Control of an integrated starter/alternator in an automotive application

Master of Science Thesis

ANDREAS HEDBERG
CHRISTOFFER KARLSSON

Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2010

Control of an integrated starter/alternator in an automotive application.
ANDREAS HEDBERG
CHRISTOFFER KARLSSON

Department of Energy and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Chalmers, TeknologTryck
Göteborg, Sweden 2010

Control of an integrated starter/alternator in an automotive application
ANDREAS HEDBERG
CHRISTOFFER KARLSSON
Department of Energy and Environment
Division of Electric Power Engineering
Chalmers University of Technology

Abstract

The master thesis aims to develop an electric drive system controlling a specific type of electric machine.

A part of the master thesis has been to evaluate and analyze whether the proposed machine can perform the desired tasks for this system. The machine has also been analyzed and measurements has been performed. The electric drive unit should control the machine as both a motor and a generator.

An electric drive system prototype has been developed and manufactured, also an implementation of control algorithms has been made in a microcontroller. The prototype can control the machine in both motoring and generation. The performance of the system has mostly been evaluated in terms of torque and rotational speed. Such high speeds that were desired for the function of the system was not reached.

Improvements and alterations to the system in order to fulfill the desired specifications is proposed an the possibilities to use the specific machine is discussed.

Key words: Integrated starter/alternator, Motor control, Claw-pole machines, Digital implementation, Hybridization

Styrning av en integrerad startmotor/generator för fordonsapplikationer
ANDREAS HEDBERG
CHRISTOFFER KARLSSON
Institutionen för energi och miljö
Avdelningen för elteknik
Chalmers tekniska högskola

Sammanfattning

Examensarbetet syftar till att ta fram en drivenhet för att styra en specifik elmaskin.

Som del i examensarbetet har ingått att utvärdera och analysera hurvida den föreslagna maskinen klarar av att användas för den tilltänkta funktionen. Den maskin som används har även analyserats och mätningar har utförts. Drivenheten skall klara av att styra maskinen som generator och motor.

En drivenhetsprototyp har utvecklats och tillverkats samt att en reglering av elmaskinen har implementerats i en mikroprocessor. Prototypen fungerar för både motordrift och generatordrift. Prestanda har främst utvärderats i former av vridmoment och varvtal. Så höga varvtal som önskades för full funktion i det tilltänkta systemet har inte uppnåtts.

Förslag på förbättringar eller förändringar av systemet som skulle kunna möjliggöra de höga varvtalen läggs fram och möjligheterna för att använda den specifika elmaskinen diskuteras.

Nyckelord: Integrerad startmotor/generator, Motorstyrning, Klo-polsmaskiner, Digital implementering, Hybridisering

Contents

Preface

This master thesis has been a part of a development project with the purpose to develop and commercialise a new mild hybrid system for internal combustion engines. Within this project a fully functional 1.6 l prototype engine equipped with this new hybrid system has been developed. Extensive work has also been done in order to build up a strong portfolio of intellectual property rights for protection of the system and ways of optimising system functionality.

This thesis has been carried out on a customer-supplier basis with the project owning company acting as customer and XDIN acting as a supplier.

Acknowledgements

We would like to say thanks to following people and organisations: Commissioners Isak Löfgren and XDIN for giving us this opportunity, supervisor Henrik Engdahl for his support, examiner Torbjörn Thiringer for all advice, the department of Energy and environment at Chalmers for letting us use their equipment and Adrian for always being there.

Notations

$\boldsymbol{\alpha}$ A direction in a created space

$\boldsymbol{\beta}$ A direction in a created space, perpendicular to α

$\boldsymbol{\omega}$ Rotational speed

$\boldsymbol{\Psi}_d$ Flux in the direction of the rotor angle

$\boldsymbol{\Psi}_q$ Flux in quadrature to the rotor angle

θ Electrical rotor angle

$\mathbf{d}$ Rotor direction in $\alpha\beta$

$\mathbf{e}$ Energy

$\mathbf{E}_a$ Induced voltage in the stator

$\mathbf{i}_d$ Voltage in the direction of the rotor angle

$\mathbf{i}_{diode}$ Current in diode

$\mathbf{i}_f$ Field current

$\mathbf{i}_q$ Current in quadrature to the rotor angle

$\mathbf{i}_\mathbf{s}$ Currents in the stator

$\mathbf{T}_e$ Torque from an electrical source

$\mathbf{K}_b$ Flux factor

$\mathbf{L}_r$**,** Inductance of the rotor

$\mathbf{L}_s$ Inductance of the stator

$\mathbf{n}_p$ Number of pole pairs

$\mathbf{P}_{loss}$ Power loss

$\mathbf{q}$ Direction perpendicular to d in $\alpha\beta$

$\mathbf{R}_r$ Resistance of the rotor

$\mathbf{R}_s$ Resistance of the stator

$\mathbf{v}_d$ Voltage in the direction of the rotor angle

$\mathbf{v}_{diode}$ Forward voltage drop over diode

$\mathbf{v}_q$ Voltage in quadrature to the rotor angle

$\mathbf{v}_s$ Stator voltages.

$\mathbf{v}_{out}$ Output voltage

$\mathbf{v}_{ref}$ Reference voltage

$\mathbf{v}_{in}$ Input voltage

Abbreviations

ADC Analog to digital conversion

ALU Arithmetic logic unit

CAN Controller area network

DSP Digital signal processor

DTC Direct torque control

EMF Electric magnetic field

GPIO General purpose input/output

IAP In-application programming

ICE Internal combustion engine

IDE Integrated development environment

IGBT Insulated gate bipolar transistor

ISP In-system programming

JTAG Joint test action group

MOSFET Metal oxide semiconductor field effect transistor

PWM Pulse Width Modulation

RAM Random access memory

ROM Read only memory

SRAM Static random access memory

1 Introduction

1.1 Background

With the increased environmental awareness in the community, automotive companies are under high pressure to reduce fuel consumption and emissions. The system being developed can be used to downsize the engine with maintained performance or to increase performance. The main idea is to distribute energy to where it is best needed in order to optimise over-all efficiency.

1.2 Purpose

The prototype system currently has an electric generator whereas the final product should have an electric machine which work as motor as well as generator. As the electric machine may work as starter at zero speed as well as motor/generator at high speeds it has to have a wide operation range. The purpose of the thesis is to develop a drive unit with an integrated control unit which meets these system requirements. The goal is to design needed power electronics, choose a suitable control unit (microcontroller) and write a program that reads, processes and transmit the needed signals to control the speed and torque of the electric machine.

1.3 Restrictions

The electric drive used is a claw pole machine which is used as starter and generator in a small mild hybrid vehicle. The prototype which is to be produced is meant to be operated by engineer and not to be manufactured in large scale. In order to avoid costs and trouble with double electrical systems the goal is to use existing 12 V DC link.

1.4 Working process

The work was divided into four different phases in order to get a good structure to work from: study, design, construction and implementation/test. Even if the phases were sequential they overlapped each other partially and much of the work was executed in parallel.

1.5 Disposition

The report begins with a theory chapter (ch. 2) in order to give the technical background necessary knowledge to understand the concepts of the report. It is followed by a chapter where the operation characteristics are examined (ch. 3). The main part of the report consists of the chapters dealing with the different components of the machine control (ch. 5-8). This is where all design considerations and other work will be described. The report ends with an analyse of the results (ch. 9 and 10). As come to measurements each setup is discussed in connection to the results.

2 Theory

2.1 Claw pole alternators

The Claw-pole machine is a special type of electrically exited synchronous machine very often used as an alternator in modern cars. The field windings are concentrated to a single coil around the shaft of the machine and are exited by a DC-current. A claw structure of the rotor provides the saliency of the flux. In general the advantages of this type of machine are simplicity, robustness, low cost and a rather compact design. One obvious disadvantage is the often low efficiency, which is claimed to be around 50% in many cases [1]. The number of poles can vary and the most common configuration is a 12-pole set up [1], a higher number of poles can increase the output power and torque by making the flux change more rapidly, on the downside of increasing the number of poles can be noted an increase in frequency which increases the iron losses and puts a higher demand on the control system. Control of these machines can be done in several ways. Most control schemes that can be used for synchronous and induction machines can be applied to the claw-pole machine with no or small modification. Among the most common control methods is space vector control, direct torque control and V/Hz control.

For modelling of the machine a dynamic equivalent circuit according to figure 1 is used [2].

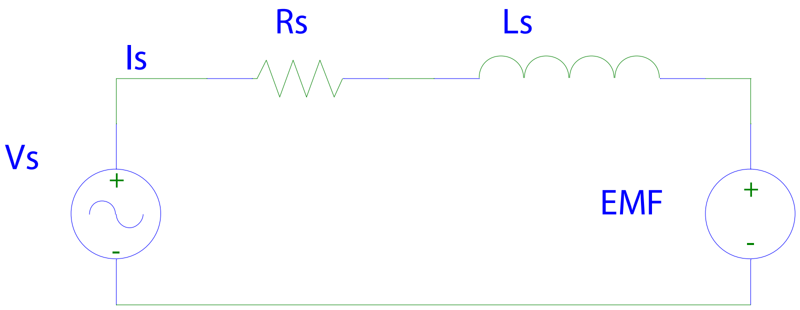


Figure 1: Dynamic model

To be able to calculate estimates of the flux and torque, a direct-quadrature model [2] will be used and can be expressed as

$$i_s = i_d + ji_q \tag{1}$$

$$v_s = v_d + jv_q \tag{2}$$

Where the d-q reference frame is given by

$$\begin{bmatrix} d \\ q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{3}$$

x, y and z is the three phase quantities and θ is the rotor angle of the machine. The relationship between the field current, rotor speed and the induced stator voltage can approximated as a linear function with the flux factor K$_b$ [2].

$$E_a = i_f K_b \omega \tag{4}$$

As the number of poles (n_p) is greater than the number of phases, a mechanical rotation can be divided in electrical rotations. Due to the symmetrical design of the machine it is quite straightforward to convert between electrical and mechanical degrees since there is only a multiplicative factor that depends on the number of poles in the stator and rotor.

2.1.1 DTC

Different variations to this type of control exists and some of them are called direct torque and flux control. The main concept is however very similar and distinguishes from pulse width modulated vector control.

The main idea in DTC is to evaluate the torque and flux of the machine and chose the pattern that moves the flux to the desired position, a kind of hysteresis control that acts directly on estimations of torque and flux. A three-phase bridge may be used to realise this control scheme since it can be switched in eight different ways, each producing a voltage vector (except the two zero vectors), each voltage vector either increases or decreases flux and or torque as shown in figure 2. For choosing switching pattern based on the position of the flux vector is whether to increase or decrease torque, resulting in only two choices, one increasing the flux vector, the other decreasing the flux vector. The zero vectors can be used for the cases when either the flux or the torque production coincides with the desired one. There are different models for the flux estimation which we decided to consider.

Statically compensated voltage model is a flux estimation strategy that utilise that the flux EMF is equal to the rotor flux derivative. Low pass filtering and adding of a compensation term to ensure a stable system without a steady state error. Calculation is made by integration of stator quantities and the utilised parameters are the stator resistance, the stator inductance and the speed [2].

A direct interpretation of the flux in the stator is the currents in both stator and rotor circuits multiplied by the respective equivalent inductance. As the position and current of the rotor is measured, a direct calculation can be made as

$$\Psi_d = i_d L_s + i_f L_r \tag{5}$$

$$\Psi_q = i_q L_s \tag{6}$$

The torque error can either be calculated from the flux and current, or as a hysteresis control of the speed or what parameter you would like to control. If a calculation of the electrical torque is to be made it is given by the following equation

$$T_e = \frac{3n_p}{2}\left(\Psi_d i_q - \Psi_q i_d\right) \tag{7}$$

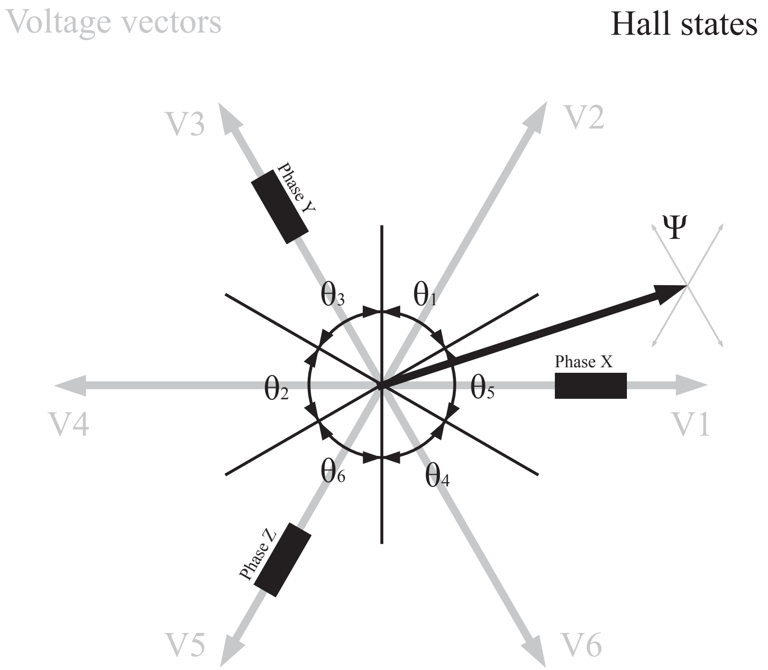


Figure 2: Flux vector in relation to phase windings and Hall states in alpha-beta.

2.1.2 Hall effect sensors

A Hall effect sensor is a device which changes its output voltage in relation to the magnetic flux. There are different kinds of Hall effect sensors, in this thesis there are two applications of special interest. The coupling between flux and current allows for methods to use Hall effect sensors for current measuring. Hall effect current transducers utilises the magnetic field from the current through a conductor, the output voltage of the transducer varies with the current. One common type uses a ferrite toroid around the conductor, this gives the opportunity to either increase the sensitivity by passing the conductor or decrease the sensitivity by only passing a part of the entire conductor splitting the current.

Hall effect encoders are often used in different motor applications for determining the rotor position. A number of Hall elements are placed in the stator and one or several magnets on the rotor to alternate the flux over the Hall elements. The rotation of the rotor creates a pattern from the Hall elements which can be used to calculate the speed or determine the position of the rotor. The value of the digital signal from such an encoder is in this thesis denoted a Hall state.

2.2 Power electronics

2.2.1 Three-phase inverters

In order to obtain control of a three phase machine, a bridge of the type shown in figure 3 is commonly used. This type of three-phase inverter can provide the voltages needed to provide suitable voltages to the machine. This configuration also provides the function of a rectifier bridge.

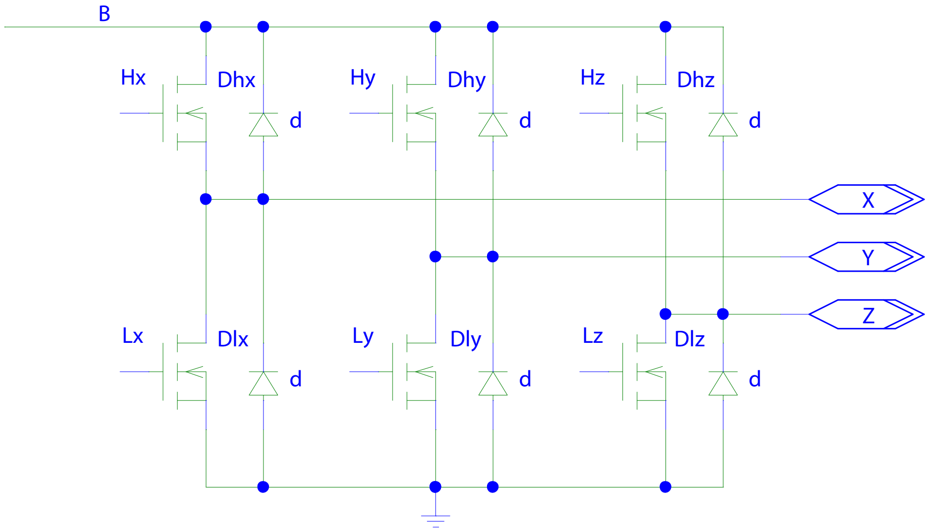


Figure 3: Example of bridge circuit

2.2.2 Transistors

There are several transistor types that can function as switches in a bridge circuit, two alternatives are described in this chapter, MOSFET and IGBT as these were considered as good candidates.

A MOSFET is a type of semiconductor that is often used for low voltage and high switching frequency applications as increasing the blocking voltage of the MOSFET imposes a rapid increase in on-state losses. MOSFETs can easily be parallelled in order to increase the power handling capability [3].

IGBT is in some ways similar to a MOSFET but constructed to use conductivity modulation to lower the on-state losses. The IGBT is slower than a MOSFET but faster than a bipolar junction transistor, it has lower on-state losses than a MOSFET and in the same region as a bipolar equivalent [3].

2.2.3 Gate driver

In order to use a MOSFET as a switch, a gate drive circuit must be used. Since a logic level output is not enough there are several kinds of circuits available. For the high side of the bridge, a bootstrap function must be added to be able to apply a gate-source voltage high enough to turn the transistor on. Such functionality can sometimes be provided as part of the drive circuit.

2.2.4 Diodes

For the rectification of a three phase source a diode rectifier as seen in figure 3 might be used. The power loss in the rectifier depends on the forward voltage drop of the diodes which is to be held as low as possible.

$$P_{loss} = v_{drop} i_{diode} \tag{8}$$

2.2.5 Capacitors

To ensure a fast and reliable voltage source capacitors might be added as a buffer between the battery and the bridge. This also provides the reactive power consumed by the machine. The stored energy of a capacitor is given by

$$E = \frac{CV}{2} \tag{9}$$

2.3 Microcontroller, DSP & Microcomputer

2.3.1 Definition

A microcontroller or DSP is an integrated circuit that perform arithmetic, logic, communication and control functions. It can be said that the difference between the two is that the DSP is better suited for high speed floating point operation, but there is no clear line and most of the manufacturers has their own definition. The term microcontroller will be used in the rest of the report for convenience. If the circuit is mounted on a board together with interface, clock and memory components, it is called a microcomputer [5].

2.3.2 Calculation speed and data processing

The microcontroller has an ALU that performs mathematical operations on binary words. A word is a set of data bits and the bit architecture of a microcontroller refer to how large words it can handle. Usual sizes are 8, 16 or 32 bits. The advantage of a microcontroller which work with large words is that it has higher resolution and can handle larger numbers. The drawback is that it is more expensive as all parts of the circuit has to be adjusted [5]. Most microcontrollers can handle larger word sizes than their architecture suggests but with heavily increased computational time as a result. Another important aspect is how the microcontroller deals with representation range as numbers expressed in binary form is usually integers. Two ways to solve the problem is to either use fixed- or floating-point processors. In a fixed-point processor the number of decimals for each variable are set in advance while a floating-point processor does this continuously with respect to the current data. The advantage of the floating-point is that it always has the maximum resolution at the same time as the risk of overflow is minimised. The drawback is that the calculations are slower [6]. The calculation speed of a microcontroller is decided by its components and is controlled with some kind of oscillator.

2.3.3 Memory

There are two main types of data storage in a microcomputer: volatile and nonvolatile memory. Volatile memory such as RAM needs power supply in order to retain data while nonvolatile memories like flash and ROM does not. On the other hand flash and ROM are slower and can only be programmed a limited amount of times. For this reason a microcomputer is usually equipped with both volatile and nonvolatile memory. The nonvolatile memory are used for storing the program while the volatile is used for execution of the program and storage of temporary variables.

2.3.4 Programming

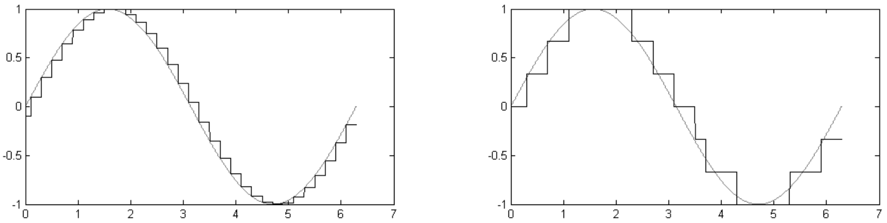
When programming microcontrollers the two main options regarding which language to use is C or Assembly language. While Assembly is a low-level programming language, C has a higher degree of abstraction. This means that Assembly is closer to machine code which can make programs faster to execute, if well programmed, at the same time as it is much more complicated to program and read. As the speed gain is relatively small, C is commonly used while Assembly is limited to time critical sections of the programs [5]. A IDE consist of a source code editor, a compiler and possibly other features. The program is written in the editor and the compiler then translates it to machine code. Once the code is compiled there are several techniques to download it into the device. Some of these are: JTAG, ISP and IAP. The major difference between these is that JTAG allow debugging of the device while ISP and IAP does not.

2.3.5 ADC

Converting an analog signal to discrete digital numbers is necessary in order to read most sensors. This is done by a A/D converter. The voltage of the signal is sampled and converted to the digital form figure 4(a). The result of the digitisation is decided by four factors: voltage resolution of the converter, signal range in respect to the converter range, sampling rate (time resolution) and filtering [5]. The result of low voltage resolution can be seen in Figure 4(b). The converter voltage resolution is usually fixed but can in some cases be decided by the programmer to some extent. As the converter is more expensive and the conversion is slower for higher voltage resolution it is important to only use sufficiently high voltage resolution [5]. If the signal range is small in comparison to the converter range the result is the same as having low voltage resolution. This is easily solved by scaling the signal. If the sampling rate is low (figure 4(c)) the result is low resolution even if the converter voltage resolution is high. If the sampling rate is lower than twice the signal frequency there is a risk of aliasing [5] where a frequency is perceived to be lower than it is. This can be seen in the noise of the signal in figure 4(d). In order to remove noise a hardware low-pass filter with cutoff frequency lower than half the sampling rate should be used [5].

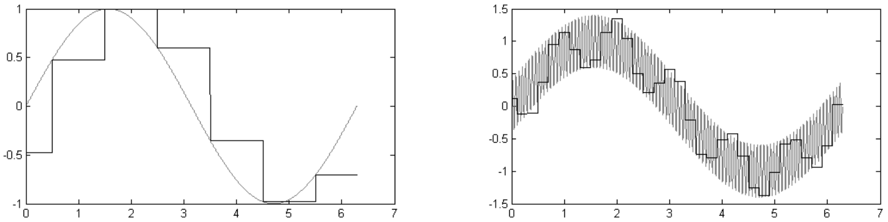
2.3.6 Digital to analog conversion

Microprocessors only deal with digital output. One way to achieve analog signals is to use PWM. The idea is to modify the on-time and frequency of the output. By running the signal through a low pass filter with a frequency much higher



(a) Reference sampling

(b) Low resolution



(c) Low sampling rate

(d) Reference sampling of unfiltered signal

Figure 4: ADC examples

than the filter constants and the on-time as a percentage of the period, the current through the pin can be controlled and an analog signal is accomplished.

2.3.7 Interrupts

Polling signals when needed may be inefficient as the reading is carried out even if the signal haven't changed since last poll and if the signal changes the necessary measures isn't taken until the signal is polled next time. The interrupt routines on the other hand monitor the signal and carry out their task as soon as possible after a change. When there is a change the processor finish the ongoing operation and then execute the task connected to the interrupt.

2.3.8 CAN

CAN is a message based communication technology used to allow electric control units in a system to communicate without a host computer. The idea is that the transmitting unit broadcast a serial message on the entire network instead of connecting specifically to the receiving unit. All units (nodes) connected to the network can receive and broadcast messages but not at the same time. If two messages are sent simultaneously the one with the lower priority will be interrupted while the one with higher priority will be broad-casted without delay. The technology was originally developed for the automotive industry in the middle of the 1980's and is now standard in most production cars and trucks where it is used to communicate sensor values and control signals [7].

3 Operation characteristics

The context in which this machine is to be used puts a number of requirements that have to be fulfilled for the system to behave as intended. Most notably is that the machine should act as a starter and generator for a car. There is also a demand that the machine can provide motoring power at high speeds. There are a number of systems available today that utilises this type of machine to work as a starter and generator.

3.1 High torque

In order to work as a starter for an ICE the most important feature is the static torque before the rotation starts. There is also demands that the machine can run the ICE until combustion can start. Normally the combustion starts after three compressions have occurred [8]. This demand is applied to all components of the system as it is projected on the currents and other factors that can be saturated in some way.

The specific torque needed depends on the specific ICE used, the required torque also depends strongly on temperature. Figures of the static friction torque has been found to vary between 30 and 200 Nm giving approximately 15 to 85 Nm load on the electric machine [8].

A signal to trigger the starting sequence is to be provided to the control unit. In a finished product this will probably be provided via the CAN bus but for this prototype other solutions might be used.

3.2 High speed motoring

The speeds that motoring of the machine is desired ranges up to at least 16 000 rpm and possibly even higher up to 20 000 rpm. The most important aspect is to determine whether the specific claw-pole machine could be driven to such speed with the proposed solution.

3.3 Generation

Generation of power, replacing the functionality of the usual generator used in most cars, typical values for power consumption in modern cars has been estimated to be in the region of up to 3 kW. Since the rating of the claw-pole machine used in this thesis is in the order of 1.7 kW this value for continuous generation will be aimed for and up to 3 kW for peak generation.

The control unit should manage the charging of the battery with respect to electric power consumption in the car and state of charge. This applies over the whole speed range above the idling speed of the ICE.

4 Electric drive system

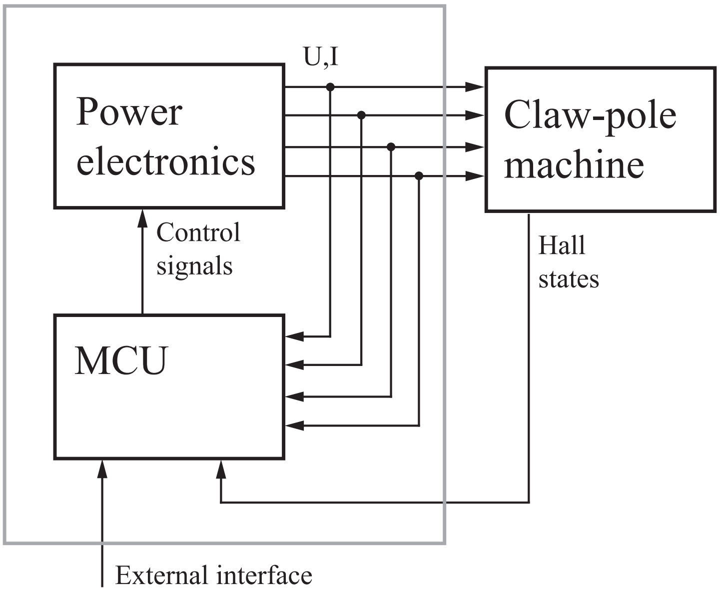


Figure 5: Schematics of electric drive system

The drive unit consists of two parts: power electronics and a control unit. The control unit collects the needed information from the other parts of the system. It then processes the information and sends the necessary signals to the power electronics. The power electronics then converts the voltage from the DC-bus to the electric machine. In this application the drive unit works both as generator and as motor in an automotive environment at high speeds and powers.

The drive unit is constructed to be driven by a 12 V DC-link, more specific a regular lead-acid battery found in most modern cars. The electronics in the drive unit is designed with this in mind and there are obvious reasons to maintain the DC-bus voltage as a voltage source for most of the components. Some of the components including the control unit requires 5 V supply, therefore a linear voltage regulator is mounted.

The size of the components is not crucial in this prototype, but for further development the size and shape of components has been taken into consideration. The need for bulky components has not been high, and among the largest can be noted the capacitance for the reactive power and the current transducers. Although the most bulky component has been the heat sink, the heat sink might in a future application be integrated or tailored to fit close to the electrical machine, this also opens up for the use of a fan or otherwise created flow of air or liquid to act as a coolant for the power electronics.

The environment that the drive unit should operate in is subject to vibrations and both high and low temperatures, the actual temperature intervals depends on both the climate and the design of the engine room. The temperature ranges of the components were taken into account and all components could be fitted into the span of -40C to +85C, many exceeding these ratings why there is a possibility to extend the range if it would be considered necessary.

The high frequencies used both for the PWM signal to the field current and the supposed high frequency of the phase switching's, increase the possibilities for problems regarding electromagnetic interference. There haven't been any extensive research on rules or standards neither have any attempts been made to measure or estimate the amount radiated or captured by the drive unit. Some arrangement has been made in an attempt to reduce the electrical noise created by the different parts of the drive unit.

After evaluation of space vector control, direct torque control and V/Hz control schemes we decided to focus on DTC, which has its advantages mainly in being robust and stable, it can also be altered to handle transistor switching in generator mode [1].

4.1 Interfaces

There are some interfaces that are set by the already existing terminals and sensors on the electric machine as seen in figure 6. The phase conductors is three wires that are connected to the windings of the stator. The Hall sensors are connected with one 3.3 V supply, one ground and three data wires, the data wires is compatible with the logic level of the microcontroller. The interface between the microcomputer and the prototype board consists of a supply voltage of 5 V from the prototype board, ground, a PWM signal for controlling the field current, six digital outputs for controlling the transistors, one enable signal to the transistor gate drive circuit, seven analog signals for current and voltage measurements. There is also an USB interface between the microcomputer and a computer to be able to load the program into the microcontroller.

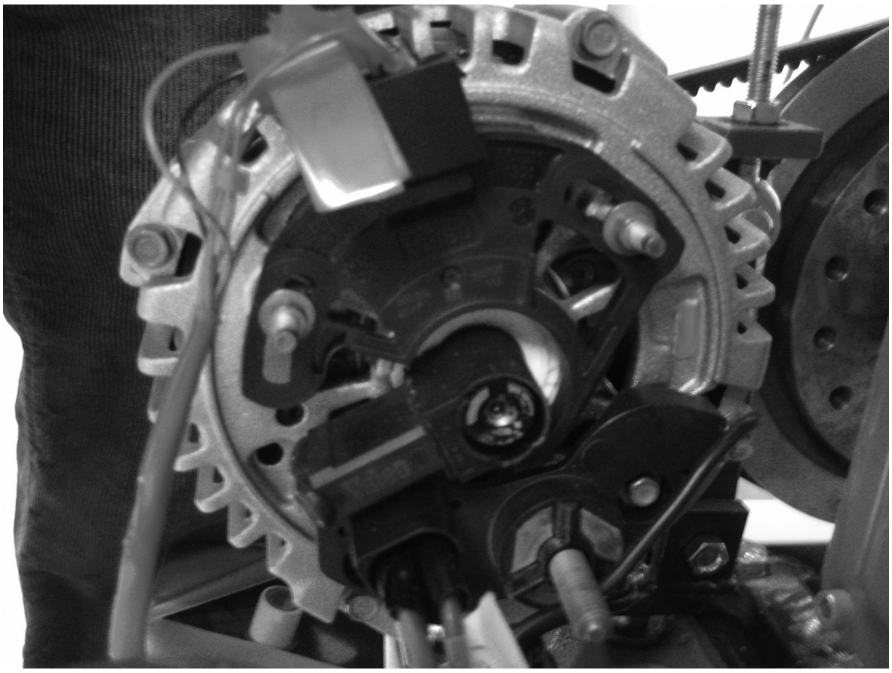


Figure 6: Back plate of the machine

5 Electric machine

Examinations of the machine (figure 7) without destruction lead to a number of observations. The machine is delta coupled with three phases. There is a connection for field windings. There is a connector for a Hall effect encoder. The rotor of the machine is partially visible and indicates a claw-structure. Excitation of the field windings lead to the possibility to determine the number of poles by counting the reluctance torque ticks.

The electric machine was assumed to be an electrically exited claw-pole machine with 12 poles. The Hall effect encoder was compatible with both 5 and 3.3 V logic levels and the resolution was found to be 60 electrical degrees or 10 mechanical degrees. The position of the phases in relation to the encoder signals was determined by analysing the waveforms of the induced voltage and compared to the Hall state the order and position of the different states were determined.

5.1 Modelling and machine parameters

A simplified electrical model of the motor was used to estimate the capacity and needs for the power electronics. This model was also used when designing control algorithms. The rotor and stator circuits are separated, the windings of the rotor was modelled with a resistance and an inductance, the same applied for the stator circuit with the back-EMF as a function of angular speed gives us the circuit in figure 1.

The machine parameters with the most importance for this thesis are

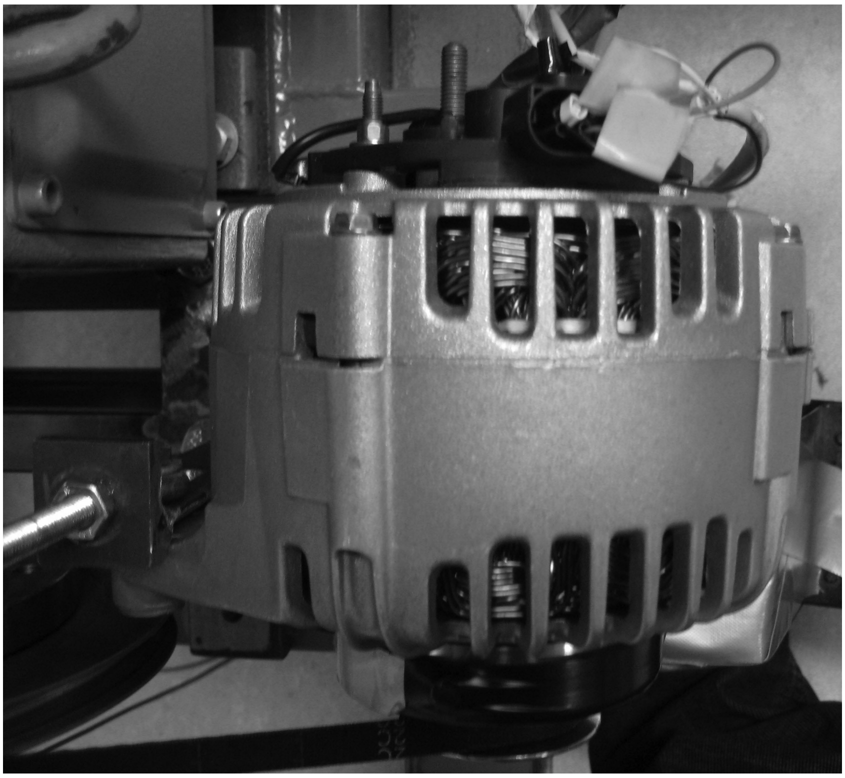


Figure 7: Picture of claw-pole machine

considered to be the following:

R_s Affect the calculation of the flux and has an impact on the efficiency of the machine.

L_s Also affect the flux calculation.

R_r This parameter is needed for the design of the field current circuit and the control of it.

L_r Same as for the resistance of the rotor.

K_b This factor determines the coupling between induced stator voltage, rotational speed of the machine and the field current.

The induced voltage vectors are also considered to be of importance when designing the control algorithms. An attempt to measure these parameters with acceptable accuracy was made and the results were used to evaluate and design the system.

5.2 Measurements

In order to examine the parameters of the machine, the measurements described in this chapter were performed. The measurements were performed at "grundkurslab" at the division of Electrical Power Engineering at Chalmers University of Technology. This lab is normally used for laboratory practises in electric drives courses and is prepared for measuring and controlling DC and induction machines, data acquisition and storage of many of the signals is made possible. The existing induction machine was removed from the rig and our machine was mounted. A belt gear was used to expand the speed range of the set-up and transfer the torque between the machines.

The initial tests consisted of driving the machine in order to examine the resulting frequencies, wave shapes, voltages and currents.

The electric drive used to motor the machine was a 4 kW DC-machine with a rated maximum rotational speed of 3 835 rpm. To be able to test rotational speeds close to the desired 20 000 rpm a speed ratio was set to 1:5.15. A belt drive was chosen because it damps load and speed fluctuation, it is simple to implement and it does not require the axles to be exactly aligned [9]. The rig was then designed and constructed with regard to the existing components. To measure the rotational speed an optical encoder was used for speeds up to 7000 rpm where it reached the Nyquist frequency. At higher speeds the DC-machines built-in tachometer was used. As shown in figure 8, the tachometer give bad readings at low speed why the encoder was used in these areas. It can be seen that the ratio between the speed of the DC-machine and the claw-pole machine approaches the computed one as the speed increases.

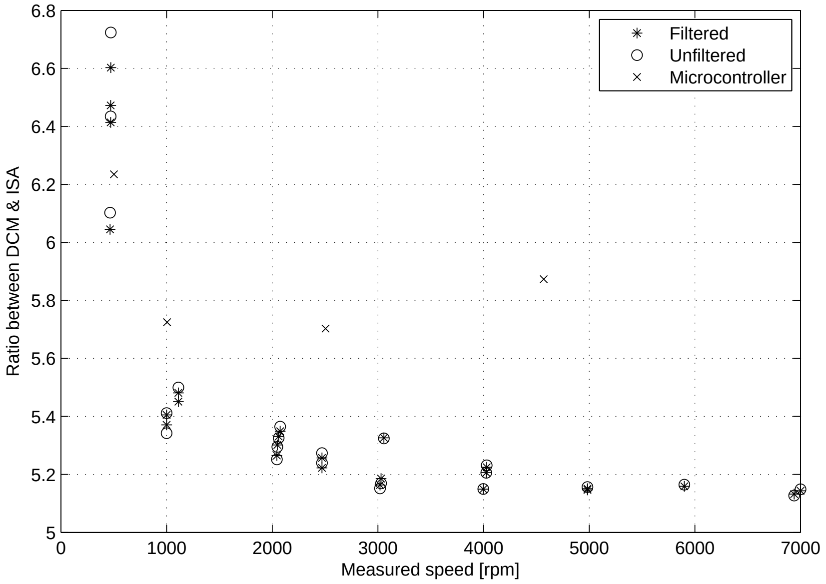


Figure 8: Speed ratio between the claw-pole machine and the DCM

5.2.1 Rotor windings

Since the machines rotor windings will be fed by a DC-current, we performed a test to measure the resistance of the windings.

The resistance in the windings is given by Ohms law.

$$R = \frac{U}{I} \tag{10}$$

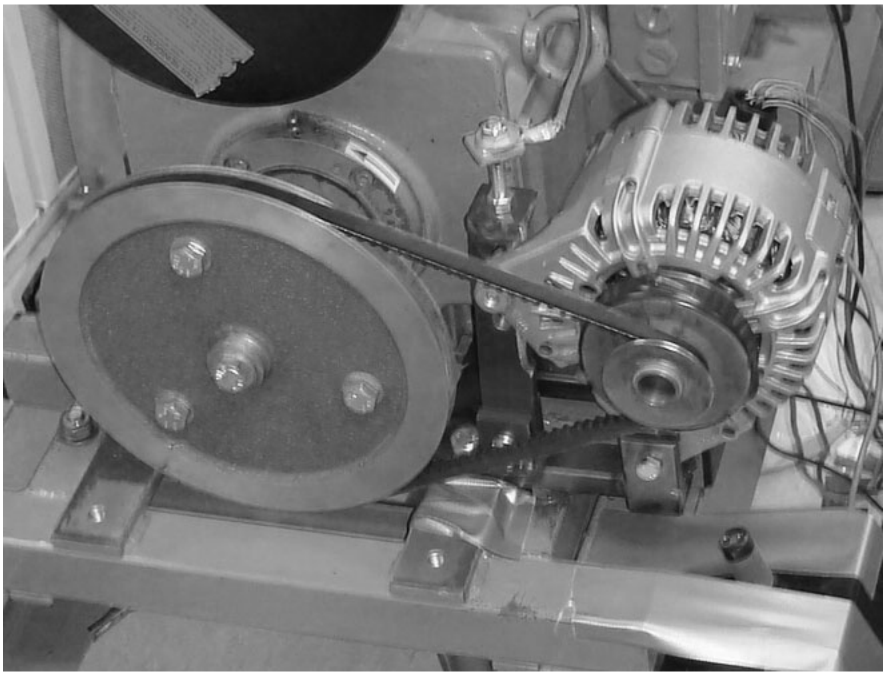


Figure 9: Measurement setup

A three-phase Y/D transformer was connected to the grid; the D side was connected to an auto transformer, which was connected to a diode rectifier. The current was increased to 2 Ampere and the voltage over the windings was measured. Digital multimeters of the type BS1704 were used during the experiment.

The inductance in the rotor windings is also given by ohms law, but with complex impedance.

$$Z = \frac{U}{I} \tag{11}$$

$$Z = R + jX \tag{12}$$

$$X = \omega L \tag{13}$$

Where in this case omega is given by the grid frequency of 50 Hz.

The rotor was connected to the same set-up as above without the diode rectifier, a current of 2 Ampere was fed to the windings and the voltage was measured.

5.2.2 Stator windings

The same set-up as for the rotor windings was used, but the current applied and the voltage measured between the three phases, the phases are denoted x, y and z. xy denotes the resistance between phase x and phase y and so on. Because of the lower resistance of the stator compared to the rotor the current was increased to around 6 Ampere instead.

The characteristics of the stator windings are modelled to be the same for all phases and a mean value of the measured is used.

5.2.3 Open circuit

The purpose of this measurement is to characterise the machine in order to design a control scheme for the rotor current controller.

The induced voltage in the stator is proportional to the field current I_f and the angular speed ω_r by the flux factor K_b.

$$E_a = K_b I_f \omega_r \tag{14}$$

The machine was mounted in the test rig and the voltage between the stator phases were measured with the built in voltage meters. The EMF was measured for different speeds and rotor currents. The rotor was fed using the same set-up as for the rotor winding test and the DC machine was controlled by an in the lab existing thyristor converter to different speeds. In order to determine the shape of the flux-linkage, the waveforms were transformed to $\alpha\beta$-coordinates and then plotted to show the voltage vector trajectories. From figure 10 one can notice that the flux-linkage waveforms is of trapezoidal shape.

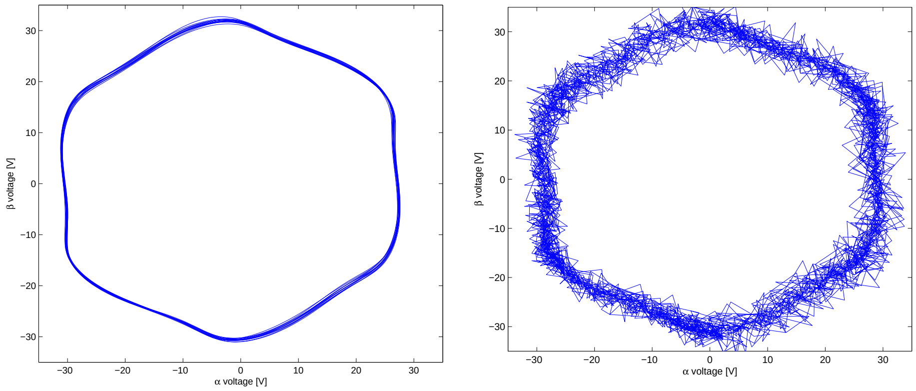


Figure 10: Comparison between filtered and unfiltered voltage trajectories during generation

Stator EMF divided by the angular velocity gives a function of rotor current and is crucial for determining the control of the rotor current. The EMF per velocity is expected to be a linear function up to some value when the flux saturates the magnetic material and decreases the EMF per current. As seen in figure 11, our measurements seem to coincide well with this assumption. We can notice that it seems to be saturated for rotor currents above 5 or 6 Ampere.

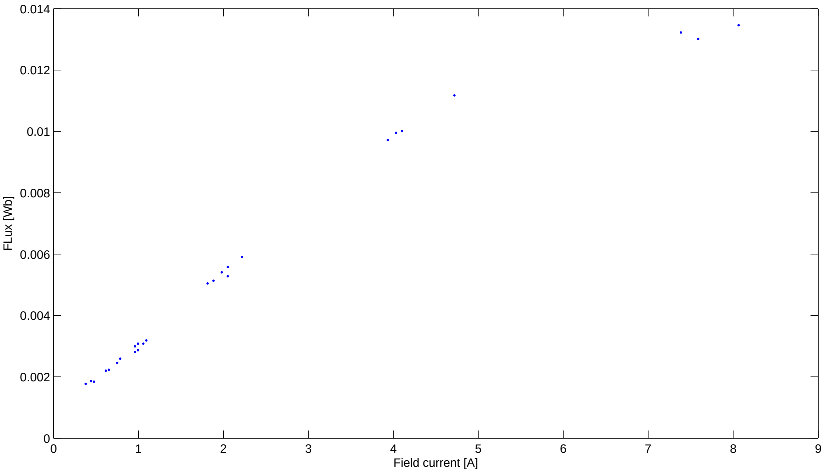


Figure 11: Flux as a function of rotor current

A mean value of the flux factor K_b was calculated from the different measurements.

$K_b = 0.0296$

The theoretical maximum angular velocity with a fixed voltage is given by the case when the EMF equals the stator voltage from the inverter. This can be seen in figure 12.

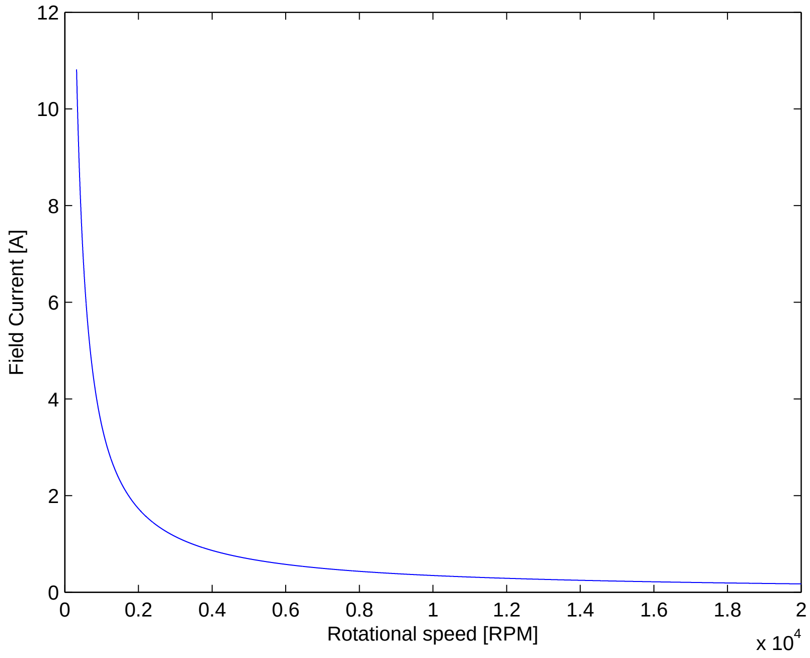


Figure 12: Theoretical field current as a function of speed

6 Power electronics

The power electronics can be divided into three main functions, as a converter for driving the machine, as a rectifier for generation mode and a current source for the field windings. Each function is described and the needs are analysed below.

6.1 Converter

In order to supply the power for driving the machine, we do not want the power electronics to constrain the system regarding power handling. The machine is rated 1.7 kW which constrains the continuous power. For peak generation we have set a requirement to handle 3 kW.

A three-phase bridge solution is chosen as the best choice for this task, this provides full capability to use the machine as a generator and motor in both rotational directions.

6.2 Rectifier

The free-wheeling diodes in the three-phase bridge solution act as a rectifier, as long as the diodes can handle the current the control function governing the generation is quite simple and fairly easy to design.

6.3 Field current

There are two main considerations regarding the field current: In order to reduce torque ripple, we aim to have a smooth field current. In order to avoid too high voltages when the motor accelerates or decelerates fast, a fast current response is needed. For obtaining a smooth response, a capacitor can flatten the output voltage and thus making the current smoother. A simple buck-converter is sufficient for controlling the current and the inductance of the rotor windings acts as a low pass filter.

6.4 Components

For simplicity, we chose the same components for both the half-bridge and the field current converter. The component requirements was set to provide a good performance that hopefully fulfils our requirements, a deeper analysis is complicated to perform until the control algorithm and the performance of the machine is decided and measured.

A calculation of the power handling capabilities depends on the on-time for the transistors and therefore is much dependant on the speed. Much of the limitation lies in cooling capabilities at high power. The rated continuous current of the transistors is 75 A limited by the casing which is lower than the rated current of 120 A. Each transistor only conducts on one third of a revolution and the thermal limit of the casing is assumed to be expanded by a factor close to three. If the cooling works well enough the power electronics should be able to handle about 2.7 kW with this current in mind.

6.4.1 Transistors

A high current demand and low operating voltages in combination with the possibility that we might need a high switching frequency made a MOSFET transistor a suitable choice. There are several components on the market designed for automotive environments.

The demands on the transistors are mainly the current handling capacity and the voltage ratings, the switching times, on-state resistance and temperature ratings should also be considered.

Since some kind of bootstrap functionality is needed for the high-side of the bridge [4], an integrated MOSFET gate driver for three-phase motor control was chosen. This circuit also provides blanking-time and acts as an interface between the transistors and the microcontroller. As the field-current converter also needs a gate driver, a separate circuit is mounted.

The gate resistances affect the rate of change of the voltage. The gate resistances that were used were the recommended standard value from the manufacturer.

6.4.2 Diodes

Our needs for the diodes are high current and a low on-state voltage drop is preferable to reduce losses. In low-voltage solutions the voltage drop over the diodes play an important roll as the high currents reduces the efficiency of the rectifier. MOSFETs do have an intrinsic body diode, but to ensure a low voltage drop an additional diode was chosen. A low voltage drop increases the span which the generation function can be used.

A schottky diode was decided as a good candidate. This in combination with the body diode of the MOSFET allows for a high current. The full current needs for a finished application is not yet determined but as a guideline the diodes should handle at least the rated current of the machine and considerably higher for peak values.

6.4.3 Current transducer

Two solutions seemed to be applicable to the prototype, either using shunt resistances or Hall effect transducers. Advantages of hall effect transducers are that there are available solutions that does not require further construction, frequency characteristics, cooling and other problems or considerations could possibly create problems during the evaluation or construction of the rest of the system. The main advantage of shunt resistances is the cost, while producing only one prototype, the cost of a few components is not that important and hall effect transducers was chosen.

Both the stator and rotor currents are interesting to measure. The stator currents can be very high and we therefore need a large span to measure. Transducers that can handle up to 200 Ampere were chosen so that the mark current of the machine can be surpassed and the transducers could be used if only the DC-link current is to be measured. For the rotor current, the currents are rather small, typically 0.1 to 10 Ampere and we can choose a cheaper component.

The output of the stator current transducers is governed by the following equation

$$V_{out} = V_{ref} + \left(\frac{1.25 V_{in}}{200} \right) \tag{15}$$

The output of the field current transducer is governed by the following equation

$$V_{out} = V_{ref} + \left(\frac{0.625 V_{in}}{12.5} \right) \tag{16}$$

Where in both cases

$$V_{ref} = 2.5V \tag{17}$$

The ADC of the microcontroller measures in the interval of 0-3V, a differential operational amplifier connected as in figure 13 in order to adapt the signal from the transducers to the ADC.

The component values chosen for this prototype can be seen in Appendix B.

6.4.4 Mounting and accessory components

A prototype board which connects the driver circuit with the transistors has been made. This board was made to leave space for other external component to some extent. The current transducers require a voltage source of 5 V, a linear voltage regulator was mounted on the prototype board to achieve this,

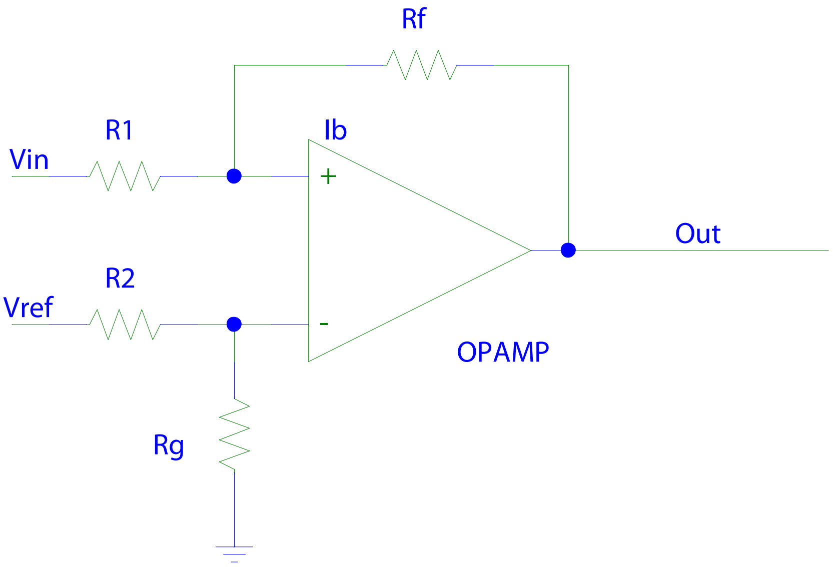


Figure 13: Example of connection of an differential operational amplifier

the microcomputer is also driven by 5 V and the current rating of the voltage regulator allows for this usage as well. The voltages of the machine phases and the battery voltage must be converted to fit the interval of the ADC unit. A voltage divider followed by a buffer amplifier manages the conversion of the voltages and ensures that the impedances are well matched.

The transistors were mounted on a heat sink and to ensure a low stray inductance the length of the component legs should be as short as possible. Unwanted stray inductance causes high voltage spikes when the current changes rapidly, this can cause a dangerously high voltage over the transistors. A plastic sheet with bus bars mounted on it was used to provide the pressure on the components, all the legs except for the gates of the components were soldered directly to the bus bars trying to minimise the inductance. The measured voltages of phases were drawn from cables connected to the bus bars.

Zener diodes were mounted on the connections between the microcomputer and the prototype board, this was done to minimise the risk of overvoltage's and thus ensuring a safe interface between the two.

6.4.5 Capacitors

To provide reactive power and to stabilise and ease for high starting currents, a capacitor was mounted in the power electronics. The quantity of this capacitance is much a function of cost opposed to performance, a high capacitance can decrease the load on the battery and especially at starting when high currents are needed. As a rule of thumb, we dimensioned the capacitance after the power consumed by the system. The stored energy should be equivalent with the energy consumed within the region of one ms, therefore 22 mF was used. In order to reduce the problems associated with the voltage drops on the

DC-bus this was raised to 66 mF. This value can probably be lowered by a great deal in a finished application if the supply to the drive circuits is conditioned in some way.

7 Microcontroller

7.1 Requirements

7.1.1 Bit architecture

In order to achieve sufficient resolution when multiplying variables, a 32 bit architecture was considered necessary. As an example can be said that if two 16 bit variables should be multiplied without risk of overflow a resolution of only 256 is possible which can be compared with 65536 for 32 bit variables.

7.1.2 Signal interface

CAN is the standard way of communication between devices in a vehicle and the sensor values needed to calculate what is expected from the claw-pole machine is available via the CAN bus [7]. This as well as the ability to transmit the devices own condition makes CAN compatibility essential. In order to calculate the state of the claw-pole machine seven analog and three digital signals has to be read. When the received data is processed into a response it has to send one analog and six digital signals. During the development phase there will be a need of more inputs and outputs why this is premiered. This is due to that all signals wont be available via CAN and additional input/output is needed in order to debug.

7.1.3 Speed

To compare the different microcontrollers performance is hard as the manufacturers often choose to present the measures that favour their product. As seven analog signals is to be read every program cycle the ADC is a more critical measure than for example million instructions per second or clock speed. A mechanical rotational speed of 20 000 rpm with six electrical revolutions per mechanical and six switches per electrical revolution gives

$$20\,000\,rpm = \left\{ \frac{6\,electrical\,rev}{mechanical\,rev} \,\&\, \frac{6\,swichings}{electrical\,rev} \right\} = 12\,kHz\,switching \quad (18)$$

In order to get the switching at the right position a higher update frequency like 40-50 kHz is needed.

7.2 Development kits

To avoid the need of designing and manufacturing a circuit board before all peripherals or even the microcontroller is known, a development kit is used. All manufacturers provides development kits which is a microcomputer designed to be as flexible as possible with many different interfaces and features. The development kits are usually under-priced as a way of marketing as the manufacturers want to encourage use of their products. Not all microcontrollers are included in a development kit which reduces the number of available microcontrollers to choose from. On the other hand, the ones included are often representative for the whole product family and when the design phase is over a microcontroller with less features can be chosen.

7.3 Choosing microcontroller

When comparing the different microcontrollers, all the above aspects were considered. The hard demands like CAN compatibility and 32 bit architecture were used to weed out the unwanted candidates and then the remaining performance was compared. The microcontrollers were equivalent in all aspects except for the ADC in which the a processor from Texas Instruments turned out to be more than ten times faster than the others. It has a floating-point processor with the possibility to run as fixed-point which makes the freedom bigger when programming as floating-point needs lesser consideration while fixed-point can be used if faster operation is needed. The microcontroller comes in a microcomputer with a built-in JTAG-emulator allowing to debug the program as it runs on the microcontroller.

8 Programming

8.1 Programming the specific microprocessor

The code was written in an IDE specially designed for developing code for the chosen family of microprocessors. The IDE support JTAG and can be used together with the built in JTAG emulator to read values from the running microprocessor via an USB cable. The problem is that when the values is sent serially via JTAG, the execution of the program halts which can cause trouble if a PWM signal is left high or the program is in a critical phase. A possible solution to this, is to handle communication with the microprocessor via CAN as the signal being watched is put in a message box and sent in the background without interrupting the execution. This requires suitable hardware and software to interface a computer and is out of range for this master thesis.

8.2 Program

As can be seen in figure 14 the program consists of two parts: Operation control which decide what the machine should do and Machine control which decide how it is going to do it. The work has been focused on the later and it will be described below.

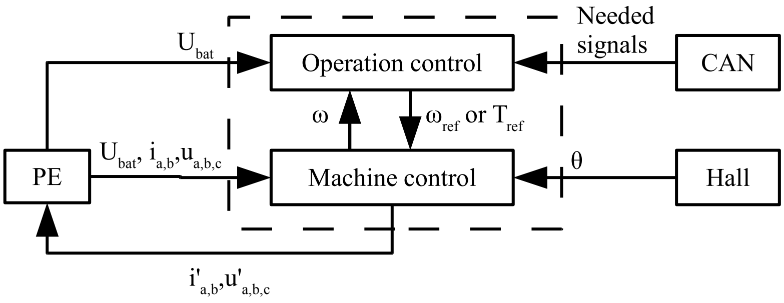


Figure 14: Main program overview. The dashed line indicates the microcontroller.

8.3 Files

During the programming, the code is divided into separate files in order to make it structured and readable. In order to avoid reinventing the wheel, most of the basic functions is pre-programmed and placed in so called help files which can be included. Examples of functions in help files is register/memory maps, mathematical functions like trigonometry and drivers for PWM, ADC etc. This also shorten the starting time as the programmer doesn't have to get familiar with such things. When compiling the program the compiler merge the own files with the help files and translates it to machine code. If the functions needed is known, the help files not needed can be excluded in order to save memory space.

8.4 Functions

Most files are divided into functions which can be called independently. This can be done in order to increase readability or to reuse code sections utilised several times in the code. As local variables are more effective the biggest part of the program is placed in the Main function [10]. Apart from Main there is a function called Init which setup all peripherals. To keep this function from being to large the configuration of GPIO-ports, PWM and ADC is placed in a separate file.

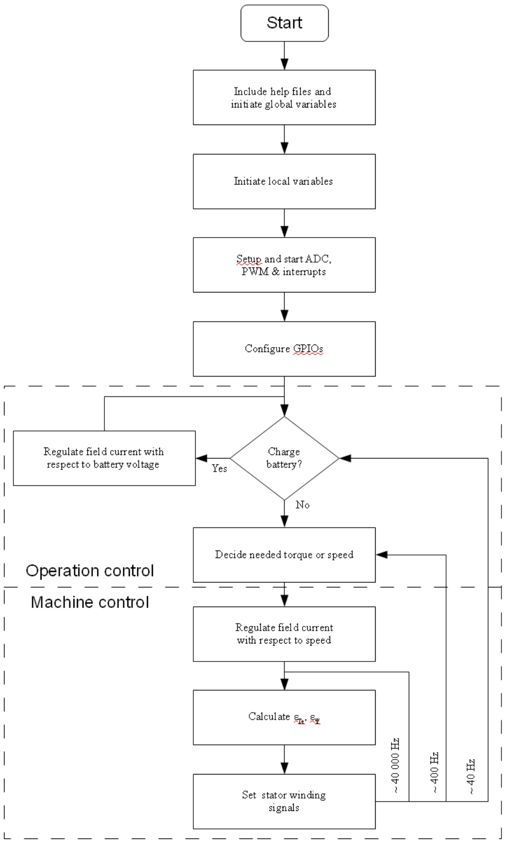


Figure 15: Program flow

8.5 Read ADC

To avoid reading the ADC during an update an empty while loop is used to wait for the conversion to finish. While the next values are sampled the results can be read without risk of corruption.

8.6 Hall read/speed calculation

In order to calculate the speed of the machine correctly it is important to read the Hall sensors as soon as possible after they change their state. For this reason the change of a Hall state is connected to an interrupt where the period since the last change is read. As there is a risk that the reading coincides with the reset of the timer resulting in a misread the result has to be checked before calculating the speed. In order to keep the interrupt short this is done in main. As the speed get higher, the influence of small angular offsets between the elements increases but at 730 rad/s the result is only varying ±2.5%. As can be seen in figure 16 the change in Hall state is not instantaneous which results in an offset between the rising and falling edge. At 100 rad/s this makes the calculated speed to differ with ±30%. The solution is to only compare the time between the rising edges which decreases the resolution.

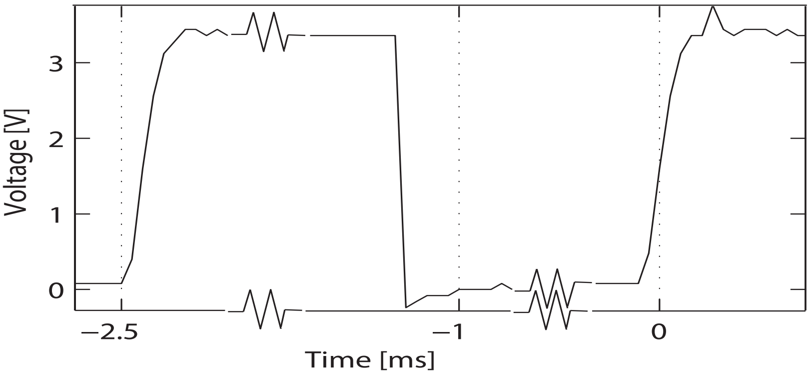


Figure 16: Hall sensor on and off

8.7 Angle calculation

As there is no way to know the position of the rotor except in the exact moment the Hall state changes it has to be calculated continuously. This is done by multiplying the rotational speed with the time since, and adding the position at, the last update. This poses a problem when the machine is either accelerating or decelerating as the speed used for the calculation is not constant. This is solved by using the calculated position until the next positive change in Hall state for acceleration respectively using the middle of the actual Hall state when the calculation indicates that the next positive one should be reached for deceleration. This automatically yields that the middle of the actual Hall state is used when the machine starts from stand still.

Figure?

8.8 Switching

The flux angle is calculated and added to the rotor position as in figure 17. If they together fall outside the Hall state of the rotor the next Hall state is used as reference when switching. As the Hall sequence is not in order (see figure 2), a table is used to decide the reference. Depending on the torque and flux errors the control signal is then chosen and set as digital output.

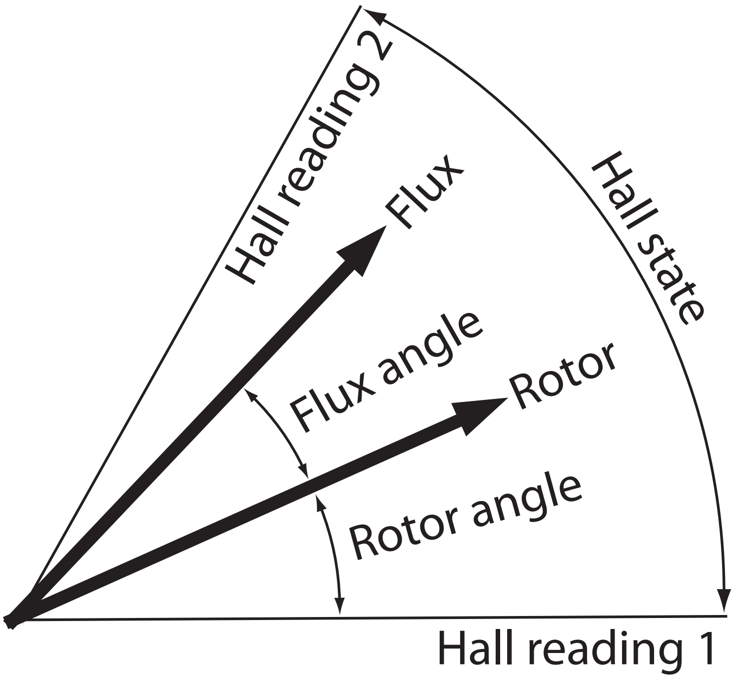


Figure 17: Flux and rotor position in relation to Hall state

8.9 Field current

The field current reference is set with respect to the speed and as it is inversely proportional, the reference is limited at low speeds. The reference is then compared with the actual field current and the error is run through a PI controller. The result is then set to a PWM pin.

8.10 Additional signals

Apart from the signals seen in figure 14 two additional are implemented:

- Battery charge: closes the transistors and uses a PI controller to regulate the field current until a desired charge voltage is achieved.
- Full torque: overrides the torque calculation and makes the machine give maximum positive torque.

9 Verification/Performance

The function of the drive unit was verified and the performance was evaluated to some extent. Some measurements has been difficult to achieve but an attempt to analyse whether the desired performances might be fulfilled or if unable how to modify the prototype to be able to fulfil them.

9.1 Power electronics

Switching waveforms of one of the phases can be seen in figure 18. The input to the gate drive circuit is inverted so the figure shows when the low-side turns off.

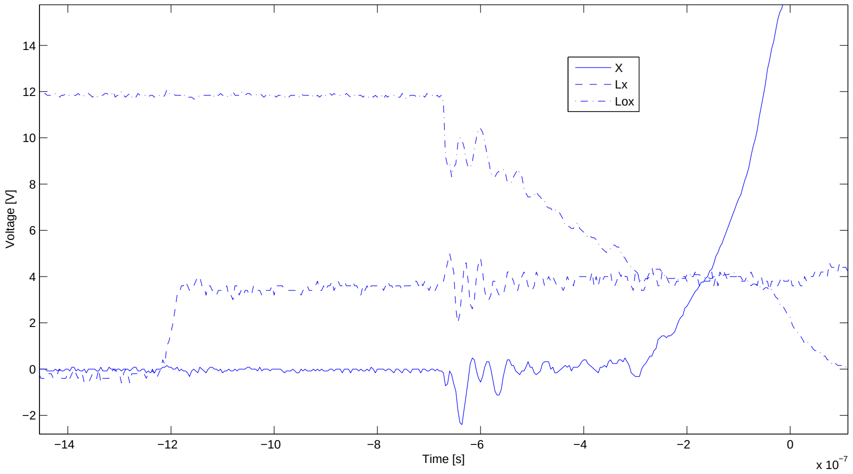


Figure 18: Switch times

The built in blanking time of the gate drive circuit can be seen as the delay between the rise of the L_x signal until the gate voltage drops. One can see that after the blanking time, the gate voltage drops until it reaches the gate threshold voltage of the transistor where the conduction stops and the voltage rises.

With the performance of this prototype the power electronics have been sufficiently sized for most situations. The peak voltages at switching have been observed to be in the safe operation region of the power electronics although the performance and safety would be increased if the voltage spikes could be reduced. In figure 19 the phase voltage of one phase can be seen during start.

The bootstrap function in the gate drive circuit is active when the low-side is turned on. The value of the bootstrap capacitors were not evaluated other than verifying the function for this specific case.

The field current is controlled by a PI-controller which has been trimmed manually. The performance of the field current converter was evaluated by creating a step of the field current reference between 1 and 2 A. The performance of the controller was also verified for currents up to 5 A without overshoot or steady-state errors.

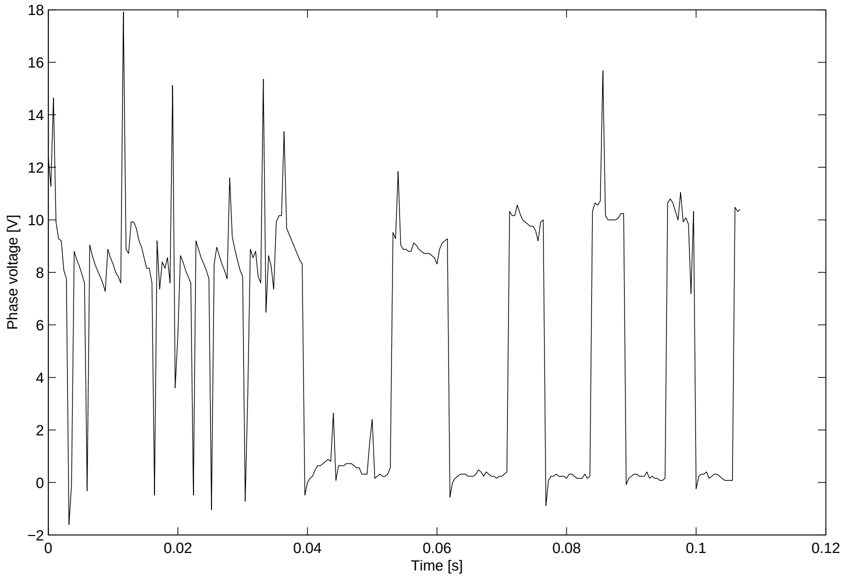


Figure 19: Peak voltage. Start with 5 A field current

9.2 Sensors

The use of Hall effect transducers for measuring of stator currents is very well suited for the prototype. A low power consumption that does not increase with increasing current which makes them more attractive than a shunt resistance. For the field current where the currents are held lower a shunt resistance would be more appropriate, this could lower the component cost. Some issues regarding electrical noise has been found, these problems can be lowered by improving the board layout and proper design of ground connections, the analog and digital ground was probably connected in an undesired way and thus letting ground electrical noise from the microcomputer affect the analog ground. The signal from the Hall effect resolver was passed through a ferrite core to reduce electrical noise, without the ferrite the electrical noise caused problems when triggering unwanted interrupts.

The voltage conversion is rather straightforward and has not yet caused any problems. The performance and reliability of these is mostly dependent on the linearity of the resistances and the operational amplifiers. Also the importance of proper board layout and shielding of cables can improve the performance.

9.3 Control unit

9.3.1 Control strategy

A feasible implementation of the control strategy has been made. The concept and the performance of the control unit program are sufficient for motoring and generating with the machine. There is also available computational time left for implementing several additional control algorithms.

As seen in figure 20 the stator voltages follows the expected path forming a hexagon.

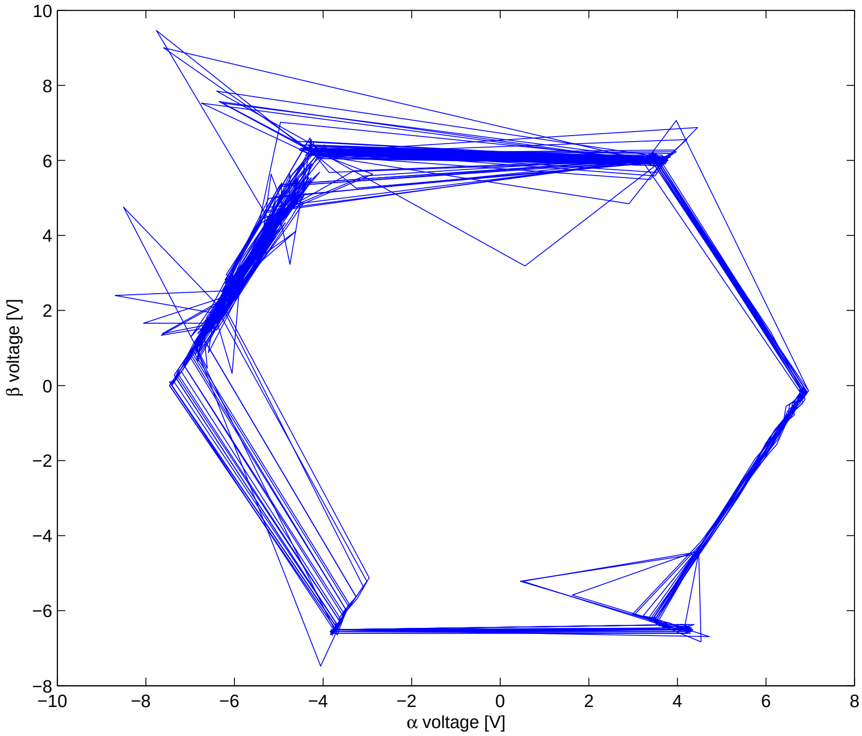


Figure 20: Switch pattern in αβ coordinates

It is most likely possible to enhance the performance of the machine by adjusting parameters and different kinds of flux estimation algorithms should be thoroughly tested and analysed for maximising the performance. An attempt to evaluate different models and algorithms were made. Among the tested models were a statically compensated voltage model, a pure integration of the voltage and a direct interpretation of the stator and field currents. The results led us to use the concept that gave us the best performance in terms of high speed and low power consumption. The lack of time left when the drive unit was complete enough to bee able to evaluate and adjust the flux estimation led to a somewhat poor analysis.

9.4 Mechanical performance

A series of tests were performed in the same rig as mentioned in chapter 5, there were also tests of speed without the coupling to the DC-machine.

9.4.1 Speed

When decoupled from the DC-machine, thus only driving its own inertia and damping, a maximum speed of about 7000 rpm was reached. This is far from the desired goal of reaching 16 000 rpm in motoring mode. At this speeds the field current must be lowered such that the back-EMF of the machine does not exceed the available voltage, this lowers the flux of the machine and therefore the torque production. The inductance of the stator also increases the difficulties for the machine to reach high stator currents. In order to maintain the same peak current at higher speeds the slope of the current change is greater. The available voltage in combination with the stator inductance saturates the slope of the current.

When connected to the DC-machine without the DC-machine running, a maximum speed of about 5500 rpm was reached.

9.4.2 Torque

The most important case for the demands of torque production is at starting, measuring this without a torque measuring device or mounting with an actual ICE is difficult. An attempt to measure the torque production at different speeds was made and the results are shown in figure 21. The torque was estimated from values from the control of the DC-machine where the armature current is related to the torque production by a flux factor which is taken from laboratory exercises for different courses at Chalmers. It can be noted that the tests were performed using the speed dependent equation for controlling the field current.

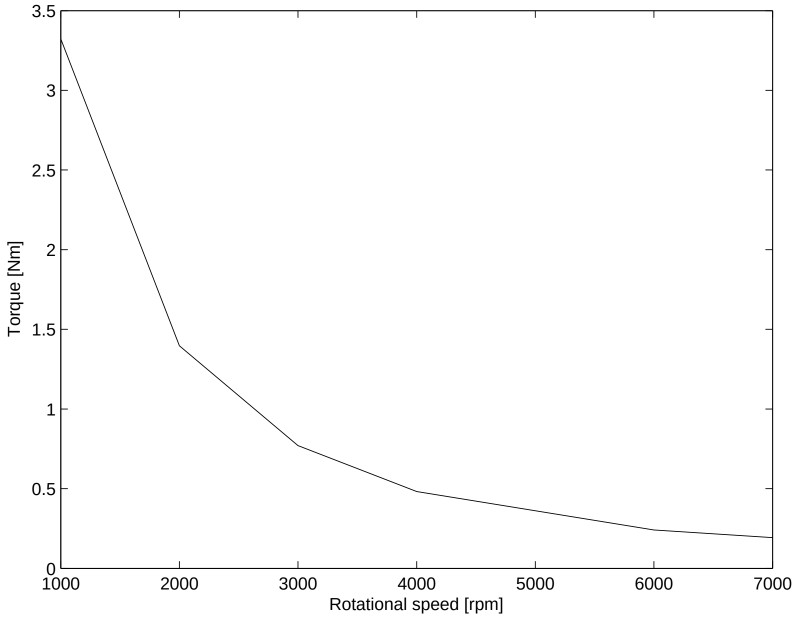


Figure 21: Motoring torque as a function of rotational speed

The maximum torque is difficult to evaluate as a high load at these speeds might cause problems with overload and the transients of the torque is difficult to measure with desired accuracy. The later discussed problem with shut down at voltage drops also contributes to the difficulties associated with measuring the maximum available torque.

Another method is to estimate the starting torque from parameters on the DC-machine. Estimations of inertia and damping have been performed as laboratory exercises for different courses at Chalmers. The torque transferred by the belt can be modelled as the acceleration times the inertia and the speed times the damping. Using this method we can get values for the torque close to zero speed which is of importance in this application. Unfortunately this method also leaves the static friction that holds the machine before the rotation starts. The tests were performed using a field current of 5 A.

$$T = J\dot{\omega} \tag{19}$$

Gives that the machine can produce a torque in the regions of 10 Nm at low speeds with a field current of 5 A. An increase of field current should increase the torque production but due to lack of time more extensive tests were not made. As mentioned in chapter 5.2.3 the flux seems to saturate somewhere above 5 or 6 A but an increase up to at least 10 A can be made and the flux still increases. These results gives great hope that the claw-pole machine can produce a starting torque high enough to work as a starter for an ICE but as also can be guessed by the origin of the specific machine in this thesis it is probably only usable with rather small engines.

Another factor of uncertainty is the dynamics of the belt when accelerating of with high torque production, but this will probably also be case when mounting in a finished product. The desired torque is also of a complex nature why a deeper analysis of whether the proposed solution could handle the desired torque is left undone.

The acceleration of the machine mounted in the test rig can be seen in figure 22.

9.5 Problems

A number of problems have been encountered. Most of them have been regarding the control implementation in the microcontroller or electrical issues regarding sensors and other components. Solutions have been found to a majority of the problems and there exists a lot of different ideas for how to solve the remaining problems. The most obvious downside with the problems that have occurred is the time that has been consumed by troubleshooting and debugging. This time would have been better spent on developing the control algorithm and improving the performance of the drive unit.

9.5.1 Shutdown at voltage drops

Most notably the gate drive circuit ceases to function due to its construction if the DC-bus voltage drops below about 10 V. This causes the gate signals to oscillate and the machine runs very fitful. A solution to this problem could unfortunately not fit within this thesis.

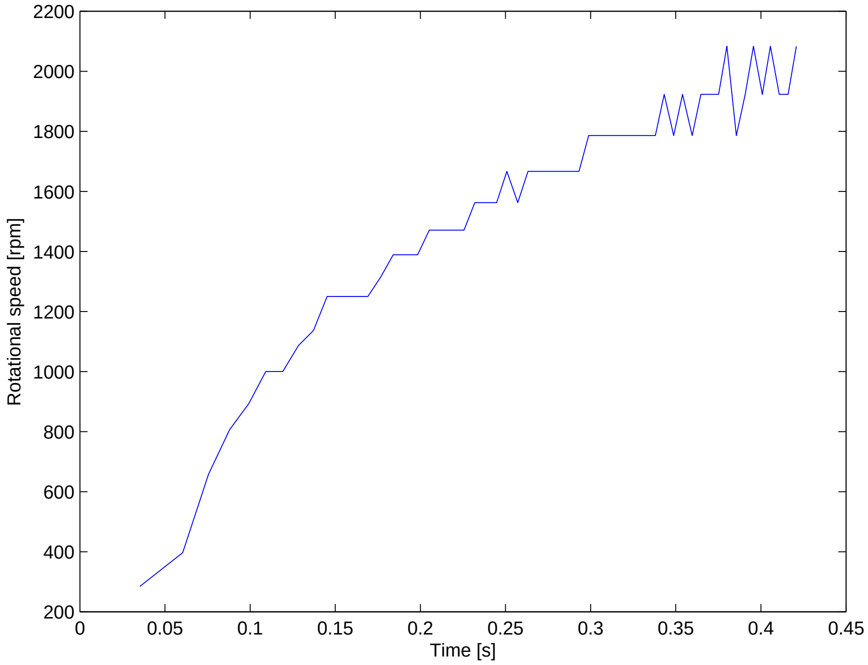


Figure 22: Acceleration

9.5.2 Electrical noise

With the motor drive concept proposed here, there is an evident presence of high frequency signals and digital switching's. These cause electromagnetic interference with the other components and signals in the system. Even if there have been attempts to reduce these types of electrical noise there are several improvements that should and could be made. One factor that contributes to the difficulty of constructing the layout in a low electrical noise manner is the cases when additional circuits and components have to be added. With a complete specification of what components and circuits that will be used, the circuit board can be constructed with much more focus on minimising the electrical noise.

9.5.3 Component failure

When handling electronic components there is always a risk of malfunction of different reasons. The large current handling associated with this project also increases some of the risks. During the tests of the drive unit there were several components that malfunctioned. There was an accident while trying to measure the maximum torque at low speeds, the problems that rose might have been associated with the control of the DC-machine making a to sudden rise in counteracting torque. The failure caused one of the transistors to catch fire and another one was deemed broken afterwards. To reduce waiting time for new components it is a good idea to keep some sensitive or high risk components in stock. Also in this case the time spent on troubleshooting has been the most degrading for the thesis.

10 Conclusions/results

The general function of the drive unit has been verified and the machine can be run. All the requirements for the drive unit have not been met but there is hope and there are many problems that have a proposed solution. This chapter aims to explain what requirement that were not met and suggestions for improvements and further development.

10.1 Power electronics

The power electronics has mostly been working well and the proposed solution has been satisfactory.

The need for external diodes has been deemed to be low since the available power from the ICE often is large and the increase of losses when increasing the forward voltage is rather small in comparison to the generated power. A full evaluation depends on the price of the components and the space available for mounting.

An evaluation of possible increase in performance with the use of snubber circuits has not been made, but this might be a way to improve the efficiency or the safe operating area of the power electronics.

The space needed for the transistor bridge is judged to be small enough that a solution for fitting the power electronics on the back plate of the claw-pole machine.

10.2 Electric machine

The claw-pole machine has been proved to suit well for the purpose of being used as a starter and generator [1] but the high speed motoring abilities have been difficult to verify. An increase in supply voltage would expand the speed range and there might be other strategies for improving the performance. Our conclusion is that the claw-pole machine is possible to use as intended if the supply voltage would be raised. Mechanical stress at such high speeds does not seem to be a problem for the claw-pole machine since it is being used as generator in several cars today [1]. Other types of machines might be considered for motoring at such high speeds. A short compilation of the most important arguments for and against for some common types of machines is listed below.

Switched reluctance machine Suitable for high speeds. Simple and cheap construction.

Permanent magnet synchronous machine High efficiency. Due to the fixed flux, either field weakening must be made by the stator at high speeds or the torque at low speeds will be lowered.

Induction machine High starting currents. Low starting torque.

DC-machine Low efficiency and wearing of the brushes which gives poor life length.

We suggest that if a change of machine would be made a switched reluctance machine would be of special interest.

10.3 Microcontroller

10.4 Control algorithm

Analysis in terms of efficiency in relation to other control schemes has not been made. The proposed solution works and the motoring of the machine is smooth. The complexity of implementing the proposed control algorithms with satisfactory accuracy makes the evaluation of the choice of control scheme a bit difficult. There have not been any

Since the implementation of a charge function using the switch table has been unsuccessful, the hysteresis of the torque in this type of application could have been simplified and the need for negative torque reference is unnecessary. The machine will only have one direction of movement in this application and the hysteresis could have been between applying the zero voltage vector and the proposed switch table.

The robustness of the system paves the way for handling control of the machine even if some sensors would be malfunctioning. In the harsh environment of a car such crucial functions as starter and generator must be able to work at all times why there would be an obvious benefit if the function could be guaranteed as much as possible.

10.5 Supply voltage

The supply voltage of 12 V is a standard in many cars today, there is however several obvious reasons that a higher voltage could improve the performance of the system. An increase in supply voltage would also decrease the conduction losses due to the lowered currents.

A higher supply voltage is also proposed by literature on similar solutions [1]. Our recommendation is to increase the supply voltage to at least the double present value.

The need for modifications on this prototype to increase the supply voltage mainly consists of creating a 12 V supply for some of the circuits. Some kind of separate supply for these circuits is also desirable even if the voltage does not increase since it could be a remedy for the problems with shutdown at voltage drops. There might also be a need to replace the transistors used for this application but there is also an ease for the transistors whom will be relaxed from switching as high current.

10.6 Sensors

The proposed sensors have been deemed good choices for the application even though some modifications might be made. We propose that the current transducer for the field current is to be replaced with a shunt resistance, this could reduce the cost of the sensor and does not add any significant complexity to the construction of the drive unit. For the stator currents we recommend that Hall effect ferrite transducers is used, the lower losses associated with these transducers is deemed to surpass the extra cost.

10.7 Future work

For increasing the generator power output at higher speeds, a switched mode rectifier could be utilised. A switched mode rectifier can be implemented using the same components as for the half-bridge, this only leaves the control of the transistors for maximising the power obtained in generation mode. The implementation and testing of such usage is not covered in this thesis.

The power electronics could benefit from improvements regarding snubbers and an evaluation of the bootstrap function for different cases should be made to ensure that the capacity of the circuit can be maximised.

Different parts of the program needs different intervals between the times they run. The field current doesn't have to be updated as often as the stator phases. This is done by placing the different parts in for-loops. In order to ensure a fixed frequency the different parts is placed in interrupts which run at the wanted frequency. If this solution is chosen it is important to rank the interrupts in order to avoid that something less important block something critical [11]. Other important aspects is to implement CAN and use of the flash memory.

In order to improve accuracy when calculating θ the derivatives of the speed should be calculated.

References

[1] Boldea I: Variable Speed Generators, Taylor & Francis Group, Boca Raton 2002

[2] Harnefors, L: Control of Variable-Speed Drives, Mälardalen University, Västerås 2002

[3] Mohan N, Undeland T, and Robbins W: Power Electronics Third edition, John Wiley & Sons, inc. Hoboken 2003

[4] Balogh L, Design and applications guide for high speed MOSFET gate drive circuits, Texas Instruments, Dallas 2006

[5] Alciatore D, Histand M: Introduction to mechatronics and measurement systems, McGraw-Hill, New York 2007

[6] Texas Instruments, TMS320C28x Floating Point Unit and Instruction Set Reference Guide, Texas Instruments, Dallas 2008

[7] Corrigan S, Introduction to the Controller Area Network (CAN), Texas Instruments, Dallas 2008

[8] Löfgren I,

[9] Mägi M, Melkersson K, Lärobok i maskinelement, EcoDev International, Göteborg 2005

[10] Texas Instruments, TMS320C28x Optimizing C/C++ Compiler v5.0.0, Texas Instruments, Dallas 2007

[11] Årzen K-E, El-Khoury J, Shi J, Törngren M, Real-Time Control Systems, Chalmers Göteborg 2008

Appendix A - Measurements

The measurements were performed at "grundkurslab" at the division of Electrical Power Engineering at Chalmers University of Technology. A three-phase Y/D transformer was connected to the grid; the D side was connected to an auto transformer, which was connected to a diode rectifier. Digital multimeters of the type BS1704 were used during the experiment.

DC measurements:

$$I = 3,210A \tag{20}$$

$$V = 2,100V \tag{21}$$

$$R_r = 0,6542Ohm \tag{22}$$

AC measurements:

$$I = 1,996A \tag{23}$$

$$U = 20,80V \tag{24}$$

$$W = 2 * pi * 50rad/s \tag{25}$$

$$X = 10,4208841283Ohm \tag{26}$$

$$L_r = 0,03317H \tag{27}$$

Stator windings Results for resistive measurements. XY:

$$I = 6,10A \tag{28}$$

$$U = 259,5mV \tag{29}$$

$$R = 0,042541Ohm \tag{30}$$

XZ:

$$I = 6,47A \tag{31}$$

$$U = 279,5mV \tag{32}$$

$$R = 0,0431994Ohm \tag{33}$$

YZ:

$$I = 5,72A \tag{34}$$

$$U = 250,9mV \tag{35}$$

$$R = 0,0438636Ohm \tag{36}$$

And for AC measurements. XY:

$$I = 5,50A \tag{37}$$

$$U = 0,325V \tag{38}$$

$$Z = 0,059091Ohm \tag{39}$$

XZ:

$$I = 7,40A \tag{40}$$

$$U = 0,444V \tag{41}$$

$$Z = 0,06Ohm \tag{42}$$

YZ:

$$I = 7,10A \tag{43}$$

$$U = 0,419V \tag{44}$$

$$Z = 0,0590Ohm \tag{45}$$

Mean values for stator resistance and inductance:

$$R_s = 0.0432Ohm \tag{46}$$

$$L_s = 0.12660mH \tag{47}$$

Appendix B - Specification of the prototype board

Component list:

- 7 pcs IRF1503 MOSFET transitors for three-phase bridge and buck converter.
- 7 pcs MBR4045PT Schttky diodes for three-phase bridge and buck converter.
- 1 pcs IRS2336(D) Gate drive circuit for the three-phase bridge.
- 1 pcs HXS 50-NP
- Hall effect current transducer for the field circuit.
- 2 pcs HTFS 200 Hall effect current transducer for the stator circuit.
- 1 pcs EL7202CN MOSFET drive circuit.
- 2 pcs 324PC Quad operational amplifiers. One for converting current sensing signals and one used as a buffer for the phase voltage divider.
- 1 pcs L78S05CV Voltage regulator.
- 6 pcs 47nF capacitors For reference see datasheet for respective transducer.
- 3 pcs 4.7nF capacitors For reference see datasheet for respective transducer.
- 6 pcs 4.3 V Zener diodes Safety feature between microcontroller and gate drive circuit.
- 5 pcs 3.6V Zener diodes Input protection for ADC-unit.
- 3 pcs 0.68uF Capacitors For bootstrap of the high side of the three-phase bridge.
- Resistances for the stator current sensing operational amplifier. 2 pcs 3.09k 2 pcs 134k 2 pcs 390k 2 pcs 2.55 k
- Resistances for the field current sensing operational amplifier. 1 pcs 30k 1 pcs 180k
- Resistances for the voltage dividers for phase voltages. 3 pcs 8.66k 3 pcs 1.5k
- 4 pcs Supply capacitors to integrated circuits (ca 1uF each) 3 pcs Bootstrap diodes (simple/unknown) 1 pcs Pull-down resistance for 7202 drive circuit (10k Ohm) and gate resistances to the MOSFETS (27 Ohm).