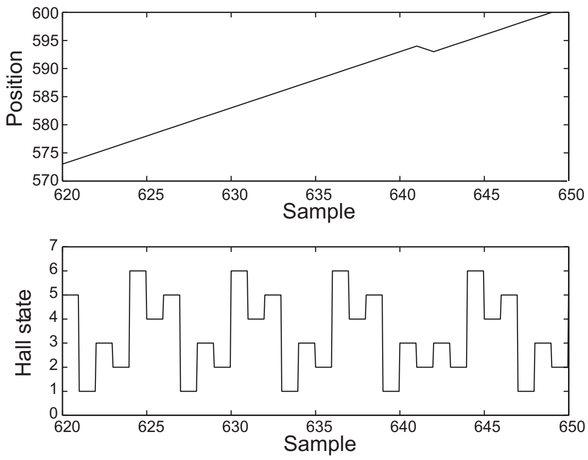


Figure 5.6: An error occurs in the hallstate counter function at sample 642.

# Chapter 6

# Motor Performance

This chapter will describe the behavior of the motor and the tests carried out. First is a normal step which length corresponds to a shift for the transmission. The result is compared to the simulation and some similarities are seen. Also a test with different PWM frequencies is performed to find the optimal frequency. The motor is not connected to the gears in any of these tests. It is running with no more load than its own inertia. The position is estimated by counting the hall state changes.

## 6.1 Adjustments of the Measurements

To compensate for the problem with the software tasks described in section 5.2.2, all graphs in this chapter are slightly adjusted. This is done by measuring the top speed of the motor with an oscilloscope to be independent of the operating system. This top speed, which is the correct one, is measured to 5500 rpm. It is then compared to the calculated top speed from the samples saved at the SCU. This value is lower since it is affected by the problems with the tasks, typically around 5000 rpm. The time axle is scaled by 5000/5500 to compensate for this and the result is a plot which probably better corresponds to the actual behavior.

## 6.2 Simulation Comparison

Figure 6.1 shows a shift between R and N. Such a shift equals 321 hall state changes, from position 446 to 767. The graph shows the position and the control signal and the similarities between the simulation and the measurements are obvious. The motor is quickly coming to its top speed and keeps running there for around 100 ms. During this time

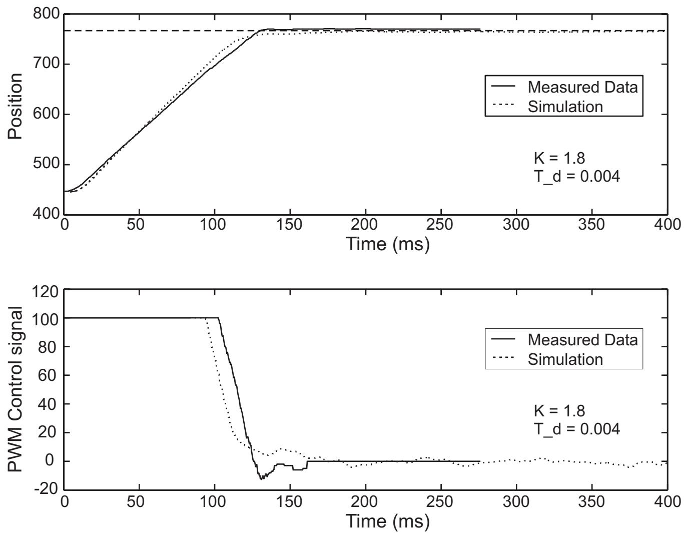


Figure 6.1: Comparison between the simulink model and measured data.

the PWM control signal is at 100%. At time 100 ms the control signal is lowered and the position quickly stabilizes at the target position. When the position has been within the stipulated accuracy limits for 100 samples the control signal is set to 0.

## 6.3 Control Parameter Settings

The system has been tested with different PID settings and reacts in a familiar way to parameter changes. An increased proportional K value makes the system faster but also increases the overshoot. Since the control signal is 100% for a large part of the step the time gain when increasing K is only marginal. A derivative part was added which dampened the overshoot. Some tests were made with an integral part but with no real improvements. It was therefor left out and finally a PD controller was used.

Until the motor is added into the transmission and can be tested in its real surroundings there is no point in optimizing the parameter settings. This report does therefore not contain any recommended settings for future use. Instead values that work and give a stable system have been found which can be used as a starting point for future optimization. The parameters will also need to be adjusted to the temperature,

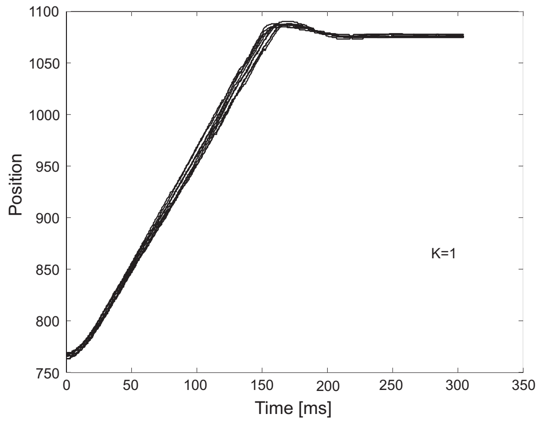


Figure 6.2: A shift from N to D using 8 different PWM frequencies.

which affects the oil viscosity.

## 6.4 PWM Frequency Test

The control has been tested using eight different PWM frequencies, 117 Hz, 469 Hz, 938 Hz, 1.875 kHz, 3.75 kHz, 7.5 kHz, 15 kHz and 25 kHz. The first test showed no difference at all, see figure 6.2. It is a shift from N to D and the results can hardly be separated. This is because during a large part of the step the control signal is maximized. This means that the PWM duty cycle is 100% and the PWM frequency is not important. Not until after about 100 ms is the PWM lower than 100% and actually switching on and off. This shows that maybe the frequency is not important for this application.

An other test was initiated. The step was made smaller so that the duty cycle never reaches 100%. Also, when the controller normally turns off after having been in the right range for a certain time, a step back again was begun. This test shows more difference between the frequencies.

The frequencies between 938 Hz and 15 kHz all show the same behavior and only one of them, 15 kHz, is shown in figure 6.3. It is the fastest to stabilize and take a step down. The lowest frequency has a much bigger overshoot than the others do and therefor needs more time to get to the target position. The second lowest has a smaller overshoot but is almost as slow. The highest frequency, 25 kHz, also

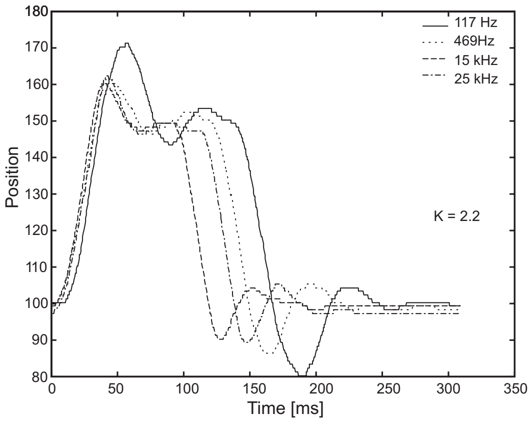


Figure 6.3: Comparison between four different PWM frequencies. Both the low and the high frequencies have problems.

had problems which was a bit surprising.

Another thing to consider is the frequency range audible to the human ear. One common guideline is to use a frequency higher than 20 kHz, which is the upper limit of which we can hear, if some resonance noise is created. This is not important now though, since the motor is only running in short intervals and furthermore in a car.

### 6.4.1 Problems at Low Frequencies

When a low PWM frequency is used the motor gets problem with the commutation. It is shown in figure 3.8. Each phase is high during 120 electrical degrees which is 24 mechanical degrees. When the motor is running at 5000 rpm, 83 rps, the time for one high phase is $\frac{1}{83} \cdot \frac{24}{360} = 0.8$ ms. If the PWM frequency is 117 Hz, its period is 8.5 ms, 10 times as long. This means that the signal does not look like the one in figure 3.8, since the PWM period is longer than the commutation period. If the PWM duty cycle is only a few percent, the time when the signal is low is up to 8 ms long and during that time there will be no signal at all for several commutation periods. If the PWM period is about the same as the commutation period you risk the situation in figure 6.4 where one phase misses the PWM high time completely. The figure shows a PWM duty cycle of 20%. Every time phase A should be active, the PWM signal is low. This leads to that no current is going through phase A. Problems like these occur when the PWM frequency is too low compared to the speed and makes it hard to say what current the

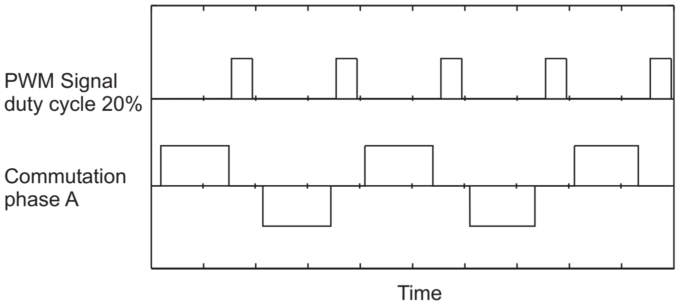


Figure 6.4: Problems occur when the commutation and the PWM signal have the same frequency. In this case will phase A always be low.

motor gets.

### 6.4.2 Problems at High frequencies

The behavior of the system when high PWM frequencies are used is surprising. It was fast but had problems when the position error was small. The reason for this is not completely clear. One possibility is an impedance problem. Since the motor basically is a coil the impedance increases with frequency. Low currents will be dampened and too small to overcome the initial friction to move the motor. Another reason could be that heat production in the high current switches affects the resistance. With a higher PWM frequency for the switches the heat production is also larger.

# Chapter 7

# Conclusion

The nature of this thesis is one that leaves little to be analyzed and concluded. The motor runs satisfactorily and that is the thesis objective. Due to time limitations the motor was not tested in oil inside the transmission. That has to be done to be able to come to any final conclusions. Some things can however be said about the performance of the system.

The switch from a normal to a brushless DC motor does not create any new major problems. Dedicated components help the microcontroller to handle the more complex control algorithms. The use of the brushless motor results in a slightly slower system than for a normal DC motor. However, since it has more torque, a good idea would be to change gear reduction to speed up the system. That of course depending on the speed and torque requirements. The results in chapter 6 show that the motor runs at around expected speed and handles the shifting of the driving positions well. The control algorithm performs satisfactorily and is well adjusted to the system.

The developed software will help in future evaluations. The Matlab GUI makes it easy to quickly study the performance and to save the data. Adjustments of the parameters can then be made via the CAN bus.

## 7.1 PWM Frequency

The PWM frequency is not vital to the performance of the motor. This is shown in the test of the different PWM frequencies. The motor works fine as long as the frequency is within a reasonable range. Not lower than 1 kHz where it is too close to the commutation frequency and not too high, more than 25 kHz, where the performance also goes down. The tests with frequencies from 1 kHz to 15 kHz showed good results.

## 7.2 Future Work

The next natural step will be to build the actuator into the transmission. Then the real system can be tested. After that it is time to build the transmission into a car and evaluate it. Finally a decision has to be made, if this is something we want in our future cars. Interesting would also be to try a brushless motor without hall sensors. That would probably be required if the system is to go into serial production.

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# Notation

## Abbreviations

| | |
|---|---|
| $AC$ | Alternating Current |
| $A/D$ | Analog/Digital |
| $AG$ | Aktiengesellschaft |
| $BDM$ | Background Debug Mode |
| $BLDC$ | Brushless Direct Current |
| $BMW$ | Bayerische Motoren Werke |
| $CAN$ | Controller Area Network |
| $CPU$ | Central Processing Unit |
| $D$ | Drive |
| $DC$ | Direct Current |
| $GUI$ | Graphical User Interface |
| $MMT$ | Moving Magnet Technology |
| $N$ | Neutral |
| $NHTSA$ | National Highway Traffic Safety Administration |
| $OSEK$ | Offene Systeme und deren Schnittstellen für die Elektronik im Kraftfahrzeug |
| $P$ | Park |
| $PID$ | Proportional Integral Derivative (Controller) |
| $PLCD$ | Permanent Linear Contactless Displacement |
| $PWM$ | Pulse Width Modulation |
| $R$ | Reverse |
| $RPM$ | Revolutions per minute |
| $RPS$ | Revolutions per second |
| $SbW$ | Shift-by-Wire |
| $SCU$ | Shift Control Unit |
| $ZF$ | Zahnradfabrik Friedrichshafen |