CODEN:LUTEDX/(TEIE-5286)/1-111/(2011)

Industrial Electrical Engineering and Automation

Further development of a pulse magnetizer

Jon Axelsson
Per Söderberg

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

Abstract

A machine for magnetizing permanent magnets is under development at LTH. The idea of the machine is to affect only small pieces of a magnet at the time to obtain magnets with an arbitrary flux density, of course with respect to the magnetic material. The final machine is supposed to work in a closed loop fashion. Every part of the magnet is magnetized, measured and magnetized again with a flux density based on the desired flux density and the measured magnetizing result until the final result is satisfactory. This thesis covers the development of a new control system for the machine including a new current controller for the coils providing the flux. It also includes performance tests of the magnetizing head and a parameter study of the magnetization result as a function of current magnitude, shape and pulse time.

Preface

This thesis has been made at LTH for the division of Industrial Electrical Engineering and Automation (IEA) in cooperation with Industrial Production (IPROD) and is the final part of our education. We want to thank both IEA and IPROD for their help, and special thanks to:

Mats Alaküla, our supervisor, for his dedication, inspiration and imaginativeness which has led the project to interesting conclusions.

Getachew Darge, at LTH, for his knowledge and experience, all his hints and his almost inexhaustible supply of “good to have” stuff which altogether has saved us a lot of time and made this project possible.

Kenneth Frogner, at IPROD, for his knowledge and hints about the machine as well as his knowledge about everything from magnets to electronics.

Andreas Jönsson and Christoffer Örndal, former DLAB, for introduction and support in labVIEW programming.

Svante Bouvin, at IPROD, for his knowledge and experience in mechanical workshops.

Contents

1 Introduction 1

1.1 Background 1

1.2 Objectives 2

1.3 Scope 2

2 Theory 3

2.1 Current control with inductive loads 3

2.2 The choice of control system 3

3 Hardware 5

3.1 Existing hardware 5

3.1.1 Enclosure 5

3.1.2 Magnetizing head 7

3.1.3 Magnet holder 7

3.1.4 Power electronics 7

3.1.5 Inrush current limiter 8

3.1.6 Hall sensors 8

3.2 Developed hardware 9

3.2.1 The usage of a CompactRIO 10

About the CompactRIO 10

Input and output modules 10

Interface 11

3.2.2 Current control 11

Overview 11

Current measuring 13

Comparison electronics 13

Variable inductance 13

Calibrating electronics 14

Voltage measuring 16

3.2.3 Level converter to the IGBT's 16

3.2.4 Power supplies 17

3.2.5 Hall sensors 18

3.2.6 Cooling of the flux providing coils 19

3.2.7 Safety 19

Control panel 19

Shake to wake ... 22
Diagnostics ... 23
Fast stop ... 23
3.2.8 The philosophy of the construction ... 24
EMC ... 24
Choice of components ... 24

4 Software ... 25
4.1 Distribution of tasks ... 25
4.2 Communication between the different parts ... 26
4.2.1 Variables ... 26
4.2.2 FIFO-queues ... 26
4.2.3 Interrupts ... 26
4.3 The structure of the program on the embedded computer ... 27
4.3.1 User interface ... 27
4.3.2 Operating system ... 35
Structure ... 35
Implementing a state machine ... 36
How the operating system is used ... 36
Current pulse generation ... 37
Hall sensor sampling ... 38
Serial communication with the servo ... 38
Positioning the servo motor ... 39
Positions calibration ... 41
Pulse state machine ... 42
Reset state machine ... 43
Scan state machine ... 44
Magnet diagnostics ... 45
Scan magnet band and data save ... 46
Performance measurements ... 46
Pause and resume sequence ... 49
Safety in software ... 49
4.4 The FPGA program ... 50
4.4.1 Overall structure ... 50
4.4.2 Current control logic ... 50
4.4.3 Generation of tolerance bands ... 52
4.4.4 Comparator calibration ... 53
4.4.5 Current pulse generation ... 54
4.4.6 Error watcher ... 55
4.4.7 Data sampling ... 56

4.4.8 Safety in software ... 57
4.4.9 Switch pattern analyzer ... 58
4.5 MATLAB programs ... 58

5 Results ... 60
5.1 Current control ... 60
5.2 Magnetizing performance ... 69
5.2.1 Reset results ... 69
5.2.2 Surfaces ... 70
5.3 Time ... 86

6 Discussion and conclusions ... 87
6.1 Current control ... 87
6.1.1 The work of the controller ... 87
6.1.2 Suggestions of improvements ... 87
6.2 Magnetizing results ... 88
6.2.1 Reset ... 88
6.2.2 Discussion about the surfaces ... 88

References ... 89

Attachments ... 91
Hardware ... 91
Connection lists ... 91
Interconnections ... 93
MATLAB code ... 95

1 Introduction

1.1 Background

In a large range of electromechanical applications a magnetic force is used in the conversion between electrical power and mechanical power in either direction. Many of these devices involve permanent magnets and in these devices there is often a strong correlation between the performance of the used permanent magnets and the performance of the final device. For that reason it is desirable with permanent magnets whose properties are within tight tolerances.

Different materials have different magnetic properties. [1] What is common for those material that are used for permanent magnets are the ability to remember a magnetic flux, this is called remanence. The properties of the remanence differ between different materials in several ways. Generally, the most important parameter is how large flux the magnet is able to store.

Magnets are magnetized by affecting the magnetic entities of the magnet called magnetic domains. This is achieved by exposing the magnet to an magnetic field, usually provided by an electromagnet. Since different materials have different properties it is not unreasonable to assume that they should be magnetized in different ways. If the desired remanent flux is large the flux applied by the electromagnet must also be large. Nevertheless, there is profit in exposing a magnet for a flux that is much larger than the possible amount of remanent flux.

The maximum applied flux is not the only important parameter. The way the flux is applied is also important. If the magnet is able to carry an electric current, eddy currents will occur if the flux is applied to fast. These will act like a magnetic shield which inhibits the magnetization since they will provide a flux that is opposite to the magnetizing flux.

As mentioned, this magnetic property differs between different magnet materials. Even the properties inside a piece of magnet differ from spot to spot. This makes it difficult to manufacture magnets of a consistent quality since it seems like it is desirable to treat every spot of it individually. To get around this problem LTH has produced a prototype with the aim to individually magnetize small spots of permanent magnets. The magnet that is to be magnetized is placed in an air gap where the flux is concentrated to a small slit. This is done dynamically with lenses made of copper where the eddy currents generated in the lenses is forcing the flux through the slit. The flux is provided by two copper coils in which it is driven a pulse shaped current.

The equipment before this thesis was not working satisfactory and was in need for improvements. The achieved magnetization was not as precise as wanted and the reason for this is not directly specified. A possible reason is that the ripple of the current driven through the flux providing coils was to large, hence a new current controller is to be implemented. To gain better control of the machine a new modern control system has been purchased. The new control system is meant to replace the old one and allow development of a more advanced control system with better performance, but still be easy to use.

1.2 Objectives

- Replace the current controller to a control system based on NI CompactRIO and introduce a method of modulation that minimizes the ripple of the current.
- Improve the usage of sensors for measuring the accomplished magnetization. The measuring width should be the same as the magnetizing width.
- Further improvement for automatic, iterative magnetization of discrete magnets.
- Initial study of the possibility to industrialize the process in terms of the cycle time and the quality of the final magnets.

1.3 Scope

The target of this thesis is to meet all the objectives of the project plan. Since the conditions for some of the parts of the project was unknown the objectives was adjusted during the project.

The current controller is built as planned, but a lot of safety devices are added to minimize the risk for damage on hardware as well as humans and hence minimize the number of delays in the work.

No advanced measuring head is developed. Instead hall sensors placed next to the magnet band are used.

Instead of studying the possibilities of automatic iterative magnetization the performance and properties of the magnetizer is studied. Only small spots were magnetized and the peak magnetization and pulse width is studied as functions of magnitude, time and shape of the current. Due to this delimitation the possibilities to industrialize the process is not studied

2 Theory

2.1 Current control with inductive loads

There are two main types of current controllers, the sampled current controller and the direct current controller. [2] This book is the basis for our view of how these two controllers work, but to make this text more readable, here is a short summary. It is assumed that the reader is familiar with switching electronics and the voltage/current characteristics of inductive loads.

The sampled current controller uses a triangular wave modulator to create a switch pattern which result in a mean output voltage that corresponds to the desired voltage reference. The current through the load is sampled in the middle of the current rise or the current fall to obtain a mean value of the current without using any averaging. The sampled current and the current reference are feed to a regulator which creates the voltage reference to the modulator. It is possible to calculate the ideal regulator parameters analytically from the inductance and the resistance of the load and the time between the samples. These parameters are called *dead beat* parameters and provide a new voltage reference that will eliminate all the error in the current. This controller has many advantages, for instance that the switching frequency can be chosen to a known value.

The direct current controller, or the tolerance band current controller is much more simple. In its most simple form it compares the actual current with two references which forms the tolerance band. If the current is below the lower band, the voltage is turned on. If the current is above the upper band, the voltage is turned off. This creates a self-oscillating controller which is very simple, but also stable. When using a four quadrant converter there are more choices than only on and off, the voltage can be reversed to. This means that there are three different current slopes to choose between, hence a little refinement is needed. The solution is to add two more bands outside the earlier two bands to find out if the chosen action was sufficient. For example: the current crosses the upper inner band and the controller changes the output voltage to zero, but this is not enough to make the current fall. Hence the current will cross the outer upper band, and a more suitable output voltage could be applied. This controller has its strength in its simplicity and insensitivity for outer variations.

2.2 The choice of control system

It is desirable to use currents the order of 300 *A* and it is known that at least parts of the magnetic circuit is saturating at the flux densities that these currents will result in. This means the inductance will vary to and hence the sampled current controller is not the wisest choice. Instead, the choice is a direct current controller, or a tolerance band controller as it is going to be called in this text.

Today, there are mainly two different ways when designing a tolerance band current controller. The old way is to use analog electronics for the comparisons and digital circuits to choose action. The new way is to sample the current extremely fast and practically implement the same thing in software. The new way requires an extremely fast (hundreds of *kHz*) AD converter and calculating performance that can handle the amount of data. But in return it is more flexible.

Our choice is to make a hybrid of these to variants. The bands are going to be generated digitally

and hence the controller will be as flexible as the digital version. But the comparisons are going to be made with analog electronics, and hence there will be no need for an extreme AD converter.

3 Hardware

3.1 Existing hardware

As you may have noticed this thesis is not about building a magnetizing machine from scratch. Most of the hardware for the prototype was already built, but in need for some improvements. But to give the reader of this report a fair picture of the conditions for our work here is a description of the hardware that we recycled for our work. This chapter will only cover a description of the hardware, not necessarily an explanation about why it is built as it is.

3.1.1 Enclosure

Image 1: Pulse magnetizer machine

In the image above the pulse magnetizer machine is seen. It is built in and on top of a metal box. The inside is split into two different volumes where the big one is inside the *feet* of the cabinet. On top of this part the *magnet holder* and the *magnetizing head* is placed. In front of the top of this part is a pult shaped enclosure. This part is electrically shielded from the rest of the machine and represents the smaller volume. On top of it the *control panel* is placed.

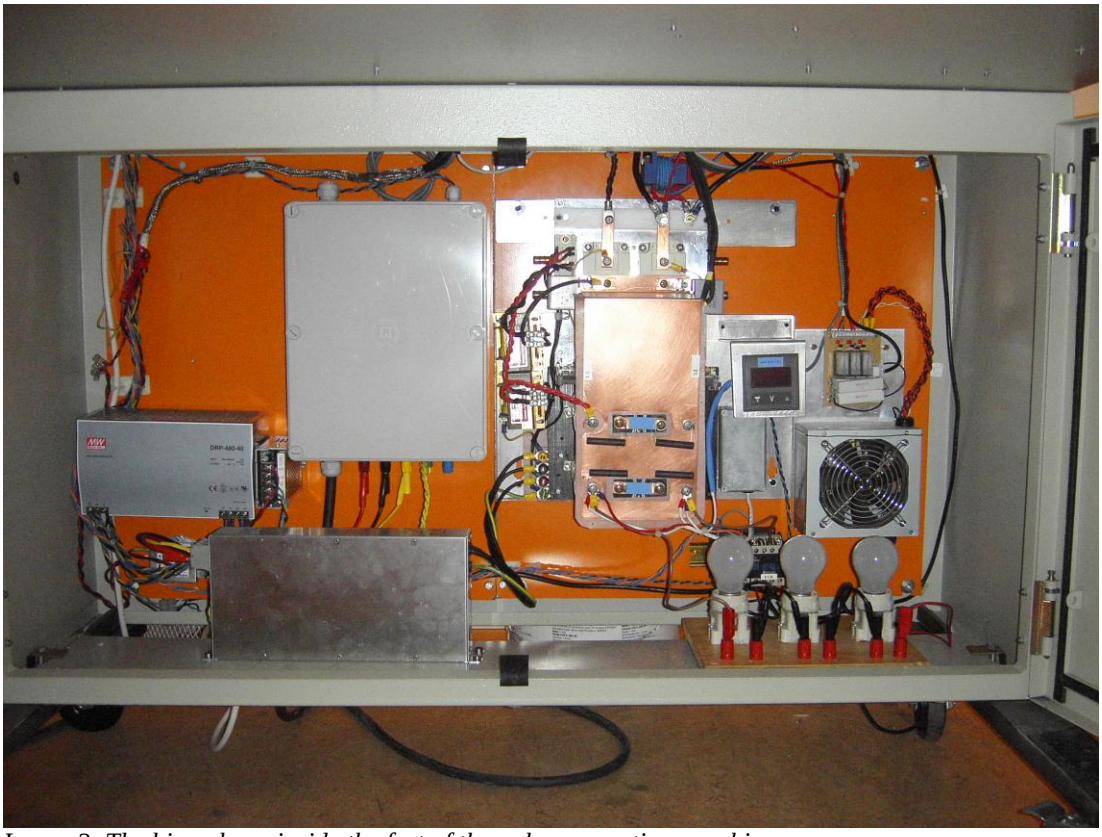


Image 2: The big volume inside the feet of the pulse magnetizer machine

In the big volume all high voltage devices such as power electronics, etc. is placed. This is seen in the image above and gives the opportunity to connect the power electronics to the magnetizing head with short cables. In the smaller volume the control system is placed, as far as possible protected against electromagnetic interference. Nevertheless, since the mains instrumentation and the power supplies for the cRIO and the peripheral electronics are placed here to it occurs mains voltage. A close up image of the inside of the smaller volume is seen below.

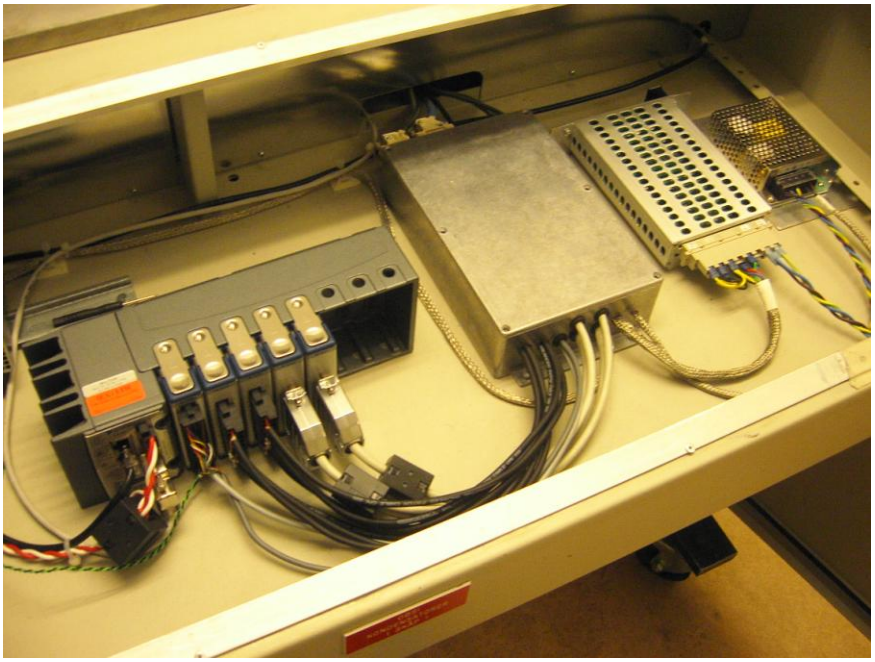


Image 3: The smaller volume with cRIO, metal box containing developed electronics and two power supplies

3.1.2 Magnetizing head

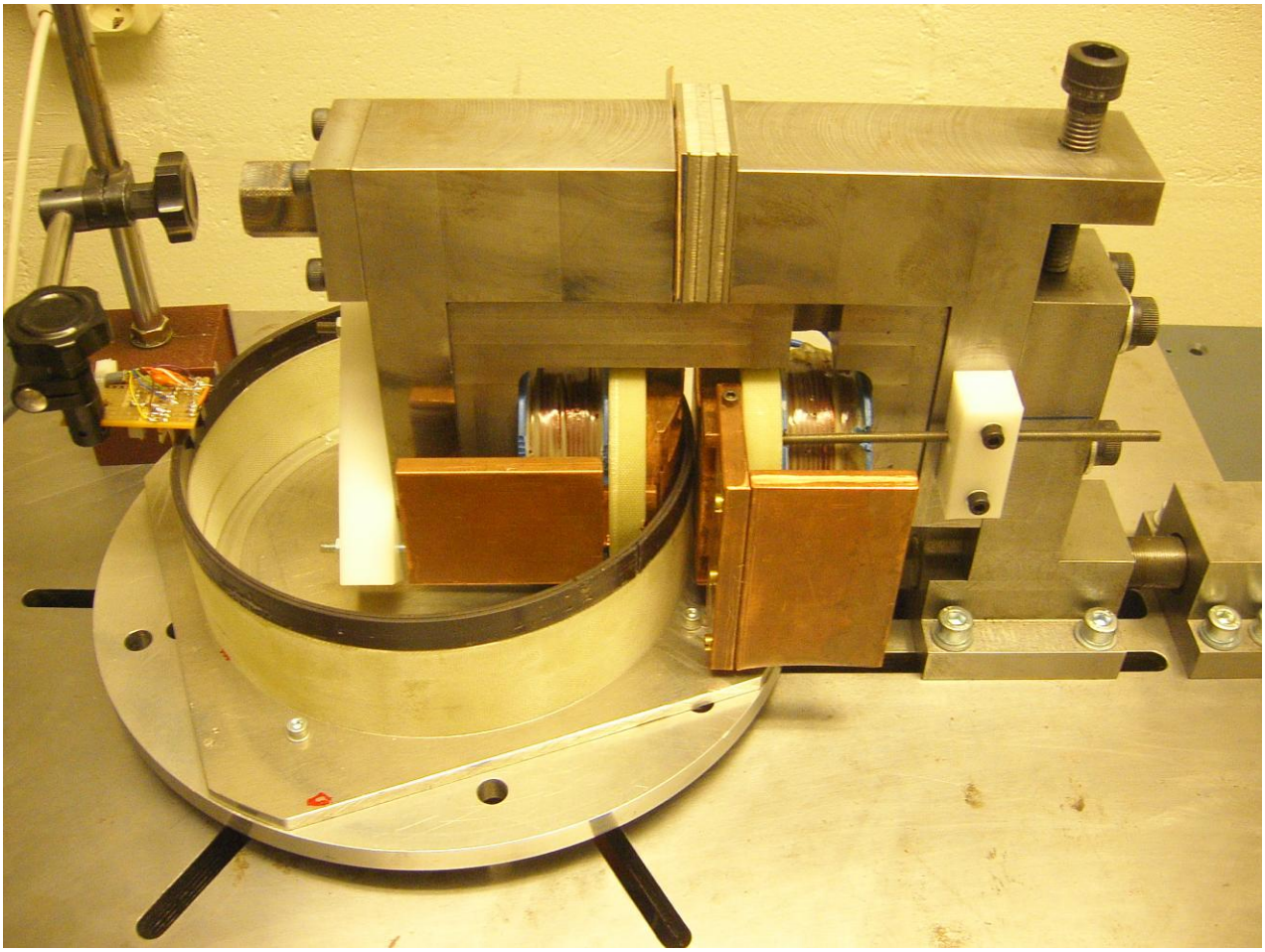


Image 4: The magnetizing head of the pulse magnetizer machine

The magnetizing head is seen in the image above and consists of an adjustable yoke with an air gap containing the magnet that is supposed to be magnetized. Next to the magnet the yoke ends up with two flux collection lenses that are concentrating the flux to a defined area. This area is shaped as an upended rectangle with the height of the magnet and the width equal to the desired resolution of the magnetization. Next to these lenses there are two coils providing the flux when an appropriate current is driven through them. These coils are coupled in series.

3.1.3 Magnet holder

The magnet holder is a prototype made for evaluation of the rest of the machine. It is simply two pieces of magnet band glued to the cutting surface of a piece of plastic pipe. The plastic pipe is in turn attached to a rotatable base consisting of an aluminum plate and a servo motor. This means that you can choose which part of the magnet band that is to be exposed to the concentrated flux of the magnetizing head by sending a position reference to the servo.

3.1.4 Power electronics

The old power electronics was used as well, however a new controller was a part of the thesis. The power electronics has been used almost as it was except for some smaller changes and repairs. It is

built like a module with IGBT's with suitable drivers, DC link capacitors, rectifier and inductors for the rectifier mounted on a metal plate. The IGBT's and the rectifier are further more mounted on a water cooling block, however this is not connected since the losses does not seem to cause any significant temperature rise.

It is supplied directly from rectified 400 volts three phase mains. There is no transformer isolating this power supply from the mains, hence it is completely isolated from the rest of the construction. This means that there is a lot of power available to the rectifier, since there is no stray inductance of resistance as in regular power supply with a transformer. To make it possible for the rectifier to survive a sudden drop of the DC voltage there are two inductors of 0,3 *mH* between the rectifier and the DC link capacitors with the aim to smooth current peaks.

Between the rectifier and the *inrush current limiter* there is a mains filter with the aim to prevent the machine from disturbing other equipment.

3.1.5 Inrush current limiter

When energizing the DC link the voltage across the DC link capacitors are usually zero. This means that the current through them will huge if the rated voltage of the machine is applied at once. To prevent this inrush current from breaking the mains fuses or even the rectifier the machine is equipped with an inrush current limiter consisting of two contactors, one time relay and three power resistors of 100 ohms. The function is very simple, the first contactor connects the mains voltages to the rectifier via the power resistors. The voltage drop over the resistors enables the DC link capacitors to be charged at a more suitable current. After approximately four seconds the time relay closes the second contactor which short circuits the resistors, however, during these four seconds the DC link voltage has been able to rise to approximately 500 volts. The first contactor and the time relay is activated by an external input for 230 volts.

3.1.6 Hall sensors

During the early test of the performance of the machine it was provided with a hall sensor mounted next to the outside of the magnet band. Unfortunately this sensor was damaged during our tests.

3.2 Developed hardware

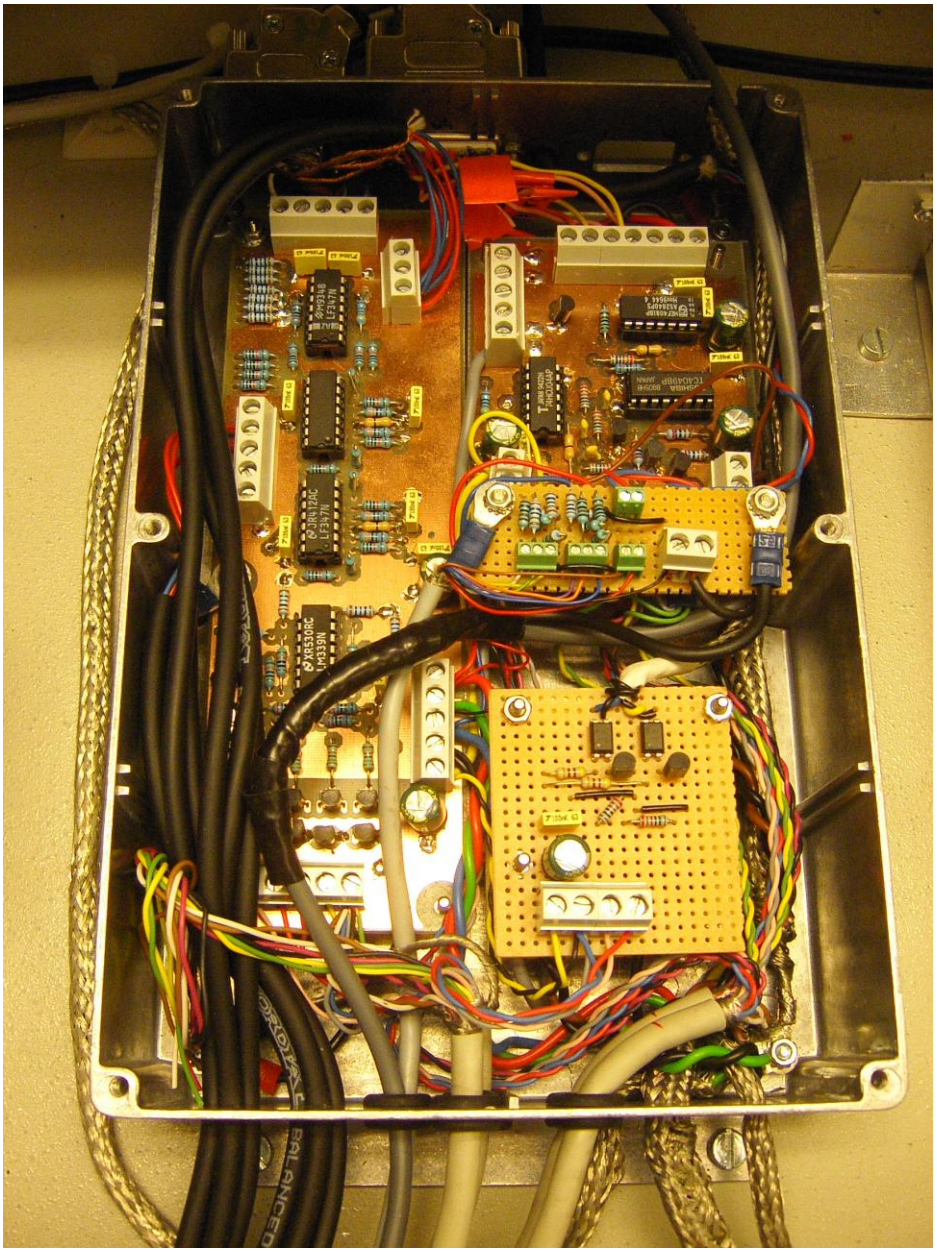


Image 5: The inside of the metal box containing the developed electronics

The developed hardware can be seen in image 2, 3, 4 and 5. On the far right in image 2 electronics for calibration can be seen, it is the card to the right of the indicator for the DC link voltage. Image 3 show the smaller volume of the enclosure with the cRIO, a metal box containing developed hardware and two power supplies. On the left side of image 4 a card for the hall sensors can be seen. Most of the developed hardware is nevertheless in the metal box and a close-up of it can be seen in image 5. The large circuit board is for the current controller. On the top right is a circuit board with level converters for the power electronics. On the small prototype board is signal conditioning and the large prototype board beneath it is more electronics involved in calibration. Since it is very tight on tight with space in the box there is another prototype board under the large prototype board the can be seen in the image. This board is involved in something called Shake to wake and is explain in Shake to wake in 3.2.7.

3.2.1 The usage of a CompactRIO

About the CompactRIO

We did not develop the CompactRIO system, but to give the reader a fair overview of the control system, here is a short description of the cRIO.

The cRIO consists of three parts, an embedded computer, a field programmable gate array (FPGA) and a number of input and output modules (I/O modules). The embedded computer that is used is a NI cRIO-9022 and the used FPGA is a NI-9114. All together they form the cRIO into a compact industrial controller and measurement system. It is up to the programmer which part of the code that is to be executed in the embedded computer and which part that is to be executed in the FPGA and the code look similar, but it is executed in very different ways. The code executed in the embedded computer executes task by task since it is a single core processor, nevertheless it is executed in a real-time operating system. The code that is downloaded into the FPGA is practically built into hardware. This sets clear limitations in the complexity and the size of the code. The big advantage is that everything that runs into the FPGA is executed simultaneously, hence it is very powerful in controlling applications if it is used properly. The FPGA is connected to both the I/O modules and the embedded computer. Hence controlling tasks can be handled by the I/O modules and the FPGA only with extremely short response time, while heavier less time critical calculations is delegated by the FPGA to the embedded computer. The embedded computer is equipped with two Ethernet ports. These are used for communication with the host PC that is used for programming and interfacing it for example. Furthermore it is equipped with one RS232 port for miscellaneous use and an USB port to connect an extra storage volume. [3]

The RS232 port is in our case used for communication with the servo used for positioning of the permanent magnet.

Input and output modules

The cRIO is very flexible in the way that you can choose I/O modules that suits you task. In this project five modules are used where two of them are the same. The used modules are:

NI 9205 that is an analog input module with 32 channel and 16 bits resolution. [4] The sampling rate is 250 kS/s distributed over all used inputs. It is also provided with a digital output. In our case it is used for non time critical data sampling as hall sensor data and diagnostics of the machine.

NI 9215 that is an analog input module with four inputs and 16 bits resolution. [5] The sampling rate is 250 kS/s, however this module is capable of sampling all inputs simultaneously at a sample rate of 100 kS/s.

NI 9263 that is an analog output module with four output and 16 bits resolution. [6] The sample rate is 333 kS/s if one channel is used and 105 kS/s if all four is used.

NI 9401 that is a TTL I/O module with 8 channels. [7] The channels can be configured as in or outputs in groups of four and the performance varies with the number of channels used. Two of these modules are used.

Interface

The interface to the user consists of two parts, the front panel on the host PC and the control panel located on the machine. During normal operation the user only uses the front panel for programming and monitoring of the machine. The control panel is there for both practical and safety reasons. It makes it possible to shut parts of the machine down during troubleshooting for example, and if something in the control system hangs up the user can safely stop the machine from it.

3.2.2 Current control

Overview

The current that is driven through the flux providing coils is regulated to a shape and magnitude decided by the user to allow maximum flexibility. To ensure good control of the current ripple a tolerance band controller is used. As mentioned earlier a hybrid between the analog and the digital tolerance band controller is used. The desired tolerance bands, in other words the current shape and magnitude, are generated digitally. But the comparisons, ie what determines if the current is within tolerance or not is done analogy which gives almost immediate response. To make this possible the generated bands DA converted with an analog output module and feed to the peripheral electronics. The comparison signals is feed back to the FPGA where the choice of new signals to the IGBT drivers is made.

There are totally four tolerance bands, two inner and two outer. The purpose of the inner bands is to know if the current is within tolerance or not. The purpose of the outer bands is to know if the chosen control action was sufficient or not.

The schematic of the peripheral electronics is found below and will be explained the following paragraphs.

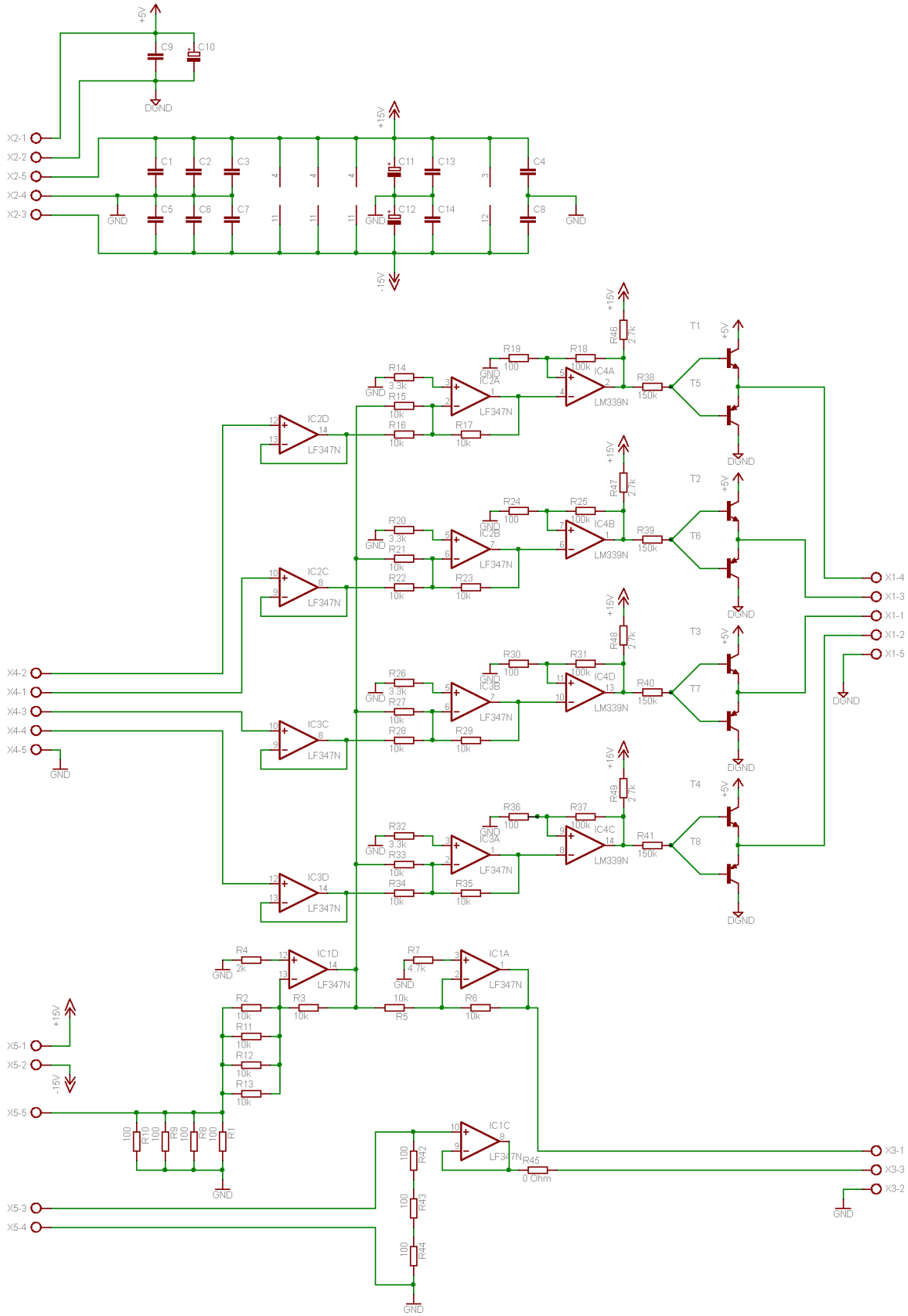


Illustration 1: Current and voltage measuring electronics

Current measuring

The current transducer is delivered by LEM. It is a LA 306-S/SP1 and it is capable of measuring $\pm 640\hat{A}$ properly configured. [8] The conversion ratio is 1:5000 and the measuring resistance is selected to 25 ohms. Since the output from the power electronics only passes through the transducer once this gives a total conversion ratio of $0{,}005V/A$. This signal is inverted and amplified four times by the *IC1D* which implies that the conversion ratio will be $-0.02A/V$. This signal is used in the comparison with the tolerance bands and for monitoring after being inverted another time by IC1A.

One of the channels of the NI 9215 are used to sample this signal. Notice that this signal is sampled for monitoring purposes only. It is used when the current controller is to be tuned.

Comparison electronics

As mentioned, the decision if the current is within tolerance or not is made with analog electronics. There are four identical couplings based on IC2, IC3 and IC4. The left most operational amplifier buffers the output signal from the analog output module. The right most IC is a comparator that is provided with a hysteresis band to minimize the risk flickering. The hysteresis band corresponds to $0{,}1\%$ of the total output voltage swing of the comparator which is equal to $0{,}03V$ .The consequences of this hysteresis is taken care of which will be explained later.

Since this comparator circuit only does the comparison around zero volts the measured current is subtracted from the tolerance band level and feed to the comparator. This is done by the operational amplifiers in the middle. When the current is approaching the the tolerance band level the output of this operational amplifier will approach zero which, if it continues will result in a comparator output change. The comparator output signal is buffered and converted in TTL level signals with the transistor couplings to the right of them.

Variable inductance

The power electronic converter and its control system are designed to handle in the order of hundreds of amperes with small amounts of current ripple but still acceptable rise times. This means that if the current reference is in the order of ten amperes instead, the ripple will probably be unacceptable. To come around this problem an extra inductor is connected in series with the flux providing coils when the current peak value is 20 A or less. The coupling is very simple and is shown below.

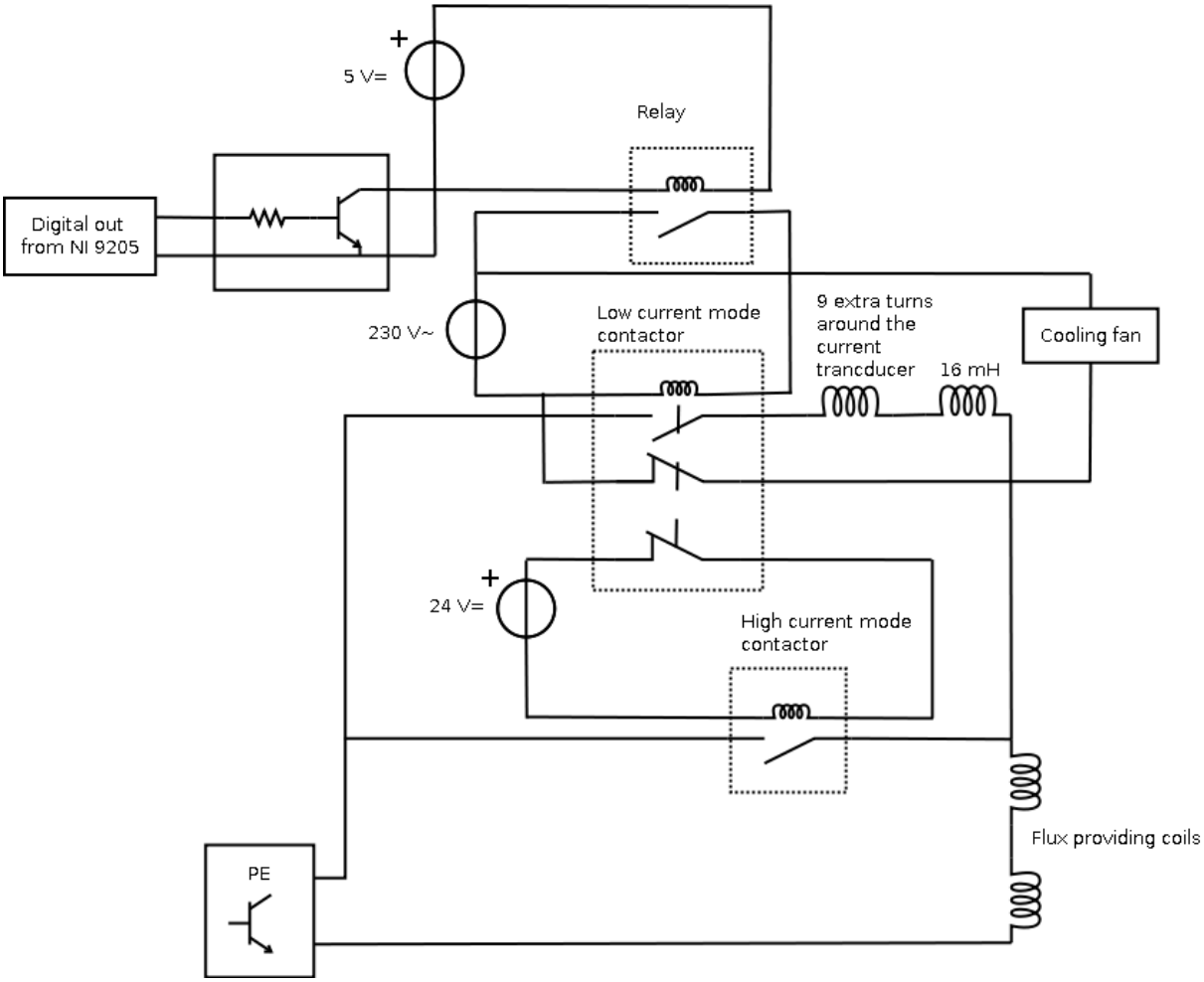


Illustration 2: Variable inductance electronics

In high current mode a contactor makes the current flow through the flux providing coils only. In low current mode this contactor is opened and another contactor is closed which makes the current flow through an extra inductance of $15{,}8mH$. To improve the signal to noise ratio in the current measurement 9 extra turns around the current transducer is added in the same way when choosing low current mode, this result in a new conversion ratio of $-0.2A/V$. Of course, this is taken care of in software.

It should be mentioned that during the development of the current controller, it was unknown that there was a need for good current quality at this low currents. Hence these parts of the hardware are implemented in a more temporary way.

Calibrating electronics

The current controller is partly an analog construction with all that it implies, and as mentioned the comparators have a small hysteresis that must be taken care of. The amplifiers and the current transducer are assumed to behave linearly but with an uncertainty in amplification and offset. All of the comparators have a certain position when the current is within tolerance and the other position tells the control system when it is not. This means that the comparator hysteresis can be treated as an offset as well.

To be able to compensate for both offset and amplification uncertainties a test current is needed. This is in principle achieved with voltage source and a resistor.

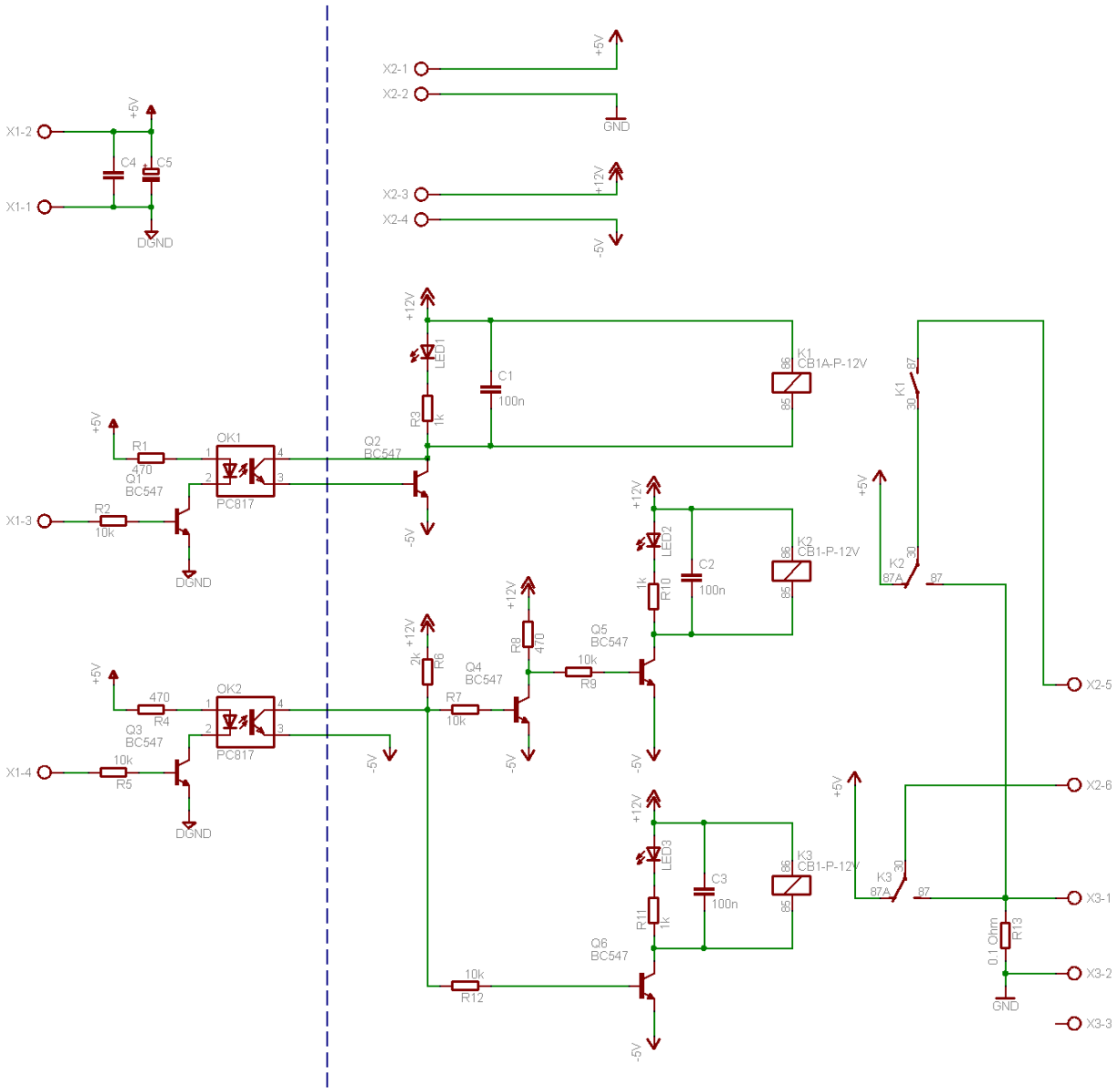


Illustration 3: Calibrating electronics

The supply voltage is 5 V and the resulting resistance is around 1 ohm which gives a resulting current on 5 A. The current runs through the current transducer 20 times which makes the control system think that the actual current is 100 A. All switches are actually relays which can be maneuvered from the cRIO, and to minimize the risk for disturbances there are opto-couplers between the cRIO and the relay driver.

The upper most relay closes the coil which thus are disconnected during normal operation. The two other relays make it possible to make the control system experience both 100 A and -100 A. The current through the coil is measured as a voltage with the 0.1 ohm shunt by the cRIO with one of the channels on the NI 9205 module during the calibration.

The execution of the calibration will be described in the software chapter of this report.

Voltage measuring

The DC link voltage is measured only for monitoring. To ensure galvanic isolation between the DC link and the control system a voltage transducer from LEM is used. It is a LV 25-P/SP2 and it is approved for measuring up to $4{,}1kV.$ [9] Actually it is a current to current converter with galvanic insulation and a conversion ratio of 2500:1000. The resistors that are used are $5 \cdot 15 \cdot 10^3 = 75\ kOhm$ for the primary side, and $3 \cdot 100 = 300\ Ohm$ for the secondary side. This gives a total conversion ratio of $\frac{2500/1000}{300/75000} = 0.01V/V.$

The used operational amplifier is a LF347. [10] The used operational amplifier is a LM339. [11]

One of the channels of the NI 9215 is used to sample this signal. As mentioned, this signal is sampled for monitoring purposes only. It is used when the current controller is to be tuned.

As an extra monitor, and a remained there is a voltmeter next to the power electronics in the feet of the cabinet.

3.2.3 Level converter to the IGBT's

The IGBT driver is configurable to handle both 5 V and 15 V signal levels on the input, however the manufacturer recommends the use of 15 V level when the signal cable is as long as for the construction. [12] The output on the NI 9401 is a 5 V TTL output, hence a level converter is needed. The level converter card does not only convert the signal levels. It inverts the signal to the *lower* IGBT in the bridge and has the ability to put zero volts on all outputs which is used to reset errors reported by the driver. The complete circuit is in *Illustration 4* below.

There are four inputs and one output to the cRIO. The upper most input is the enable input. If it is enabled the control signals will reach the drivers. If it disables, all outputs will be zero which as mentioned resets the driver. The first inverter buffers and inverts the signal. The transistor coupling makes the conversion from 5 V to 15 V and inverts one more time. This signal is used to the output AND gates.

The next two inputs are for the bridge controlling signals. The level conversion is made in the same way as for the enable signal. The capacitor in the transistor coupling shortens the fall time of the converted signal since the base current will be greater at the transition. The capacitance is experimentally determined to make the fall time as close the rise time as possible. It is feed to an inverter to buffer and make the signal to the lower IGBT and then inverted again to make the signal to the upper IGBT.

The last input is only buffered with to inverters to use for other purposes.

The level converter listens to the error output of the drivers. Since it is negated it is inverted and then converted into a 5 V signal by two resistors and feed to a input on one of the NI 9401 modules. The inverter is driving a transistor to with the purpose of providing the card with an extra error indicating signal output with the capability to driving a led or a relay for example.

The used logical gates were 74HCU04 [13], TC4049 [14] and HEF4081 [15].

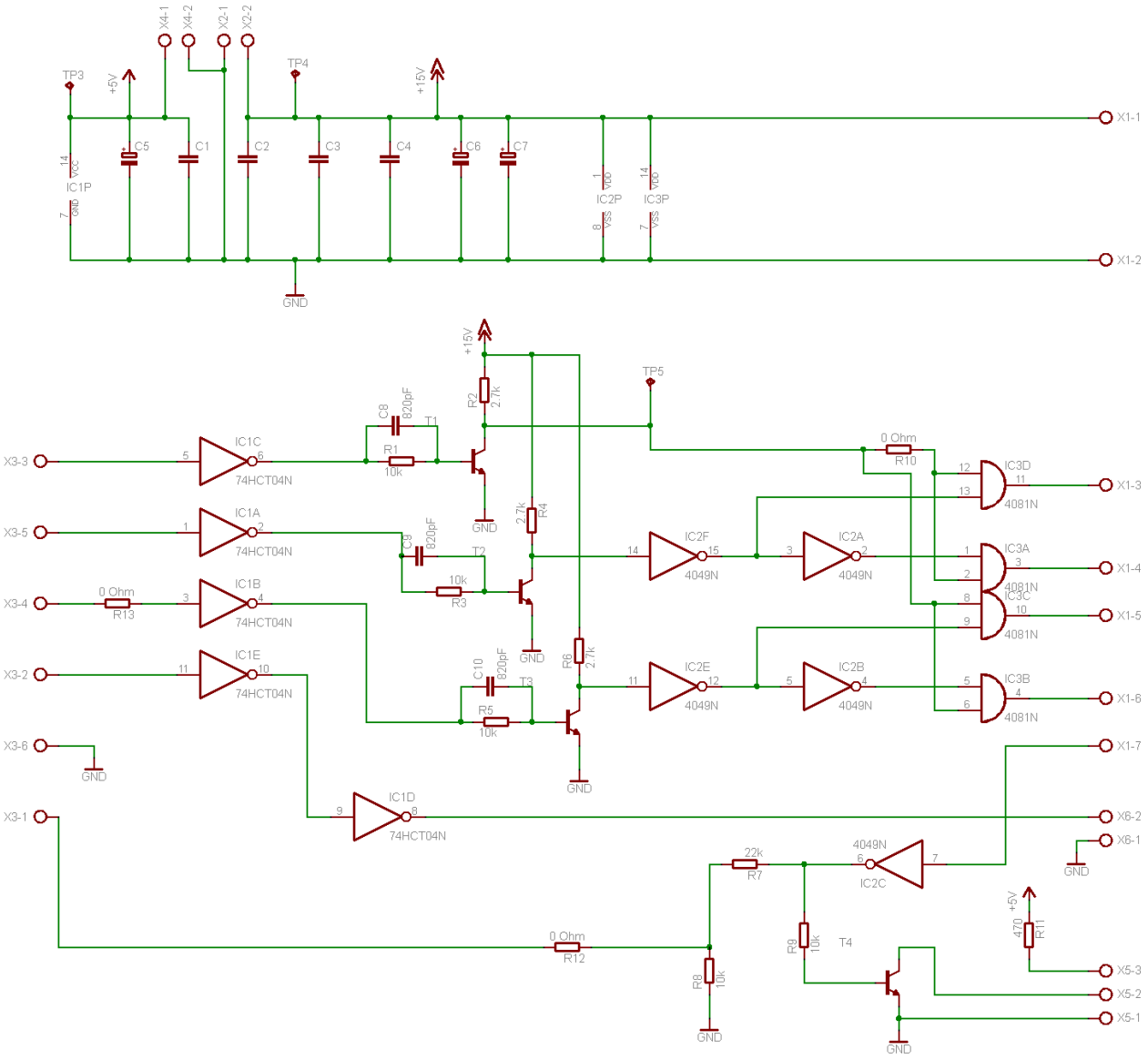


Illustration 4: Level converter electronics

3.2.4 Power supplies

There are several different power supplies for different parts of the machine. There are different reasons for using more than one power supply. First of all, many different voltages are used. Secondly, it is not wise to use the same supply voltage to feed for example both analog and digital circuits. Thirdly, if you use many different supplies you can start them up in an order that minimizes the risk for damage.

To provide power to the cRIO a power supply delivered by National instruments is used. To provide power to all peripheral electronics related to the current control and power electronics two different power supplies are used. The first one, delivered by VERO power is providing +15 and -15 volts to the analog electronics. [16] It is also providing +5 volts to the digital circuits used in the level conversion stage, the calibration equipment controller and the shake to wake. Another +15 voltage is supplied by a power supply delivered by XP power. [17] This is used for the IGBT

drivers, the level conversion stage, the relays to the calibrator and the shake to wake. This means that the analog 15 volt supply is separated from the digital one.

A separate power supply was used for the current control calibration device. There are different reasons for this, first of all, when the device is in use it requires more current that any of the other supplies can deliver. Since it is used in relation to the current sensor the main part of it is placed in the high voltage volume of the cabinet. By using a different power supply EMC problem is avoided. The used power supply is an ordinary computer power supply which is modified to start when it is connected to mains. To make the installation more clean all unused output cables are cut. The used voltages are 5 V for creating the reference current and -5 and 12 V for operate the relays.

As mentioned the power electronics is supplied directly from rectified three phase mains. The original design described earlier is used.

The servo uses two different power supplies, one that is delivering power to the motor drive and another to supply the control electronics. Hence it is possible to start the controller up to download safe controller parameters for example, before turning on the power.

All power supplies are connected to the mains via a fuse recommended by the manufacturer except the supply for the servo power which is internally protected. The power electronics is connected via three 16A fuses placed in the inrush current limiter box.

At last there is an extra power supply for the temporary installation of the variable inductance. It provides 5 V and 24 V for maneuvering a relay and a contactor.

3.2.5 Hall sensors

The magnetizing result is measured with a set of hall sensors. Both the inside and the outside of the band is measured and since the maximum field strength of the band was unknown two different sensors was mounted to ensure both high accuracy as well as high field strength measure capability. This means that totally four sensors are used.

They have a rated supply voltage of 5 volts, which is available. But since it is used to feed digital circuits it was not used for this purpose. Instead the analog 15 volt was used a regulated down to 5 volts via a voltage regulator. The output of this type of hall sensor is a function of the field strength in the measuring direction and the supply voltage. Hence, the supply voltage is sampled to and taken into account in the software. The coupling is shown below.

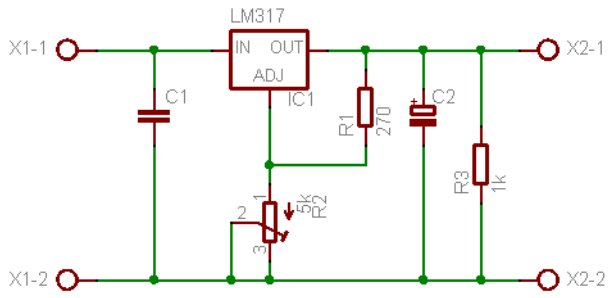


Illustration 5: Hall sensor voltage regulator electronics

3.2.6 Cooling of the flux providing coils

When using current greater than 100 A and shooting many and longer pulses the flux providing coils get hot. And in order to not take any risks with the coil insulation these has to able to cool down after more intense periods, for example a *reset*. To make the cool down time shorter a fan is placed close to the yoke and the air flow is guided through it to cool the coils as effectively as possible. The fan is activated when the inductance is set to high current mode. This leaves the opportunity to leave the fan on during a cool of pause, as well as turning it off during a hall measurement.

3.2.7 Safety

The DC link capacitors of the power electronics are able to store a lot of energy. If something goes wrong in the control system it can result in quite dangerous situations where hardware as expensive IGBTs or as well humans can take damage. Hence a little extra effort was paid when the control panel of the magnetizer was made.

Control panel

To begin with, there are four groups of power supplies, each group has its own circuit breaker. The first switch turns on the power supply to the cRIO and the power supply to the servo controller. This makes it possible to set parameters, etc. to both the cRIO and the servo before powering up anything else.

The second switch turns on the power supplies to the peripheral electronics, i.e., the +/- 15 volts to the analog electronics and the +5 and +15 volts to the digital electronics, including the drivers for the IGBT's. This makes it possible to make the calibration of the analog electronics or troubleshoot in a safe way if needed. It is also used to the power supply for the variable inductance and as a main switch for the cooling fan to the flux providing coils.

The third switch turns on the power supply to the servo. Finally the fourth switch turns on the DC link voltage by applying 230 volts to the enable input on the inrush current limiter.

The order the different switches are listed in above is the order they are supposed to be started in to. For safety they are coupled in a way which means that a higher order switch becomes ineffective if not all of the lower order switches are set to on. The switches for the servo power and the DC link are furthermore only functioning when the machine is in *Operational* mode. The condition for *Operational* is that none of the two emergency switches has been tripped. One of them is located on the control panel and the other one is represented by the *Shake to wake,* which will be explained later in this chapter. Every power supply, except for the DC link is equipped with a pilot lamp that indicates if it is supplied with mains, i.e. it will light up if the power to the supply is on and the fuse is intact.

As mentioned the machine should be started in a certain order. The same applies when shutting it down. To make sure that the controller software is not shut down while the DC link is charged the *stop execution* button on *front panel* is disabled while the DC link voltage is above 20 volts.

The instrumentation also includes an emergency stop. The emergency stop does not turn of the

power completely since this is not the wisest action in case of an emergency! As mentioned before the emergency stops only disables the *Operational* mode, which in turn disables the servo power and the DC link, if they are turned on of course. This means that the IGBT drivers will remain on so that the DC link can be safely discharged.

A picture of the control panel and the wiring diagram is shown below.

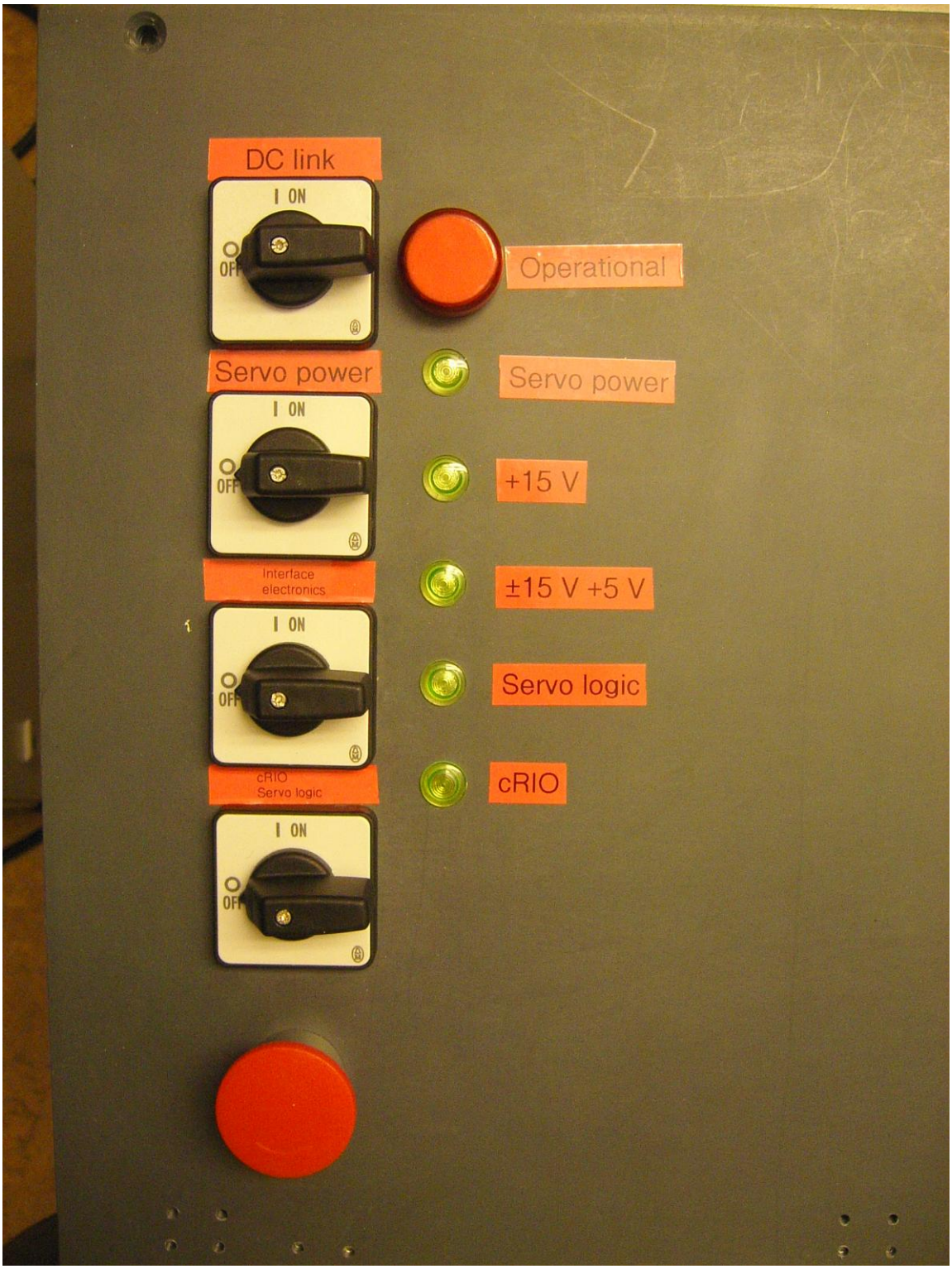


Image 6: Control panel

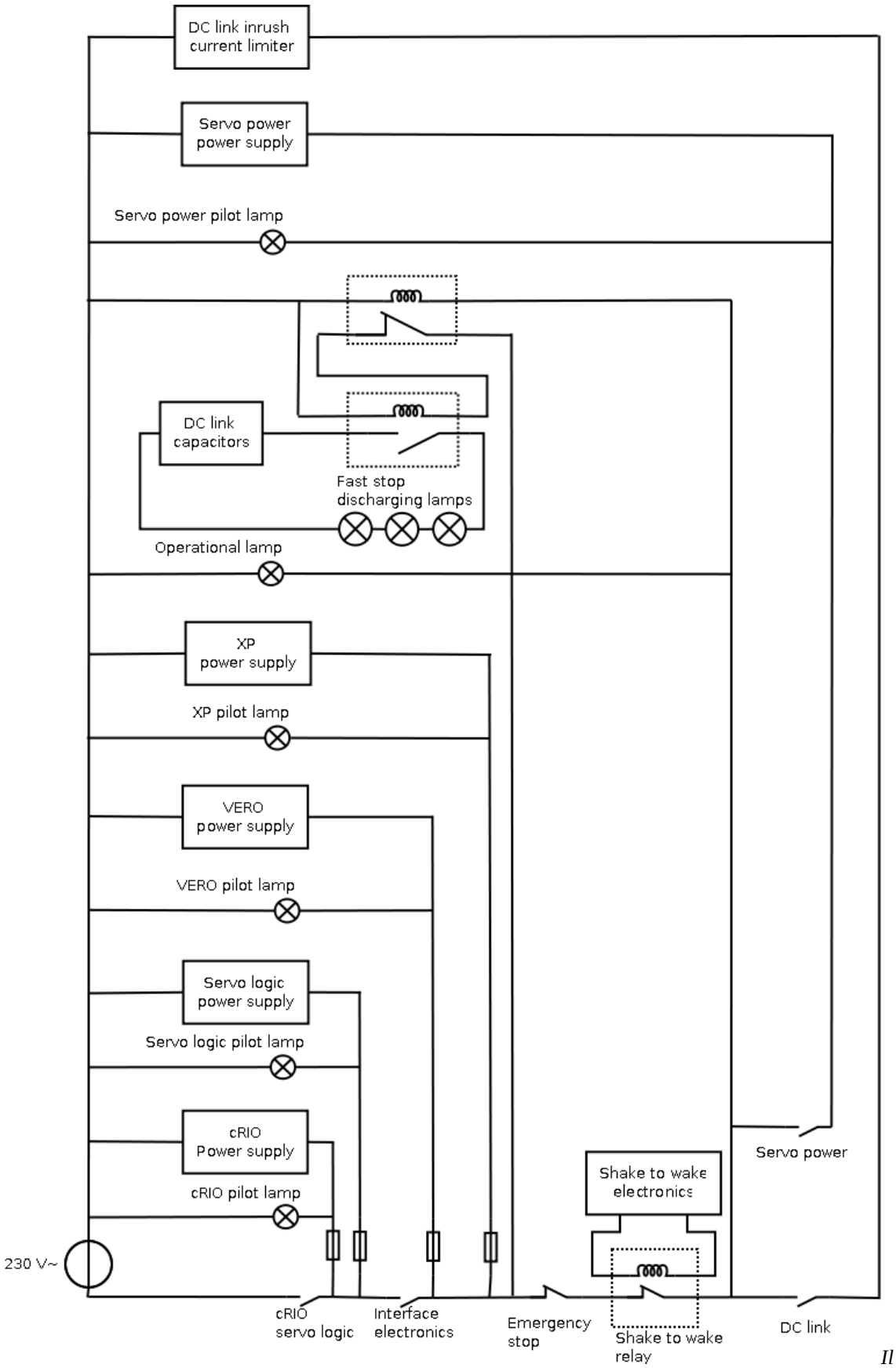


Illustration 6: Control panel

Shake to wake

The second, earlier mention emergency stop called shake to wake has the same effect as the first emergency stop. But instead of a button it is a relay connected to a circuit board connected to the cRIO. The main function is to detect if the FPGA freezes, and if it is happening it trips the emergency stop. This is done by a VI that continuously generates square wave via one of the digital outputs. This square wave is filtered by a low pass filter to obtain a signal around 2.5 volts which is compared with 2 and 3 volts. If the comparisons show that the signal is between 2 and 3 volts it will close the relay. Of course, this leaves the opportunity to trip the emergency stop from the software as well. This is used by *diagnostics*, the *activate* button and the emergency stop on the *front panel*. The activate button turns on the shake to wake if the control system is in *ready* mode. This occurs if the diagnostics part of the program does not find any faults.

The coupling is shown below and the used circuits were HEF4030 [18] and LF347 [10].

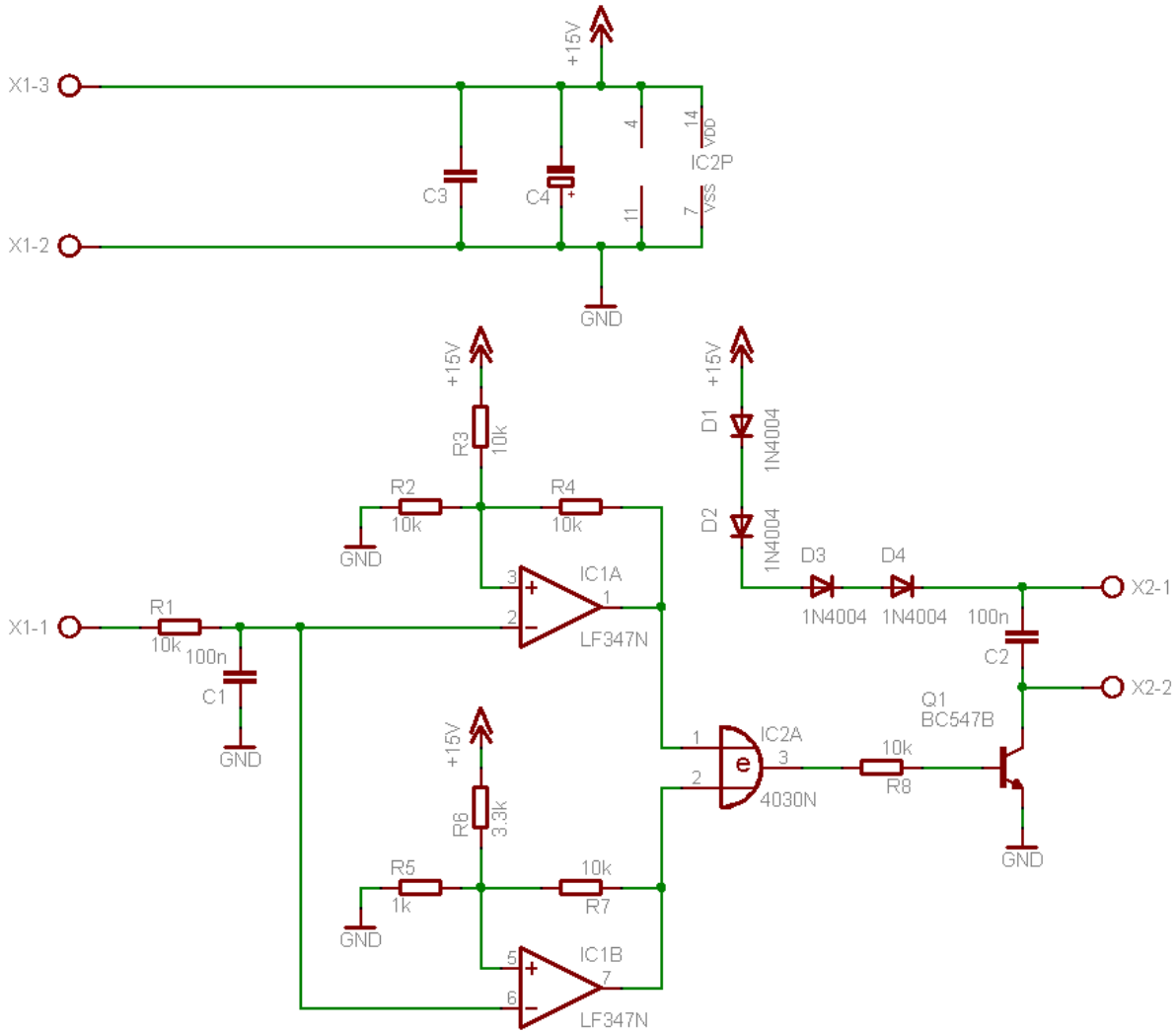


Illustration 7: Shake to wake electronics

Diagnostics

The diagnostics consists of three parts. One that is continuously sampling all supply voltages for the peripheral electronics and checking that they are within allowed limits. The next part checks the calibration data after a calibration of the analog electronics, this makes it impossible to turn on the DC link without valid calibration parameters since a fault in the diagnostics will stop the shake to wake which in turn trips the emergency stop. Of course a supply failure voltage will have the same effect. The last part is listening to the error signal from the drivers. If a driver announces an error it freezes the bridge position to make it possible for the user to see what caused the error. Of course, even this error will result in an emergency stop. The voltage dividers are shown below.

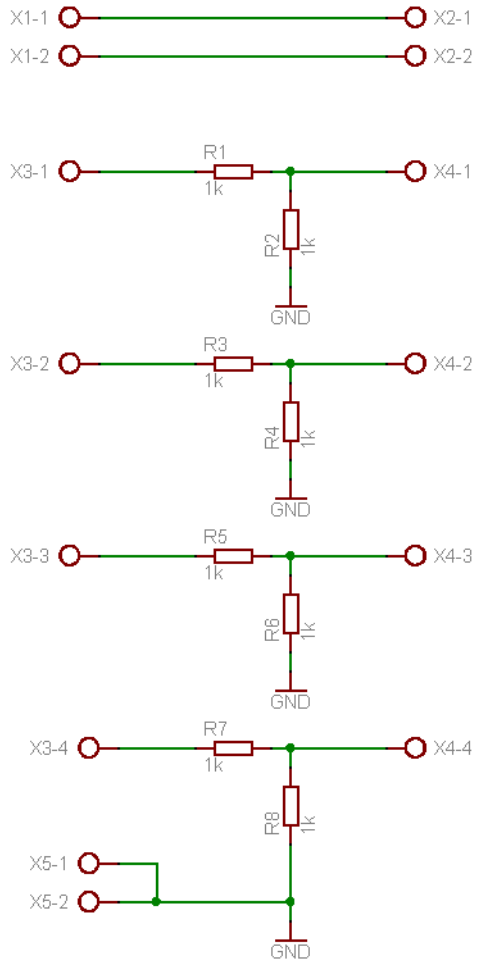


Illustration 8: Diagnostics electronics

Fast stop

If one of the emergency stops trips the power to the DC link and servo will be cut, but normally the DC link capacitors will still be charged. The only thing discharging in the normal case is the bleeder resistors connected across them. As mentioned before it is not possible to stop the controller program before the DC link is discharged properly, this means a lot of waiting during debugging for example. Hence a *fast stop* device is implemented. It is simply three light bulbs of 60 watts at 230 volts connected in series that is connected in parallel with the DC link using a contactor. The contactor is activated (closed) when the machine leaves *operational* mode, i.e.,

when one of the emergency buttons trips. This means that a fast stop will occur if the machine halts on some kind of fault to.

3.2.8 The philosophy of the construction

EMC

During the design phase of the machine EMC problems was avoided as far as possible. To begin with the control system and its peripheral electronics are placed in a separate volume electrically shielded from the power electronics. Furthermore the peripheral electronics is placed in a screening box of aluminum. All cables related to the control system are shielded as well and the shields are only connected to the screening box containing the peripheral electronics to avoid ground loops. For the same reason is the screening box the only connection between the earth of the control system and protective earth. More specific solutions will be described under the heading for each part.

Choice of components

The attentive reader or maybe the next person who are going to develop the machine further will probable find the choice of components a little strange in some parts of the construction. Therefore we want to point out that we used parts that we found in stock at IEA to minimize the number of orders and delays. The parts are selected to not compromise the function or the result, but as said some of the choices may seem a little illogical.

4 Software

The basis of our understanding how to use the program language LabVIEW and the cRIO is the course manuals [19] and [20].

4.1 Distribution of tasks

The tasks of the software in this project ranges from a user friendly measurement system with settings, graphs and the possibility to save measurements to a file down to the current controller with response times that are less than one µs. To accomplish this the cRIO system has been used since it can provide both ends on this scale and of course everything in between. To understand how to distribute tasks between the FPGA and the embedded computer in the cRIO system a little more information about the cooperation between the embedded computer, FPGA and the I/O modules, than given in 3.2.1 is needed.

The I/O modules communicate with the FPGA which in turn communicates with the embedded computer. If the embedded computer wants to communicate with the I/O modules, this is done through a program on the FPGA. The embedded computer runs a real-time operating system (RTOS) made by National Instruments. This makes the cRIO to a stable controller with features found in a normal operating system for a PC. This includes a file structure, ethernet connections, ftp server capabilities and hardware resource monitoring.

The sequential nature of executing a program for a CPU leads to latency between input and output which can be a limitation when implementing controllers with the embedded computer. Furthermore, an increased workload can decrease the performance. In that essence the FPGA has an advantage since the program is literally implemented in hardware which makes the execution parallel of its nature. Thereby an increased workload of the FPGA will not decrease the performance. It is also possible to make FPGA programs with very low latency. The limitations of the FPGA is its size and thereby the size of the program that can be implemented on it. Other disadvantages is that compared to the embedded computer the compile time for the FPGA is many times longer and the programs are thereby harder to debug. This makes the development time for the FPGA programs longer. To not reach the hardware recourse limit of the FPGA and have a to long development time it is essential to not use the FPGA unnecessarily.

The programs for the embedded computer and the FPGA are developed in National Instruments development environment LabVIEW. Except for hardware restrictions the programs for the embedded computer and the FPGA is the same and the development tool takes care of the integration in the real-time operating system on the embedded computer and with the FPGA. The programmer programs a task for the embedded computer, the FPGA or a combination of both. This choice can later be changed and the code can be reused as long as it meets the hardware restrictions of the intended target. Sometimes the choice between the embedded computer and the FPGA is easy and sometimes it is harder.

The FPGA is the link between the embedded computer and the I/O-modules and a custom FPGA program has been developed to provide communication between them. A custom FPGA program provides maximum control of the digital inputs and outputs and the sampling rates of the A/D- and D/A-converters. In the FPGA it is possible to make the signal processing fast and achieve control loops running faster than one µs when using the digital I/O signals. Tasks with a close relation to

the I/O modules, like fast control loops is also directed to the FPGA. Tasks that involve input from the user or presenting data to the user is not that time critical and is thereby natural to implement in the embedded computer. Tasks involving signal processing before presentation to the user could be implemented on the embedded computer or the FPGA. Where it is implemented depends on demands on speed, amount of data, complexity of the algorithm and the integration with the rest of the program. It is also possible to split it and do some processing in the FPGA and the rest in the embedded computer.

4.2 Communication between the different parts

Everywhere in the programs, both in the embedded computer and the FPGA there is a need to send and receive information from other parts of the program. As expected there is more than one way to do this and the ones used in this project will be explained here.

4.2.1 Variables

Sometimes a control or an indicator on the front panel is needed in more than one place in the program. This is achieved with a so called *local variable* to the control or indicator. Local variables can only be used in the same VI and in this project they are only used in the embedded computer. Related to the local variable is the *global variable*. Instead of being located on the front panel of the program it is placed on the front panel of a separate VI. This makes the global variable accessible from more than one VI. If more than one global variable is needed, more variables can be added to the separate VI with the first global variable. The structure of the FPGA program makes global variables very useful to create variables that are used within the FPGA. In the program for the embedded computer global variables are only used for communication between loops that run in parallel.

4.2.2 FIFO-queues

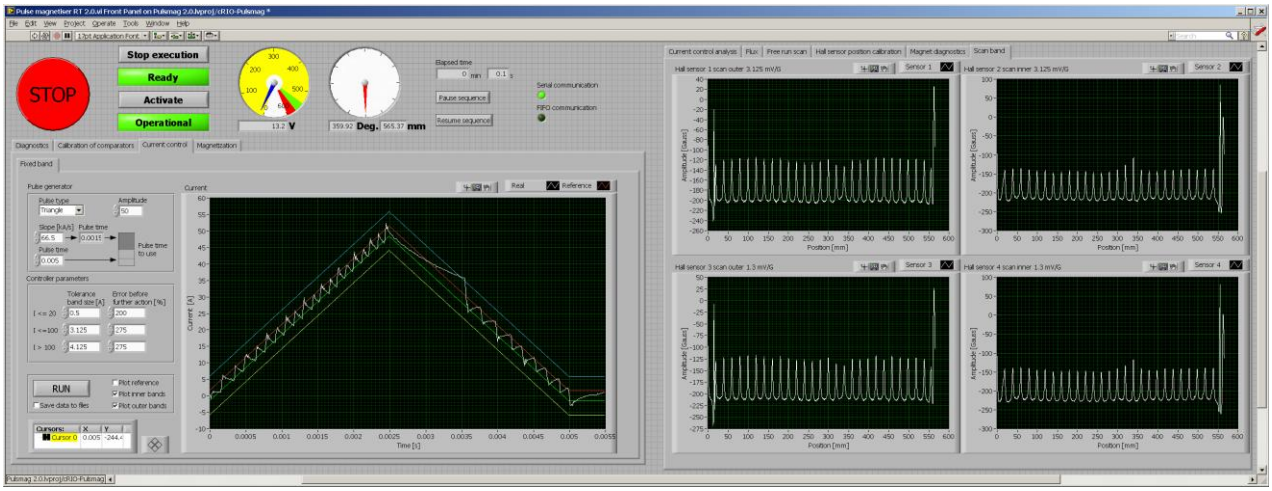
FIFO-Queues (First In First Out Queues) are essential in both the program for the embedded computer and the transfer of large amounts of data from the FPGA program to the program in the embedded computer or vice versa. A queue is a data structure that allows data to be produced and consumed at different times but still not lose the order of the data. A FIFO-queue dequeues the data in the same order as they are enqueued.

4.2.3 Interrupts

The program in the FPGA can generate an interrupt to the CPU in the embedded computer. An interrupt is meant to interrupt the normal execution of the program in the embedded computer and run a special part of the code called the interrupt routine. The interrupt routine is then supposed to take care of the reason for the generation of the interrupt. It is possible to generate up 32 different interrupts.

4.3 The structure of the program on the embedded computer

4.3.1 User interface



Front panel 1: Whole system

The front panel seen above is the whole user interface. Since it is a tab-based interface not everything can be shown at the same time. The idea with the tab-based interface is to save space on the front panel and make it user friendly but at the same time advanced and powerful by only showing the necessary controls, graphs, etc. to the user. The interface utilizes the space of two screens and can be divided into three parts. Some controls are always good to keep within reach and these are placed in the upper part of the left screen, the rest of the left screen contains the main tab interface. The right screen contains a tab interface controlling which graph to show and these tabs correspond to tabs in the main tab interface. These three areas will be described separately in the following text.

It is natural to start describing the controls that always are within reach. This part of the user interface contains a system for activating and deactivating the machine. It contains an emergency stop button which disables the servo power and the DC-link, if they are turned on. This is done by turning the *shake to wake* signal off. Next to the emergency stop button is a button named *Stop execution*, when pressed it will stop the execution of the RT- and FPGA-program if the DC-link voltage is below 20 V. The machine goes into the operational mode and a boolean indicator called *Operational* on the front panel turns green when the *Activate* button is pressed. However, there are some conditions for the *Activate* button to turn the machine into the operational state. These conditions are; no error from the IGBT drivers may occur, the supply voltages has to be within limits and the compensation values for the comparators has to be okay. This is indicated by a boolean indicator that is located above the *Activate* button. When the conditions are not met the indicator is red and contains the text *Check diagnostics* and when the conditions are met the indicator is green and contains the text *Ready*.

When a scanning sequence of the magnet band or a magnetization sequence of the magnet band is started a timer starts. The timer is used to show the time in minutes and seconds since the sequence was started and is located in the upper part of the interface. In the same area there are buttons to pause the execution of a sequence and resume it later. These buttons are called *Pause sequence* and *Resume sequence*. When the servo can not go to the desired position it will also pause the sequence in the same way as the pause button does, the sequence can then be resumed

using the resume button when the user has solved the problem.

The upper part of the user interface also contains a dial and an indicator of the DC-link voltage and a dial and indicator of the rotor position in degrees. Finally there is two boolean indicators, one that show when there is serial communication with the servo controller and the other shows when the RT uses the FIFOs for sampled current and voltage data.

Underneath this is the main tab interface with four different tabs, diagnostics, calibration of comparators, current control and magnetization. Three of these tabs have in turn a tab interface into them, these tab interfaces is referred to as sub-tabs.

Front panel 2: Diagnostics

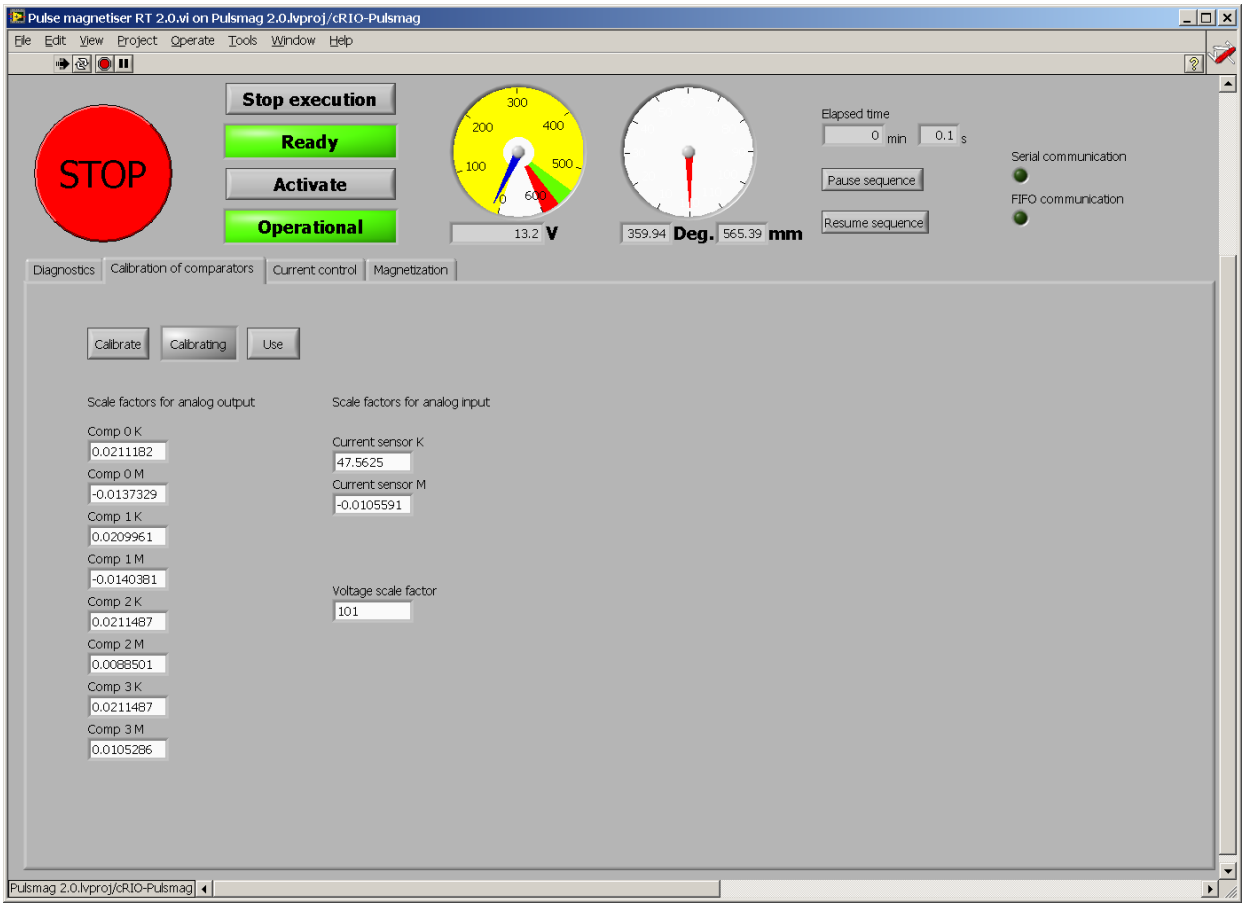
The *Diagnostics* tab seen above presents information and controls that are useful when the user wants to see if the system reports anything that is wrong. There are three sub-tabs in the diagnostics tab to limit the information presented to the specific interest; hardware, servo or software.

The *Hardware* tab shows information about the supply voltages in the control electronics. These voltages are continuously controlled to be within the tolerance limits. The nominal values and tolerance for the supply voltages are set in this sub-tab. Since resistors are dividing the voltages before they are read by the A/D-converter this sub-tab contains controls for these scale factors. Here is also information about eventual comparator- and driver-errors. Finally here are settings for sampling of the hall sensors. The hall sensors are continuously sampled just like the supply voltages. But when they are used for taking a reading of a specific position of the magnet the A/D-digital converter goes to a special mode that takes an average on a number of samples. This

number is controlled in this sub-tab. There are also settings for the sensitivity and a possibility to trim the offset error of the sensor.

Settings involving the servo and monitoring of the serial communication can be done in the *Servo* sub-tab. When the RT-program wants to rotate the magnet band it orders the servo to go to the new position and after an appropriate amount of time it ensures that the servo has reached the new destination. In the sub-tab there are settings for the tolerance of check at the new destination, diameter of the magnet band for conversion between degrees and position. There is also a setting for a variable used to estimate the time for rotation using the distance to travel. Further on there is a button to manually enable the servo controller. The servo controller can indicate errors from the servo controller electronics, the most important of these is decoded and displayed on the *Servo* sub-tab. If there is an error in the servo communication there are also indicators of that. Finally there is the possibility to save the servo communication to a log file.

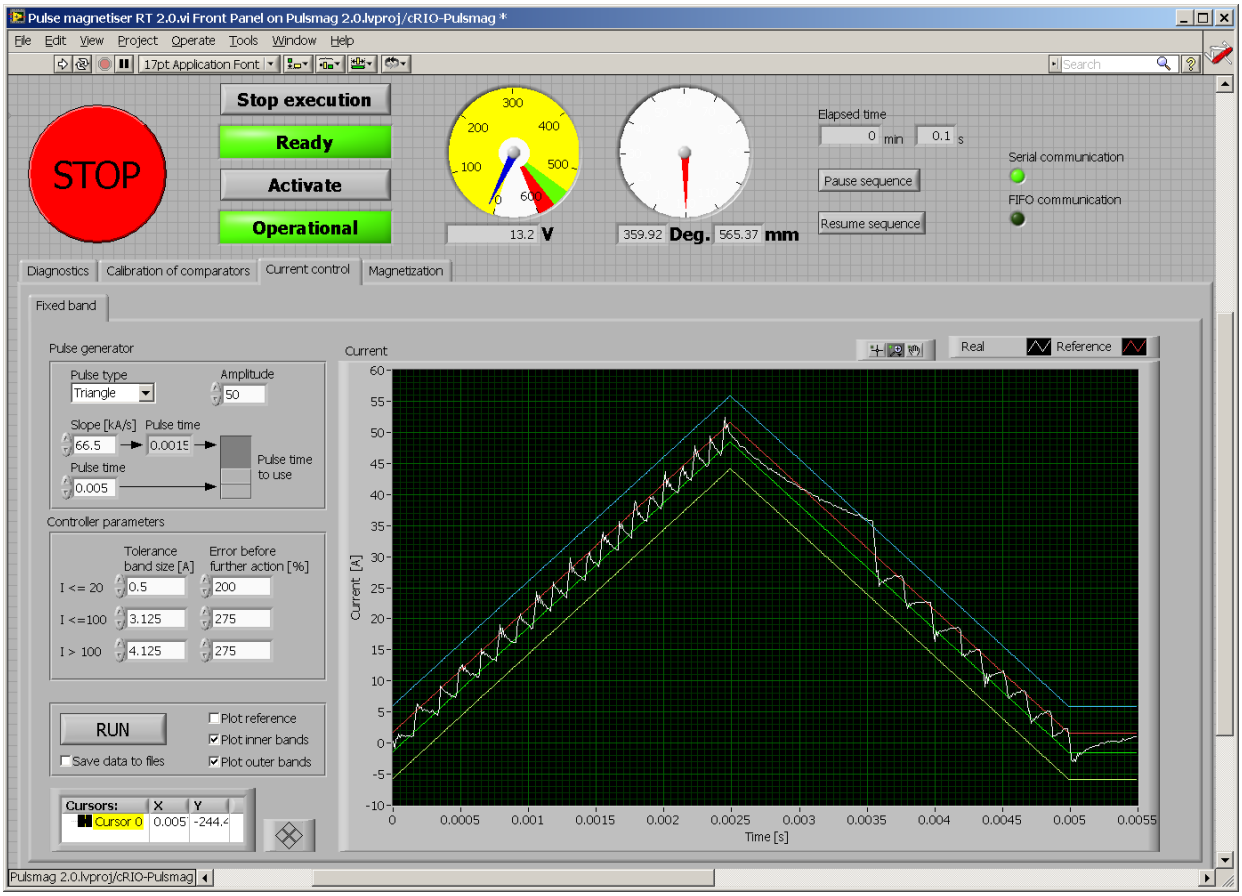
There is a sub-tab called *Software* that contains controls and indicators to debug the embedded computer program. For example, to see if the diagnostics of the supply voltages consumes too much CPU time it is possible to force the program to do or not to do the diagnostics. For the same reason it is possible to force the program to ignore the controls on the front panel. If an error occurs there is an indicator to show the error message. The rest of the controls and indicator on the sub-tab involves debugging of FIFOs. These controls and indicators are placed there because they have been useful during the debugging of the software. If there are more bugs the user may want to use these controls and see these indicators.



Front panel 3: Calibration of comparators

As mentioned in *Calibrating electronics* in 3.2.2 analog electronics have uncertainties that is

measured and taken care of in software. To perform this calibration the sub-tab *Calibration of comparators* that is seen above is used. It is easy to perform a calibration, it is just to press the *Calibrate* button. After the calibration is done the scale factors that was calculated from the measurements is presented to the user in indicators in the sub-tab. The K-factor for each channel is the calculated gain for each channel. It should be compared to the conversion ratio 0.02 V/A that was calculated in *Current measuring* in 3.2.2. The M-factor is an calculated offset and for the comparator channels it will compensate for hysteresis in the comparator and offsets in amplifiers. The fact that they compensate for the hysteresis means that they should not be zero but sill rather small. Comparing the M-factor between the channels there should be two groups, channel 0 and 1 and channel 2 and 3. If user thinks that all of the values shown in the indicators are okay they could be downloaded and used in the FPGA with the *Use* button. Finally there is a control called *Voltage scale factor* and it is ideally the inverse of the conversion ratio calculated in *Voltage measuring* in 3.2.2. Since it is a control it is hence possible to compensate if the real conversion ratio differs from ideal one.

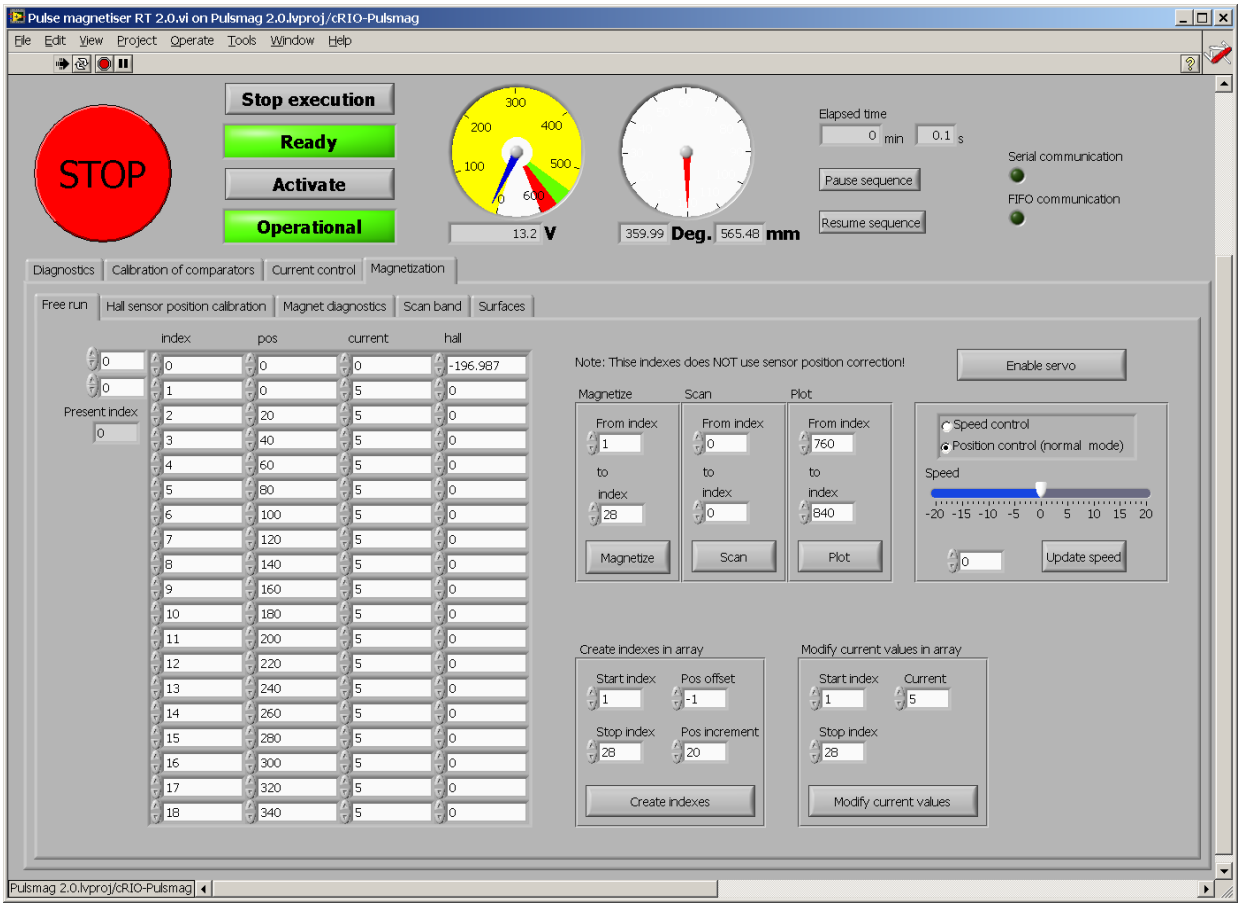


Front panel 4: Current control

The next tab in the main-tab interface is the seen above, namely the *Current control* tab. It is important that the performance of the current controller is as good as it can be and this tab is used to test and trim the performance. To do a test of the controller a set of controller parameters and settings for a test pulse is entered. Then the *RUN* button is pressed and the current controller parameters are loaded and the system changes the current reference to create the test pulse. The current controller follows the reference according to the controller parameters and the resulting current can be seen in a graph in the main-tab interface. For further evaluation of the performance of the current controller there are four other graphs available in the *Current control analysis* tab in the graph-tabs for. The first graph shows the switch time (the inverse of the switching frequency)

for each switching event. The second graph shows the resulting switching pattern of switch 1 and 2 it also tells if and when the *high switching frequency protection* was engaged. The third graph shows the DC-link voltage during the pulse. The fourth graph shows a numerical calculation on the inductance based on the sampled current and voltage. The calculation of the inductance is only valid during the time while there is an active vector applied and no switching occurs. In the settings for the pulse generator the pulse type, amplitude and pulse time can be configured. The pulse time is either entered directly or calculated from the values of the slope and amplitude controls. It should be noted that this calculation is only valid for the triangle pulse type. In the settings for the controller parameters there is a control for size of the tolerance band, this value is used for the inner bands. The value of the outer bands is given as a percentage of the inner bands. When small currents are generated inductance is added in series with the flux providing coils for better performance. This means that there are two identical sets of controls for the controller parameters. In fact there is a third set of controls since the inductance changes when the inductor starts to saturate. Depending on the peak current the system uses one of these three settings for the current controller. Finally it is possible to plot the reference, inner and outer bands in the same graph as the resulting current.

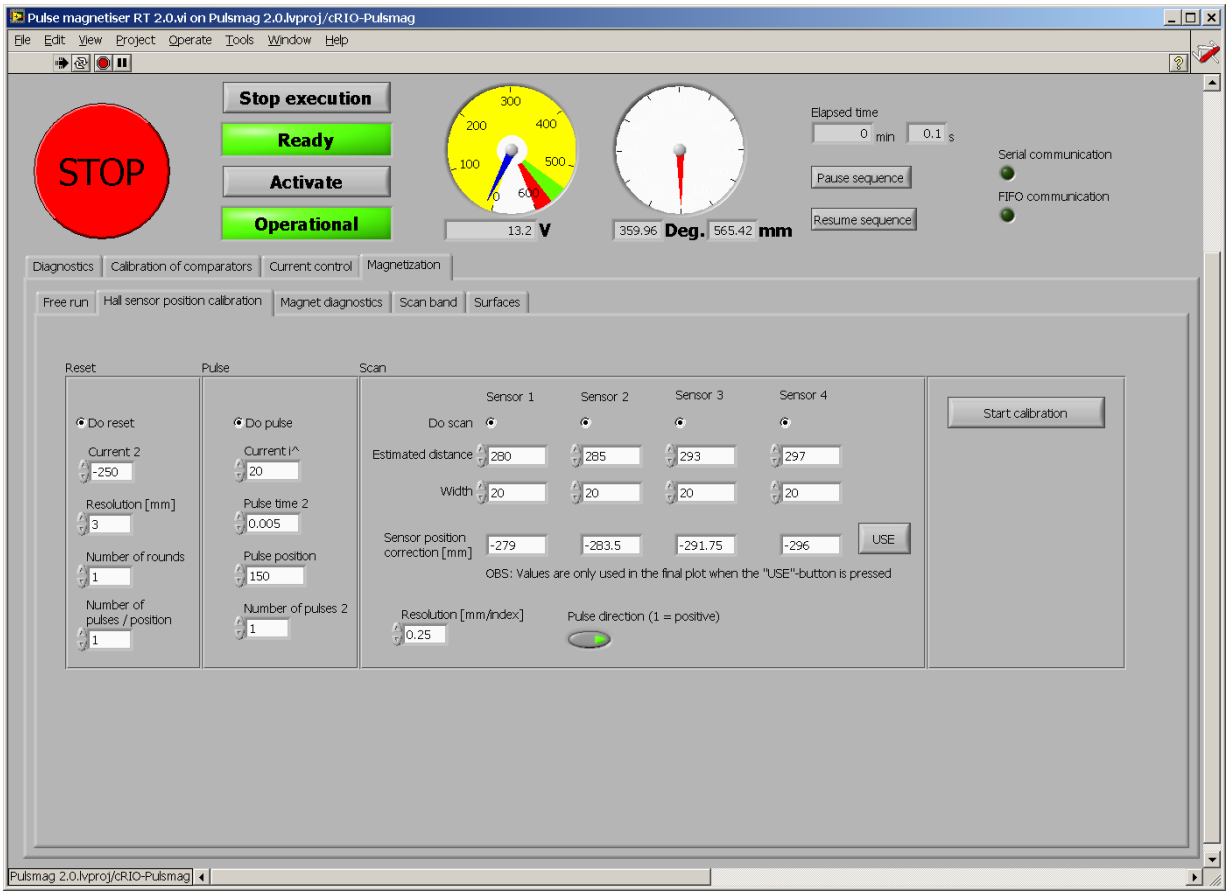
Last but not least is the *Magnetization*-tab in the main interface. It is used for magnetization and measurements of the resulting magnetization. There is a sub-tab system in the *Magnetization*-tab to separate different magnetization related activities.



Front panel 5: Magnetization, Free run tab

The first sub tab is *Free run* and is seen above. It gives the opportunity to rather freely program an array with pairs of positions and currents. The values in the array can then be used to magnetize

the magnet band, scan the band or to plot a result of a scan in the *Free run scan* tab in the graph-tab interface. The positions to magnetize, scan or plot can be made arbitrary in the array. To make that possible in this tab all references are made to the array indexes and not the position values. To manually enter many values in the array is time consuming so there is two toolboxes to do that. The first creates equally spaced position values and the second fills them with current values. The servo motor can run in two different control modes, speed control and position control. Normally the position control is used because it is the position that is interesting to control. The speed control is used to make the servo and thereby also the magnet band spin at a constant speed. This could be used to check mechanical variations and other testing. To change between the two control modes the servo needs to be disabled before the change and enabled after by the *Enable servo* button.



Front panel 6: Magnetization, Position calibration

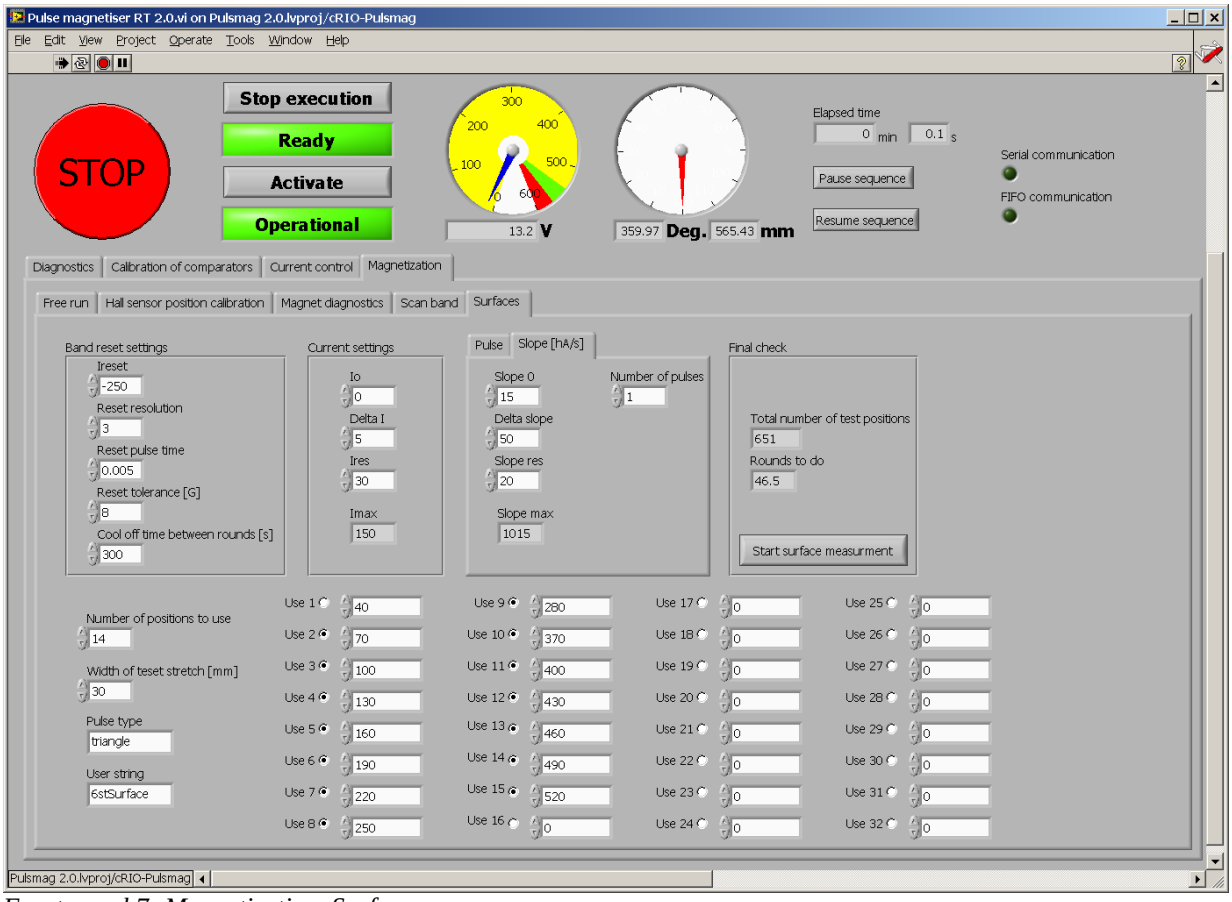
The next sub-tab is seen above and it is used for the next step in the creation of a working magnetization system and that is to calibrate the positions of the hall sensors. When the servo is at 0º, the position 0 mm is defined as the middle of the magnetization head. When this position of the magnet band is scanned the servo motor will not be at 0º, for example it could be at 180º in the case that the hall sensors is at the opposite of the magnetization head. This offset needs to be calibrated using this sub-tab. The method for this calibration is to have a band with a constant magnetization level and then magnetize one position in the band. This position can then be found by scanning the band and find the position of the peak value of the magnetization level. This sub-tab gives the opportunity to do a reset of the band (which will be explained later), a pulse at a specific position in the band and of course scan the band and find the peaks. For each sensor the estimated distance and a search width is specified, this is to make sure that only a healthy part of the magnet band is used in the analysis of the peak value. The value for the *Estimated distance* is

the distance between the magnetization head and hall sensors along the magnet band. When the calibration is done the correction values are updated and the uncalibrated result for the four sensors is plotted in the four graphs in the *Hall sensor position calibration* tab in the graph-tabs. When the *Use* button is pressed the calibration values will be used in the rest of the program and the four plots will be updated using these correction values. So if the pulse was done at the position 100 mm all plots should show a peak at 100 mm.

The earlier mentioned reset method has been found experimentally. It uses a large current that saturates the magnet band on a wider distance than the width of the magnetization slit due to the leakage flow. This makes it possible to use a greater distance between the magnetization pulses than the width of the magnetization slit.

It is good to control that the magnet band is in good shape, and if it is not it is good to know where and how it is differing from the rest of the band. This is done in the third sub-tab *Magnet diagnostics*. The diagnostics is done with a reset of the band in one direction and then a scan of the band. This is repeated but with a reset in the other direction. The result is then plotted in the *Magnet diagnostics* in the graph-tabs. It is possible to plot the raw data from the scans and/or the difference between the two scans. If the absolute value of the magnetization level is the same for the reset with positive current and negative current the difference will be zero.

To do a quick scan of a segment of the whole band the *Scan band* sub-tab can be used. The result is plotted in the *Scan band* tab in the graph-tabs. The data can be saved to a file using the controls in this sub-tab.



Front panel 7: Magnetization, Surfaces

The last sub-tab in the interface is called *Surface* and is seen above. It is used for testing the performance of the magnetization device. These tests always start with a band that is evenly magnetized, this is done with the same reset method that was mentioned earlier. The simplest test imaginable to then perform is to shoot a pulse and scan the affected stretch of the magnet. An analysis of the result can then tell how much it was magnetized and how long section of the magnet that was affected. The result will depend on a number of things and this sub-tab is used to investigate them. Things that have been tested are to vary the current, pulse type, number of pulses and the slope. Again, it should be noted that the calculation for the slope is only valid for the triangle pulse type. The tests in this sub-tab are designed to vary two of these parameters the current and the number of pulses or the current and the slope. This will result in a number of test configurations. To cover these configurations the test starts at a point on the magnet band. The servo then moves the magnet band so that a new test point comes up and a second test is performed. It is important that these test points do not interfere with each other. This procedure is done over and over again until all the test points have been used. Now it is time to scan the whole magnet band for the analysis. This procedure can then be started over again to cover more test points. Of course the magnet band needs a reset before each round with set of test pulses.

The test points are specified in the *Surface* sub-tab and it is possible to specify up to 32 points. These points should be points on the magnet band where the band is healthy. It is also important that the different points behave in a similar way to the same test conditions since this contributes to the uncertainty of the measurement. To check the condition of the magnet band the *Magnet diagnostics* sub-tab is recommended to use. To perform a test it is also important to state the number of positions to be used and the width that should be used to examine the result. The scanned result is saved into a file for further analysis and that requires a file name. The file name contains information about the test conditions and the word entered in the *User string*. The pulse type is determined by the setting in the *Current control* sub-tab but since it is a part of the file name it also needs to be put in a string in the *Surface* sub-tab. To ensure that the magnet band has been reseted properly a test is done to ensure that the magnetization level is within a certain tolerance entered as a reset setting. Since the magnetization head and in particular the coils get hot when running large currents there is a fan to cool off the magnetization head. This fan could potentially disturb the measurements. Therefore there is a timer that starts after the reset and pauses the testing until the timer runs out. This time is also entered as a reset setting. Next of is the settings for the current.

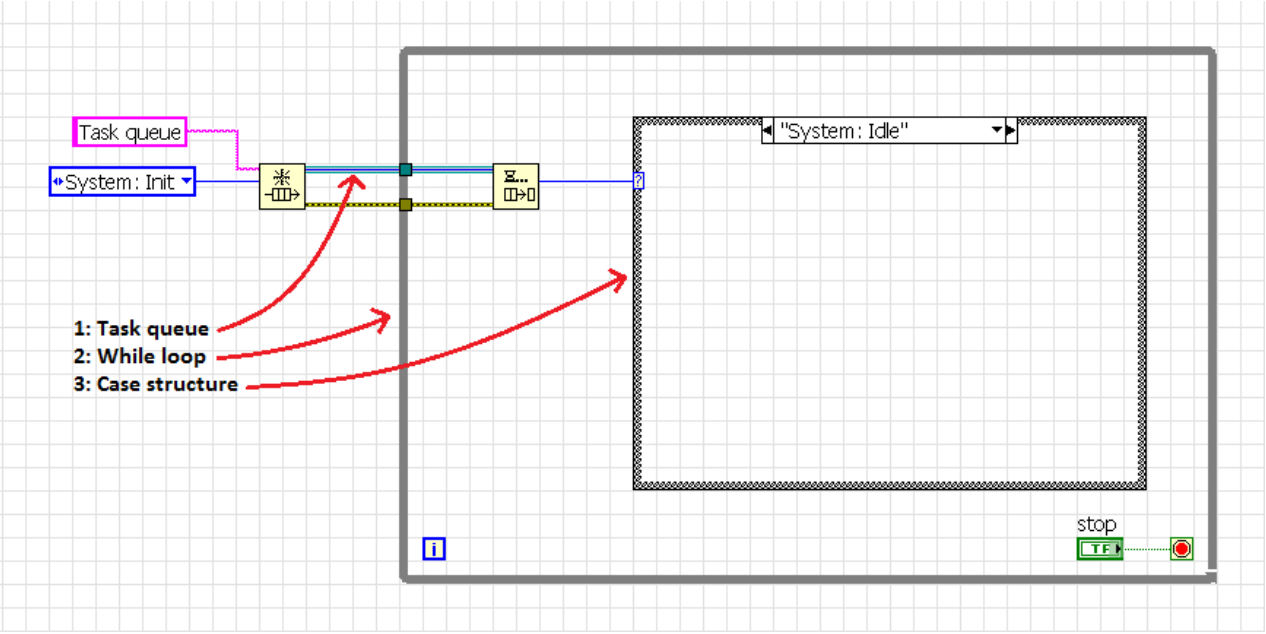
Since the goal of these measurements is to investigate what happens at different currents there needs to be a way to get different currents. The way it is done is by three controls. The first is the starting current, *Io*. A typical value for the starting current is zero. The current is then increased in steps with amount of *Delta I*, this is then repeated the number of times entered in *Ires*. These three settings will result in a maximum current that is displayed in the indicator *Imax*. The current is one of two parameters to vary. The second is the number of pulses or the slope. In the sub-tab there is another tab interface with two tabs where each contains settings for the number of pulses or the slope. Both of these sets of settings are similar to the settings for the current with a start value, delta and the number of times to increase. Beyond that the *Pulse* tab has a setting for the pulse time and the *Slope [kA/s]* tab has a setting for the number of pulses to do at every position. Finally there is button to start the testing called *Start surface measurement*. Here it is also good to know the total number of test positions and the number of rounds that is needed to do.

4.3.2 Operating system

Structure

When making a program for the embedded computer it is important to have some sort of plan from the beginning. Especially if the program will have as many features as this program have. From the beginning we knew roughly what type features the structure of the program would need. There is a need to run different parts of the program in parallel and that is easy to do with parallel loops in LabVIEW. Related to parallel features is that the user wants to be able to give the machines various commands in arbitrary order. Some of them might even need to run in the background after they have started. In addition, many of the tasks need to share variables. To implement that kind of program with a state machines and parallel loops would probably be hard. It would also grow in size and complexity considerably fast. This would have a negative impact on other features of the structure of the program, namely that it needs to be easy to develop the program and add more tasks with ease.

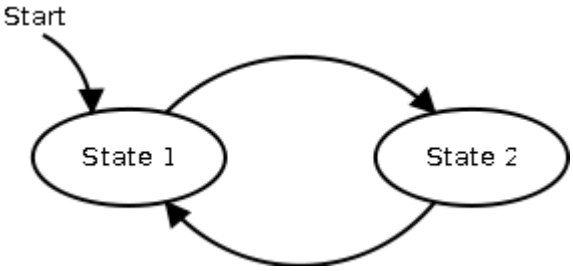
The solution used to satisfy the needs was to develop a structure that could be seen as a very simple form of operating system. The first building block of the operating system is a FIFO-queue called the task queue. It contains elements that refer to a task to do, so when there is a new task to do the corresponding element is enqueued in the task queue. The second part of the operating system is a while loop that starts to dequeue one element from the task queue. That element is then used to execute a piece of code that implements that task. Each task is implemented in a case is a case structure and the case structure would then contains one case for each task. The case structure is the third and last part of the operating system. These three building blocks are shown in LabVIEW code below.



LabVIEW code 1: The three main parts of the operating system in the embedded computer

Implementing a state machine

This simple operating system can be used to implement a state-machine. Imagine a simple state-machine with two states that enqueues each other like in the one below.



State machine 1: Example of state machine

To implement the state machine the case structure in the operating system would contain two tasks, one for each state. The program in each task would simply enqueue the other task. When this state machine is started it would continue forever. Imagine that two of these state machines are implemented and that they are independent of each other. Now this operating system starts to be useful since it is easy to see that this could be expanded to more than two state machines. It is also possible to see that this could be used to implement more advanced state machines. In fact each state in a state machine could be rather advanced in itself. When the programmer understands the structure of the operating system well it is a very powerful tool. It will be easy to develop a state machine and change it during the development, without the need to be concerned about the other state machines in the operating system. This operating system has one drawback nevertheless. When a task executes, it executes and it will only stop when it is finished and hands the control to the operating system. This implies that a task can not make a busy wait because that will stop all other tasks to execute. A busy wait is seldom a good idea anyhow. More important is that the execution time of a task can get so long that it will interfere with other tasks. The programmer thereby needs to ensure that a task does not take too long time. Of course it is possible to create a loop next to the operating system loop to deal with time critical tasks. These will then use the RTOS on the embedded computer take care of the parallelism of the loops. Luckily it is possible to enqueue elements to a queue in one loop and dequeue the elements in another parallel loop in LabVIEW.

How the operating system is used

The operating system structure described above was considered to be a good starting point for the program for the embedded computer and has been that throughout the project. The heart of the program developed is a state machine looking much like the state machine with two states above but it is expanded to four states. There are four tasks that implement these four states and these tasks are *Idle*, *Check front panel*, *Diagnostics* and *Background activities*. The *Idle* task enqueues the other tasks and itself as well. This will work since they are enqueued in a FIFO-queue. It can also stop the program by dequeueing all elements if a stop condition is met. The last purpose of the *Idle* task is to keep the cycle time of the state machine constant. When the *Idle* task is finished next up is the *Check front panel* task. The name describes it very well since its job is to read the front panel controls and start the corresponding state machine if a control implies that. It does this for all controls on the front panel that could imply that a state machine should be started. Next up is the *Diagnostics* which gathers information from the FPGA program and presents this in the *Diagnostics* tab in the main-tab interface. It also checks so that the monitored power supply

voltages are okay and reports this to the FPGA program. Finally *Background activities* have various tasks to do, hence the little more generic name. It implements three timers where two of them were mentioned in 4.3.1, namely the elapsed timer and the cool of timer. The third timer involves the servo motor and more specifically the time it takes for the servo to move to a new position. It also now and then asks the servo controller if there are any errors and checks if the servo controller has sent any new messages.

Another interesting thing is how the state machine described above is started. It is started by a task called *Init* which enqueues the *Idle* task. The *Init* task also initiates some variables and the communication with the servo. The *Idle* state in turn is enqueued before the while loop that is a part of the operating system.

In program like this the number of variables used within the program to store values and send values between tasks get fairly large. To cope with this a cluster containing the variables is used. The cluster is coupled to a shift register on the operating system while loop. This means that the values stored in the cluster from one task can be read by the next task. If all tasks pass on all the variables except the one that they change a value that is stored can be read by any task that later executes.

The FPGA program can generate three different interrupts. To deal with this a while loop parallel to the one of the operating system is used. When an interrupt occurs it will simply enqueue a task to the task queue of the operating system that handles the interrupt. The FPGA program generates interrupts when the calibration for the comparators is done, when a magnetization pulse is done and when a sampling of the hall sensors with averaging is done.

Current pulse generation

To shoot a current pulse the pulse needs to be generated in software first. The method used in this project is to generate the pulse in the software of the embedded computer and then load the data points to FPGA. The FPGA then consumes the data points at a constant rate and uses the value as the present current reference. During a period of time this will create a current pulse. To send the generated data from the embedded computer to the FPGA a FIFO-queue called *Current to play* is used. Using a FIFO-queue is a good idea since that is are made to send large amounts of data from the embedded computer to the FPGA or vice versa. The task *Current: Generate* generates the current reference described above and writes the data to the *Current to play* FIFO. To get the desired current the current controller in the FPGA needs the correct tolerance bands. The *Current: Generate* task therefore also sends the correct values for the tolerance bands to the FPGA. When the data is loaded the only thing remaining to do is to start the playback of the data. This is done by the *Current: Run* task.

After a current has been played the user may want to see how the resulting current was. Therefore the FPGA program samples the real current at the same rate that current reference is played. These samples are written to a FIFO-queue called *Analog samples*. The DC-link voltage is also sampled during the current pulse. It would be neat to put these samples in another FIFO-queue. However it is only possible to have three FIFO-queues and the third is needed for another thing. The solution is put both the current sample and the voltage sample in the same FIFO-queue. The samples are taken at the same time, thus there will be equally many of them and they will be interleaved in the FIFO-queue. The software in the embedded computer needs to take care of this and to make the data useful in needs to separate it into two vectors.

The third FIFO-queue is called *Digital samples* and it transfers data about the switching instances of the power electronics to the embedded computer. When a switching instance occurs an element is written to the FIFO-queue. This elements contains information about which switch was activated, the boolean value after the switch and on which clock cycle it occurred. The embedded computer can then reconstruct the entire switching pattern from the data in the FIFO-queue.

When a current pulse has been played and the FIFOs *Analog samples* and *Digital samples* is filled with data the FPGA program generates an interrupt. This means that the program can continue with the next step. That could be analyzing the data or continue with a magnetization procedure. Therefore the *System: Read FIFOs* task that is enqueued by the interrupt enqueues other tasks so that they can continue.

Hall sensor sampling

To make the measurement of the hall sensors more accurate averaging is applied. As described in 3.2.5 the supply voltage for the hall sensor is needed to calculate the magnetic flux. The FPGA program sums up a number of samples from a sensor and does the same for the supply voltage. This is then repeated for the other three hall sensors. The task named *Hall: Start sampling* makes the FPGA program start this measurement. When the measurement is done the FPGA program sends an interrupt to the embedded computer. The embedded computer then enqueues a task called *Hall: Read sample*. This task reads the values from the FPGA program and divides them with the number of samples that were taken. It then calculates the magnetic flux. Since this procedure is started by the *Hall: Start sampling* there is always a task that is interested of the result. Of course this is tasks that are scanning the band. To let these continue on their work the task *Hall: Read sample* enqueues the one that initiated the sampling.

Serial communication with the servo

For the serial communication there are two while loops parallel to the one of the operating system. One of them is used to send data and the other is used to receive data. To write and read from the serial port the standard VIs in LabVIEW to do that is used.

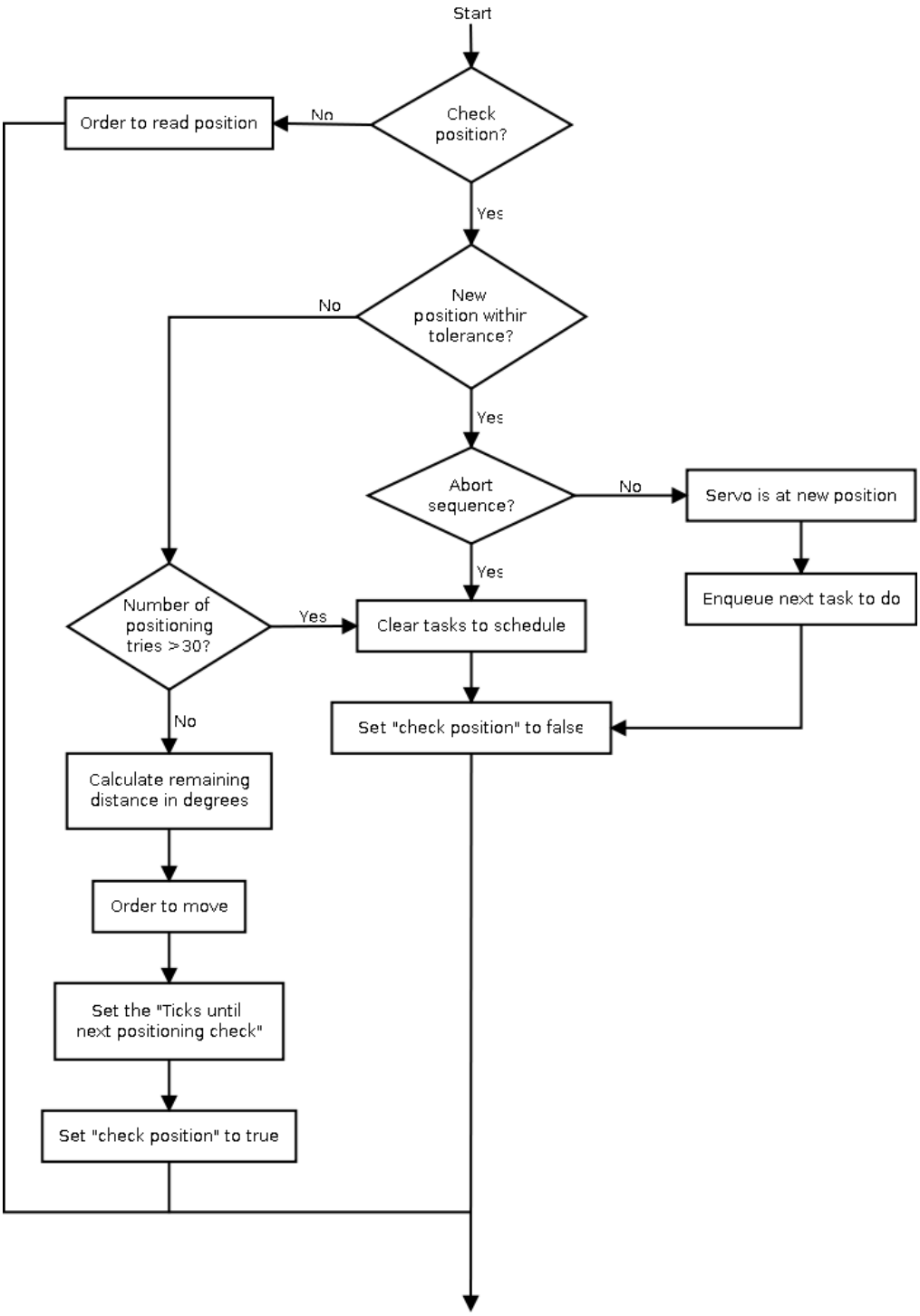
To communicate with the controller for the servo motor a special protocol is used. It is described in depth in [21]. It is a protocol where the computer is the master and the servo controller is the slave. The master is always the initiator of communication. This means that to get information from the servo controller to the embedded computer the embedded computer needs to ask for it first. When a message is sent to the servo controller it will always answer. If a value was requested that value will be sent back. If a value or command was sent to the servo controller it will respond with a message that tells if it was okay or not. The request used continuously in this project is requests for errors and a request for the current position of the servo motor. The commands sent to the servo controller are enable, disable, clear errors, change to position control, change to speed control and go to new position. Also two commands that sends a value to the servo controller is used, these values are new position and speed set points. The *Init* task also uses some commands not mentioned above for the initialization of the communication with the servo controller.

A FIFO-queue called send queue contains commands to send. This is a good solution since it is tasks in the operating system that know when to send a command and it is the while loop parallel to the operating system that sends the message containing the command. It will also be easy to

send commands from a task since it is just to enqueue the command to the queue. The rest of the job is handled by the parallel while loop for sending data with the serial port. To have a FIFO-queue for communication between tasks in the operating system and the parallel while loop that reads the serial port is also a good idea. But in this case it is called receive queue and received messages is enqueued in the while loop and dequeued in the operating system. When a message is available in the receive queue a task called *Decode* is started. If the decoding finds that requested data was received it starts a task that can use it. If the message got corrupted on the way it will be enqueue again to the send queue. To be able to know what the message was there is a third queue called sent queue. This contains the messages that has been sent and they are enqueued in the parallel while loop that sends commands. In the normal case the message is not corrupted but the element in the sent queue needs to be dequeued and thrown away.

Positioning the servo motor

The servo motor is used to rotate the magnet band and thus changing the position that is magnetized. To move the servo to a desired position a command is sent to the servo controller. It will take some time for the servo to rotate and then the position of the servo motor is checked. This is done to detect if the servo motor can not position itself correctly. There could be different reasons for this. It could be mechanical problems, power supply failure or random errors. To implement this a two state in the operating system has been added, *Servo: Display rotor position* and *Servo: Change position*. The first is enqueued when a message about the position of the servo motor is received. The message is converted from the position format used by the servo controller into position in degrees and mm. It also enqueues the *Servo: Change position* if it was the one that requested the position. The *Servo: Change position* is enqueued when a task wants to change the position. The tasks that request the change in position must provide the new position in the variable *New position in mm* in the variable cluster. *Servo: Change position* ensures that the servo motor will be at the desired position by looking at the present position and the desired position order the servo controller the move according to the difference in position. This means that *Servo: Change position* will be enqueued more than once to ensure that the servo motor will be at the desired position. If it does not make it on the first try it tries again until it decides that it is not possible to reach the goal and alerts the user. A flowchart for the logic of this task is presented below.

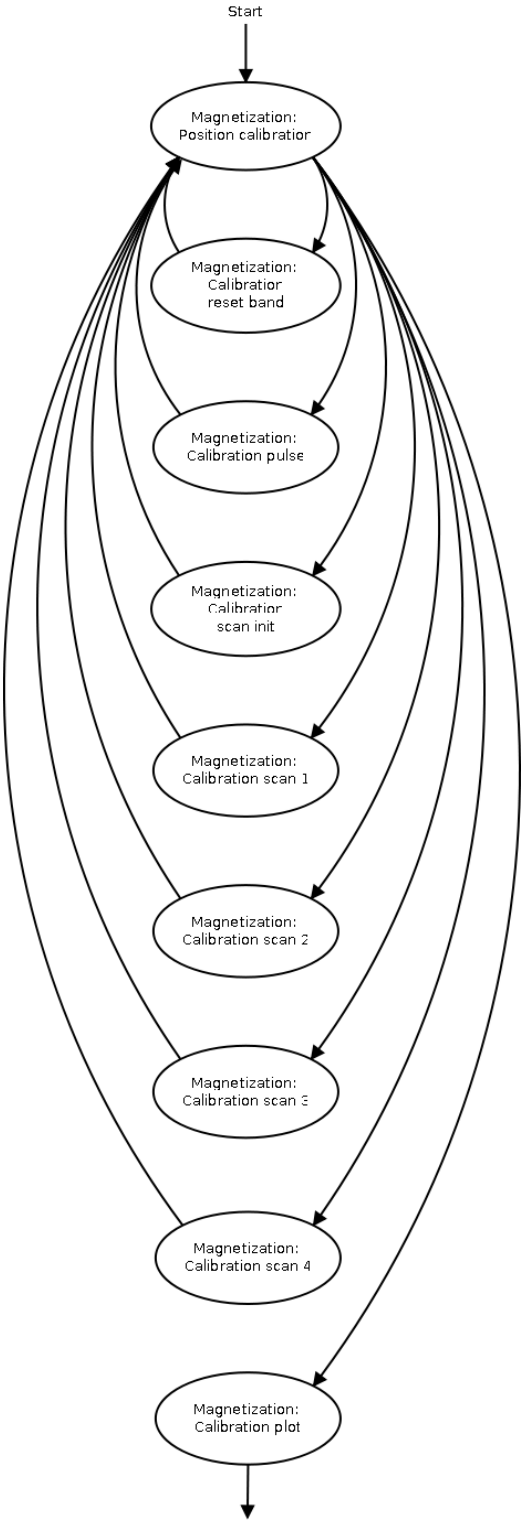


Flowchart 1: Servo: Change position

There is very often something to do when the servo motor has reached the desired position. Either a current pulse or sampling of the hall sensor should be done at the new position. Therefore a task called *Servo: Schedule at new position* is enqueued when the servo motor has reached the desired position. This task checks what there is to do and enqueues *Current: Run* to do a current pulse or *Hall: Start sampling* to take samples of the hall sensors. These tasks will in turn start a chain reaction that will enqueue the task that requested the new position.

Positions calibration

As described in 4.3.1 the calibration of the position of the hall sensors relative to the magnetization head is an important step to get a working machine. Another state machine is implemented in the operating system to do this calibration. As seen below it is a state machine with nine states.

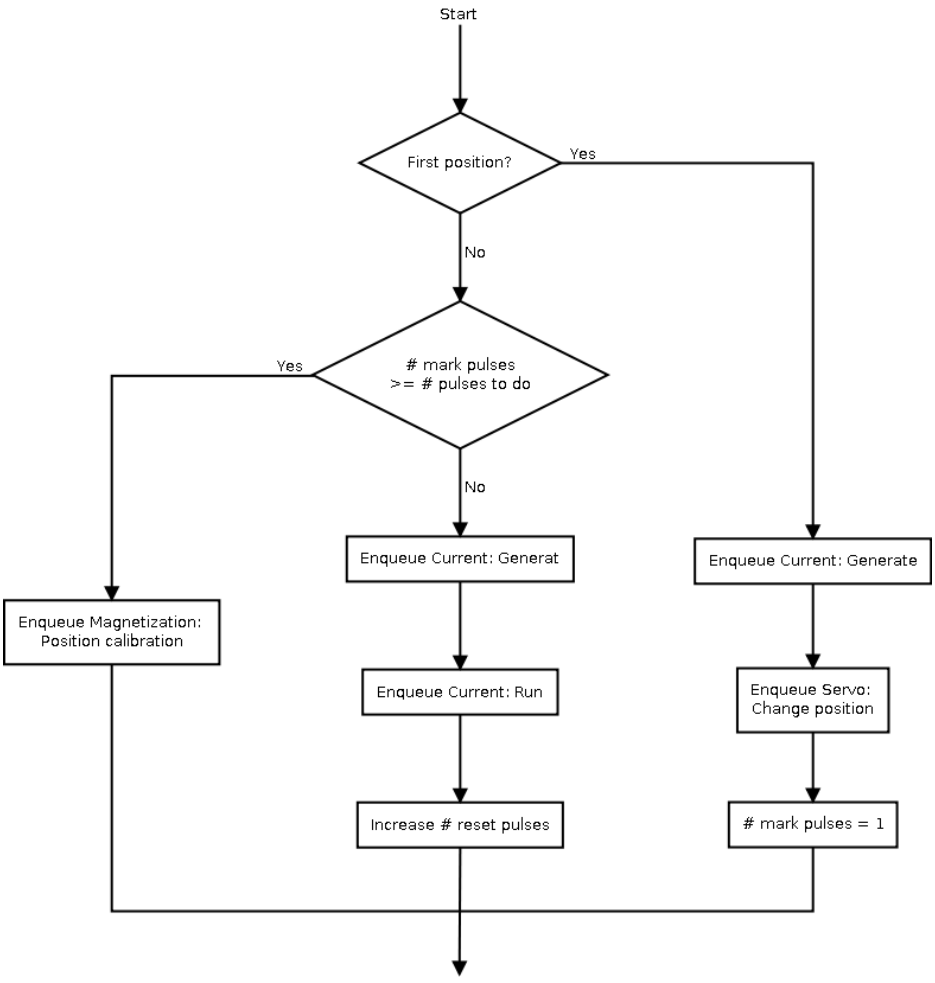


State machine 2: Position calibration

On the front panel the user has the ability to decide which of the steps in the calibration procedure that should be done. The *Magnetization: position calibration* state supervises the whole calibration procedure. A state machine with a supervising state makes it easy to skip one of the states and thus implementing the feature to decide which of the steps in the calibration procedure that should be done. A supervising state is also a convenient way to initialize variables before entering the other states. First the *Magnetization: Calibration reset band* will be executed to reset the band then a pulse at a known position is shot with the *Magnetization: Calibration pulse* state. After that it is time to scan the band and first an array to put the measurements is created in *Magnetization: Calibration scan init* the magnetization level is measured with and stored in the array with the four states named *Magnetization: Calibration scan x*, where *x* is a number from 1 to 4. Finally the result is plotted with the state *Magnetization: Calibration plot*. This state also calculates the correction factors for the position. When the *USE* button on the front panel is pressed the task that implements this state is enqueued. This time the calculated correction values will be saved in the variable cluster and the plots will be updated and use the new correction values.

Pulse state machine

Let's look a little bit closer on the *Magnetization: Calibration pulse* state since it is a perfect example of how to implement something that can do one or a series of pulses in a row. A flowchart of the state machine can be seen below.

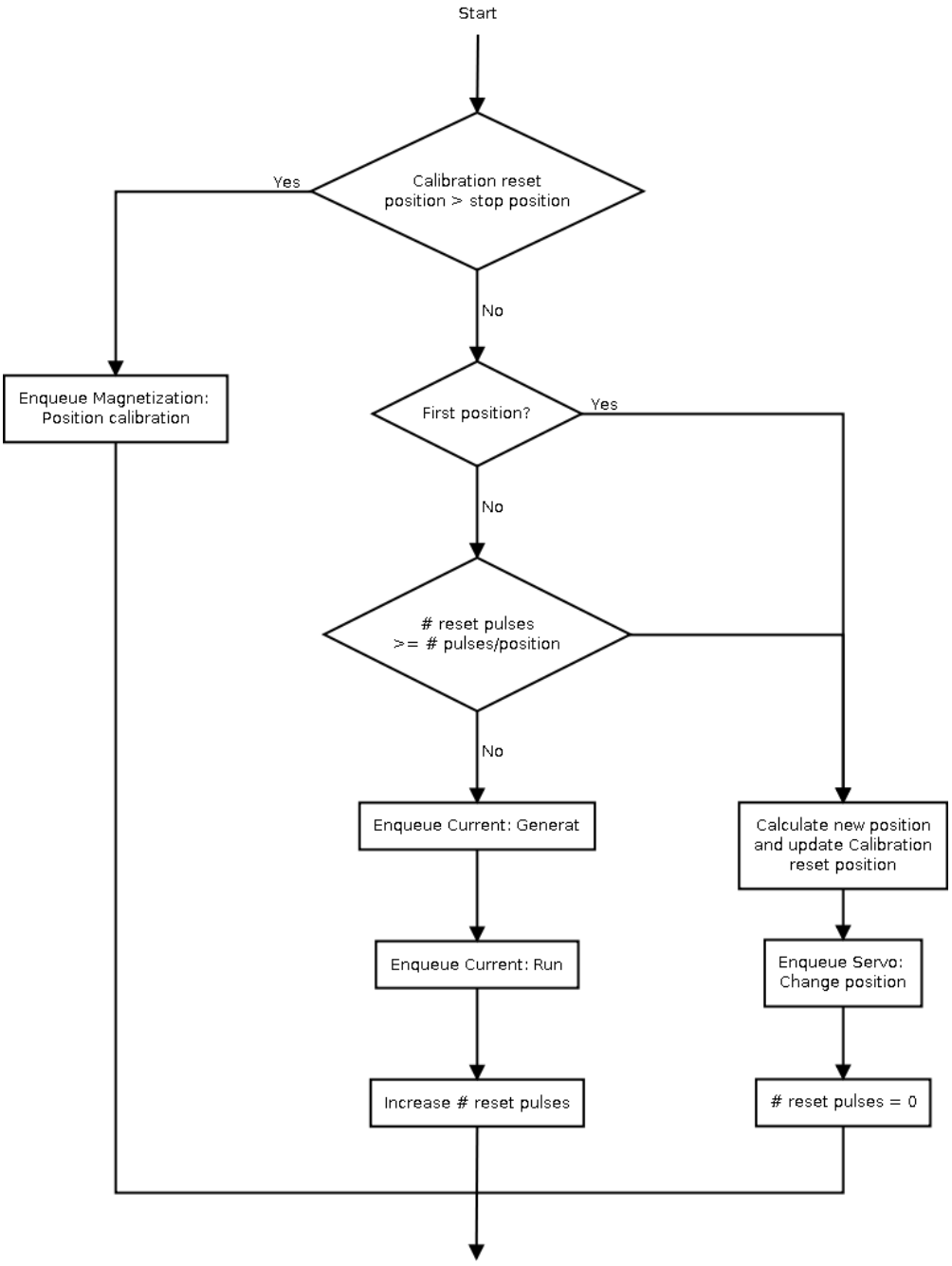


Flowchart 2: Magnetization: Calibration pulse

The variable *# mark pulses* is in the variable cluster and is initiated to zero in the *Magnetization: position calibration* state. The state machine utilizes the fact that both *Current: Run* and *Servo: Change position* will start a chain reaction that will enqueue task that implements this state machine.

Reset state machine

A flowchart of the state *Magnetization: Calibration reset band* can be seen in the flowchart below.



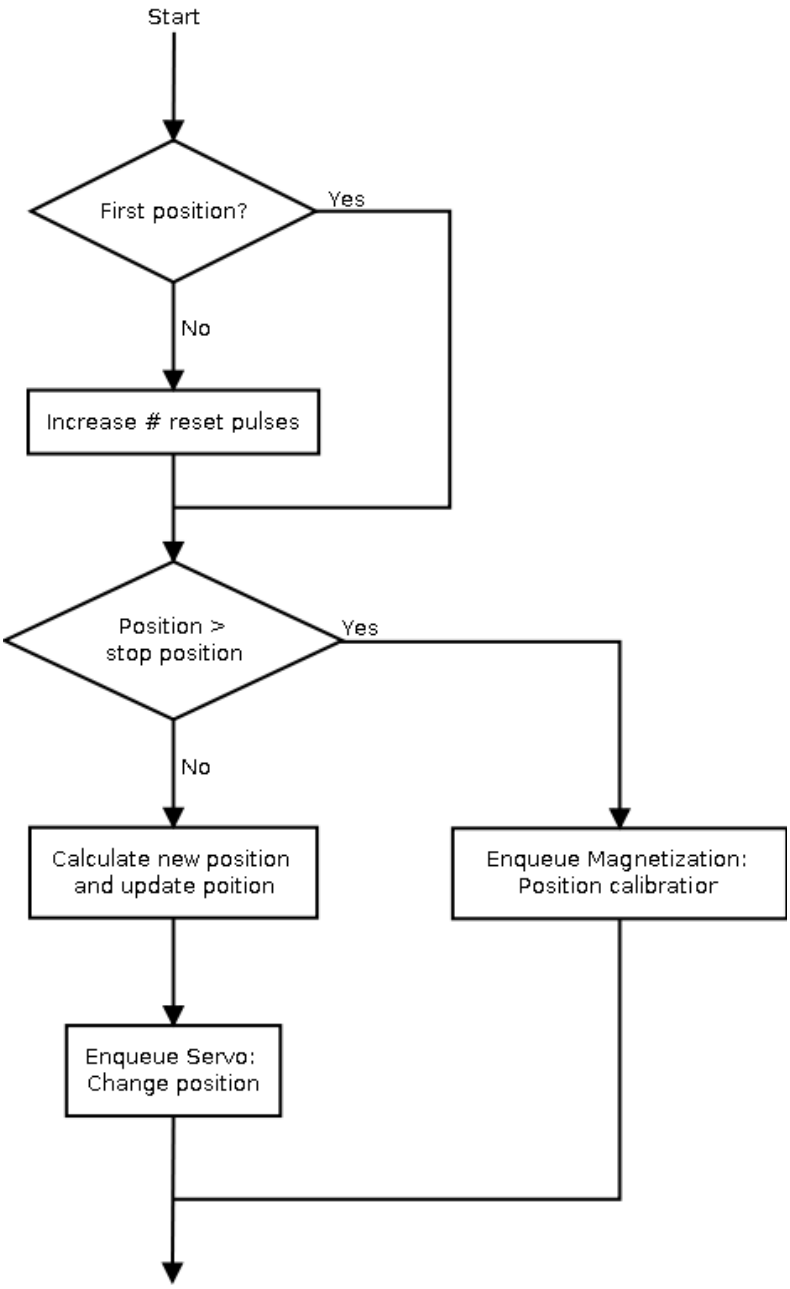
Flowchart 3: Magnetization: Calibration reset band

It looks similar to the previous flowchart and that is not a coincidence. The method to utilize the chain reaction is also used here which leads to similar logic. This state also shoots pulses but in

this case it is done on over and over again on different positions until it has iterated over the whole magnet band.

Scan state machine

Once again there is a good example how to implement a state machine with the *Magnetization: Calibration scan 1* state. The corresponding flowchart is seen below.

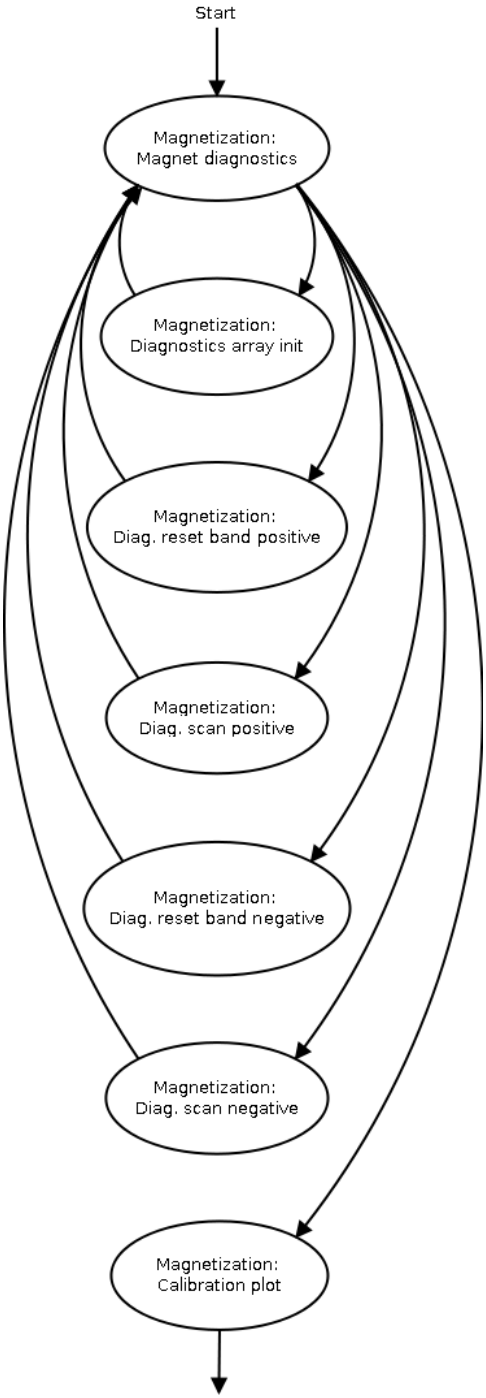


Flowchart 4: Magnetization: Calibration scan 1

Once again the winning concept to utilize the chain reaction is used and the logic of the state has similarities with the other two.

Magnet diagnostics

The same thinking when implementing the state machine for the position calibration has been used when implementing the state machine for the magnet diagnostics procedure. This makes the structures of the state machines very similar. A state machine for the magnet diagnostics can be seen below.

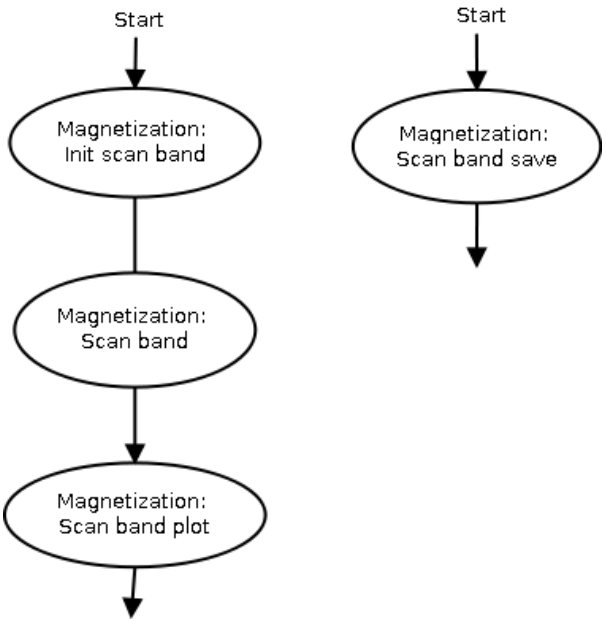


State machine 3: Magnet diagnostics

It has the supervising state *Magnetization: Magnet diagnostics* that determines the execution order of the other states. It also initializes variables in the variable cluster before the other states are entered.

Scan magnet band and data save

This is a rather simple state machine as seen below.

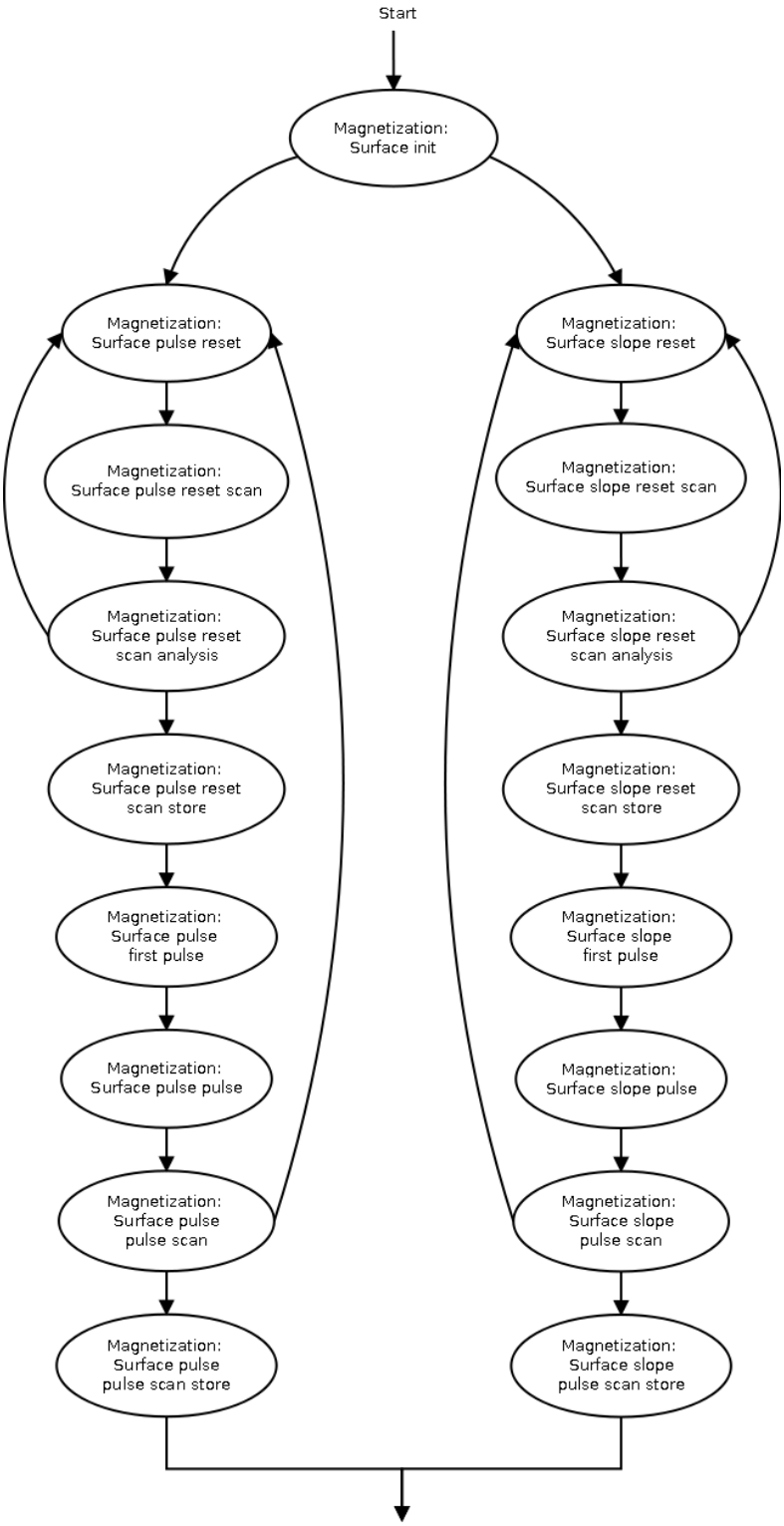


State machine 4: Left: Scan band. Right: Scan band save

It has no supervising state but that is because it does not need to be more advanced than it is. The state *Magnetization: Init scan band* initializes an array to save the measurement data into. The next state is *Magnetization: Scan band*. It utilizes the fact that *Servo: Change position* will start a chain reaction that will enqueue the task that implements this state machine again. Finally the result is presented in a plot in the *Magnetization: Scan band plot* state. As seen in the state machine the there is a separate state for saving the data to a file.

Performance measurements

As described in 4.3.1 there is a test procedure that tests the performance of the machine. The test conditions are different combinations of current and pulses/slopes and the program in the embedded computer performs the tests and saves the resulting magnetization. The state machine that implements this is rather large but has a simple structure, it could be seen in the state machine below.

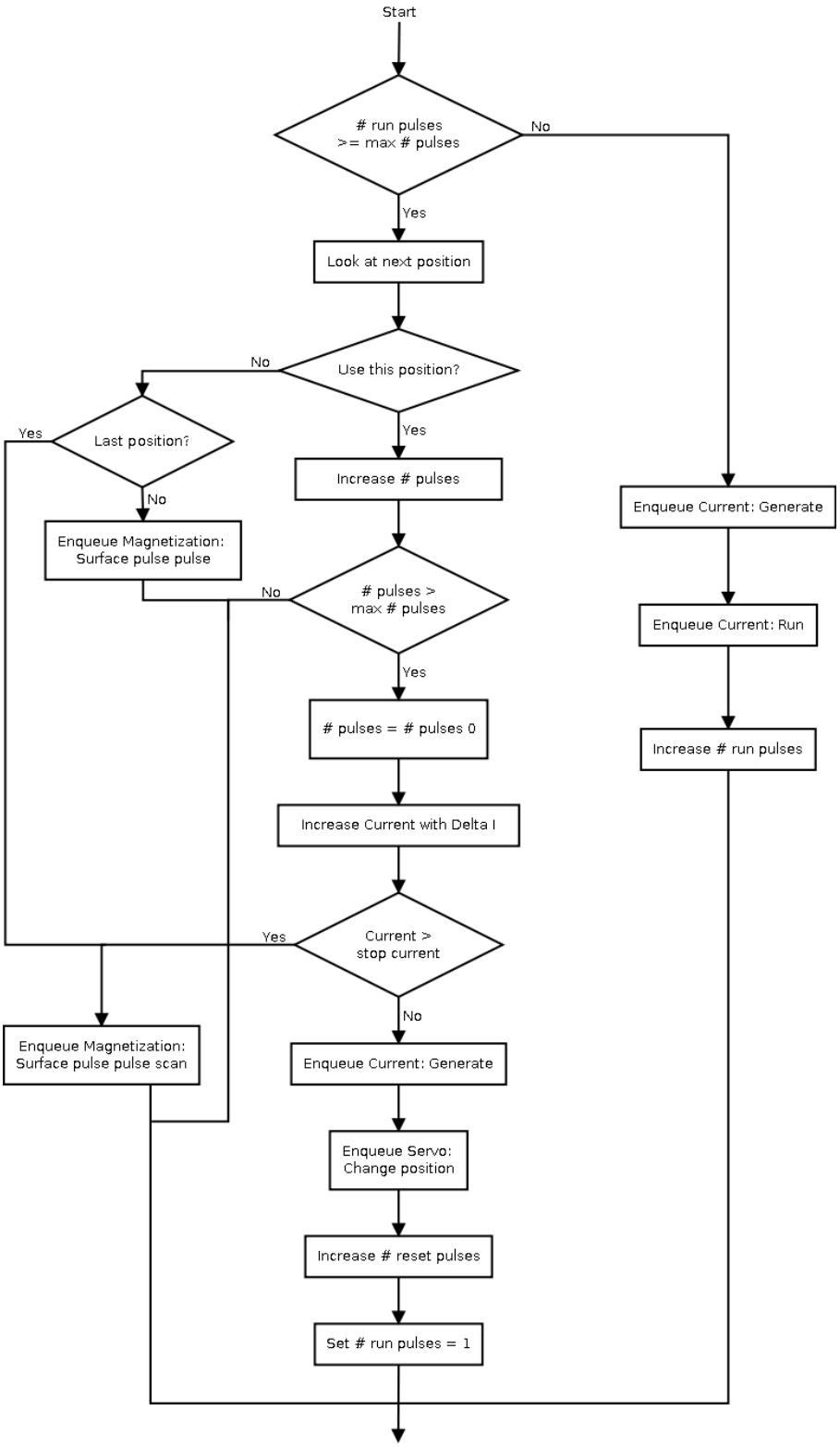


State machine 5: Performance measurements

The *Magnetization: Surface init* state initiates variables and creates a file name for the file to store data in. It also creates an array with positions to use from the controls on the front panel and saves it to a file with the created file name. The *Magnetization: Surface pulse reset* and *Magnetization: Surface pulse reset scan* states are implemented in the same way as the reset and scan states described above except that the reset starts a timer so the flux providing coils can cool down. An analysis of the achieved magnetization level with the reset is done in the *Magnetization: Surface*

pulse reset scan analysis and decision where to go next is made based on the result. When the reset is adequate it is stored in the file.

The flowchart for the *Magnetization: Surface pulse pulse* is seen below.



Flowchart 5: Magnetization: Surface pulse pulse

It is a more advanced state machine than previous once but it uses the same concept. The called *Magnetization: Surface pulse first pulse* will produce the first pulse then jump to the *Magnetization: Surface pulse pulse*. It is almost the same but with some minor differences since it is producing the first pulse. When the tasks that implements these flowchart executes the machine will start at the start current and the starting number of pulses at the first test position. Then it will increase the number of pulses with delta number of pulses and shoot the resulting number of pulses at the next position to use. The number of pulses is increased until they reach the limit of the testing interval. Then the current is increased by delta current and the number of pulses starts over again at the starting number of pulses. The task will continue to do this until there is no more positions to use for tests or there is no more tests to do. The *Magnetization: Surface slope pulse* works in the same way but the number of pulses is fixed and instead the slope.

After that once again a scan of the magnet band is performed and the result is then saved. If the machine is finished it alerts the user about that else it continues in the loop and runs more test pulses. To be able to perform the analysis of the results in MATLAB the test conditions needs to be known. This is achieved with the file name. The format of the file name and an example can be seen in table 1 and table 2 below. For the tests with number of pulses "number of pulses" is used instead of "slope" in the file name. The *Pulse time* is irrelevant for the test with slope but a value is used anyway to be consistent with the file name.

Table 1: File name format

1	2	3	4	5	6	7	8	9	10	11
Date	Io [A]	Delta i [A]	# pulses 0	Delta # pulses	Max # pulses	Pulse with [mm]	Waveform	Pulse time [ms]	User string	.xls

Table 2: File name example

11-08-02	0.0	5.0	1	5	101	30.0	Triangle	0.005	Final test	.xls

Pause and resume sequence

On the front panel there are buttons to pause and resume the execution of a sequence. Too implement that the *Servo: Change position* checks if this should be done. If so it enqueues a task called *System: Clear new tasks to schedule*. This task stores variables that determines the program flow of the sequence and sets them to do nothing. The same task can be enqueued again to restore these variables.

Safety in software

There are a number of safety precautions in software. Both the embedded computer and the FPGA are responsible for the safety. The utmost responsibility lies on the FPGA since it is considered to be most stable and besides has the fastest response time. The *shake to wake* signal is generated in the FPGA so it is also logical to put it in the FPGA for that reason. The program in the embedded computer however can unload the FPGA program from the FPGA. Therefore the program in the embedded computer prevents itself from do that until the DC link voltage has dropped below 20 V. This is done in the *System: Idle* task. There is also a task called *System: Activate* which sends a signal from the embedded computer to the FPGA that it is okay to turn on the *shake to wake* signal. The rest of the safety precautions for the embedded computer are in the *System:*

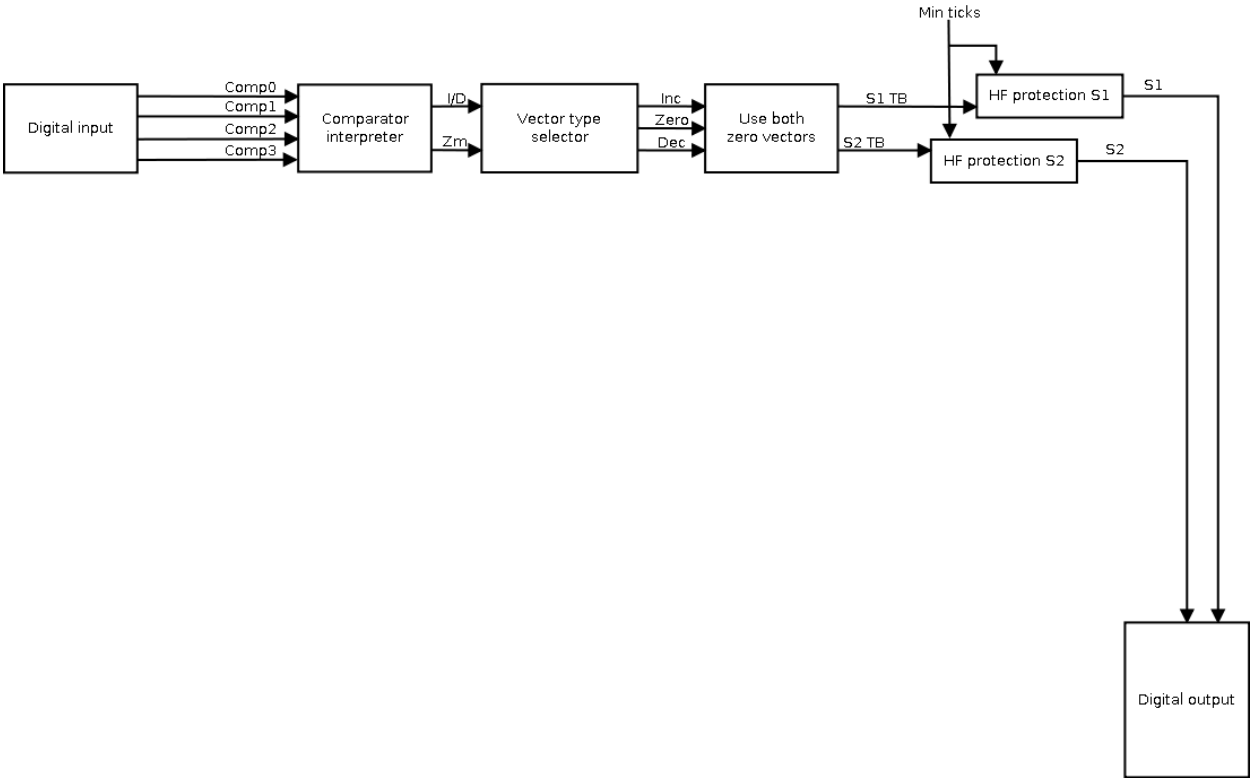
Diagnostics task. It checks that the supply voltages are within a user defined tolerance and sends a boolean to the FPGA if the result was okay or not. The signal from the emergency stop on the front panel is also sent to the FPGA. The task reads a signal from the FPGA that indicates if the machine is ready to be started (changed into the operational state) and a signal indicating if it is in operational state.

4.4 The FPGA program

4.4.1 Overall structure

The FPGA program is as far as possible implemented in a logical block structure. The thoughts behind the making of a program for the FPGA are fundamentally different from the ones used in the embedded computer in this project. In the program for the embedded computer the simple operating system makes it obvious that the execution is sequential. To get a program to work in the operating system the parallelism of the software would need to be adapted to that. To utilize the parallelism of the FPGA the program needs to be truly parallel and this makes the code harder to understand straight away. To describe the FPGA program and make it easier to understand it is explained with block diagrams. The block diagrams are as far as possible made to correspond to the actual code. The blocks are representing VIs and are all placed in a VI called *Pulse magnetizer 1.0.vi*. This makes them run in parallel. The signal lines between blocks are implemented with global variables.

4.4.2 Current control logic



Block diagram 1: FPGA code

The logic of the current controller is seen in the block diagram above. The block *Digital input* in the upper left corner provides the four signals from the comparison electronics to the logic of the current controller that is implemented in the FPGA. The logic of the controller is implemented with the three subsequent blocks, *Comparator interpreter*, *Vector type selector* and *Use both zero vectors*. The *Comparator interpreter* interprets the signals from the comparators and creates two new signals, *I/D* and *Zm*. *I/D* tell the controller if it is supposed to increase the current or decrease the current. It is not always certain if a passive voltage vector (zero output voltage) increases or decreases the current, and since it is desirable to use passive voltage vector every second switch the controller needs to be informed about what the passive vector achieves. This is done with the signal *Zm*.

This application is a special case since it is known if the pulse is positive or negative before it occurs. Therefor there is an ideal value for the signals *I/D* and *Zm* to start at and they can be forced to change by setting the *C I/D* or *C Zm* input high.

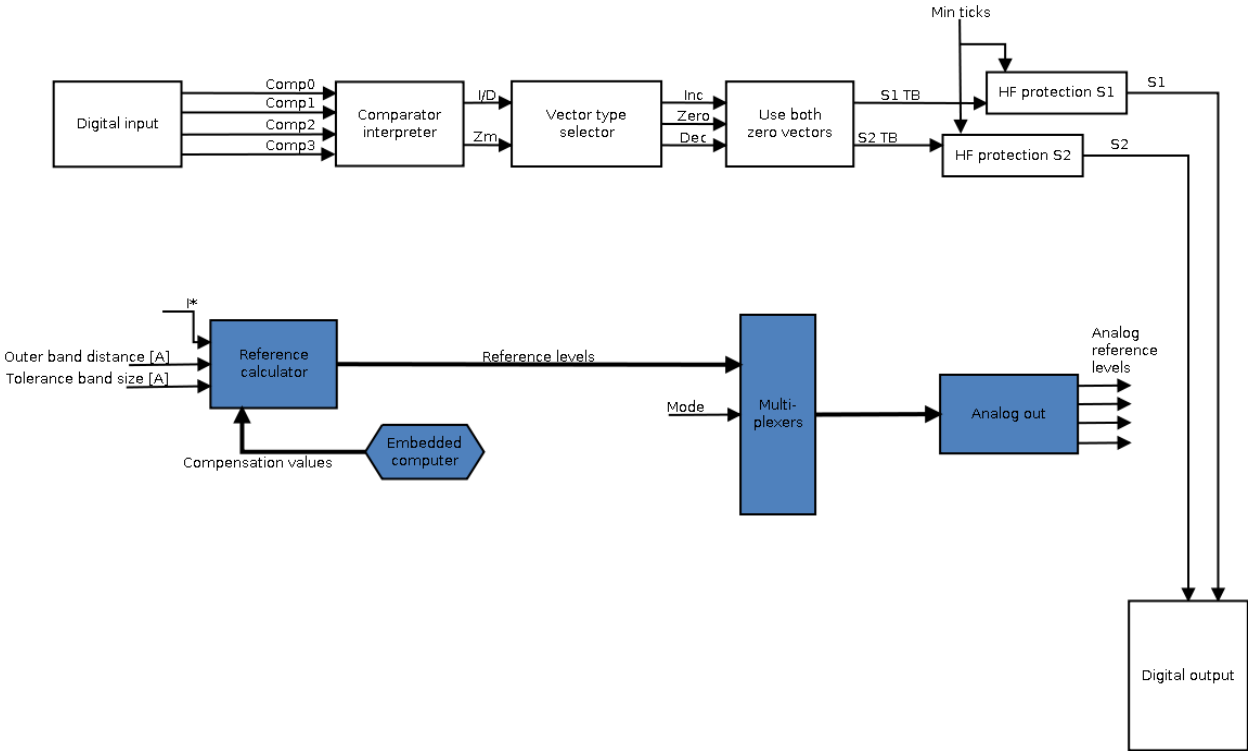
These two signals, *I/D* and *Zm,* is sent to the *Vector type selector* which only translate them into *Inc, Zero* and D*ec*. *Inc* corresponds to an active vector with a positive output voltage, *Dec* corresponds to an active vector with a negative output voltage and *Zero* corresponds to passive vector, i.e. zero output voltage.

These signals are used by *Use both zero-vectors*. It translates them into signals to the bridge where *Inc* will be translated into *S1 TB = true* and *S2 TB = false*, *Dec* will be translated into *S1 TB = false* and *S2 TB = true* and Zero will be translated into either *S1 TB = false* and *S2 TB = false* or *S1 TB = true* and *S2 TB = true* depending which of them that were used the last time. When passive vectors are used it changes the used passive vector every second time.

Since it is a tolerance band controller it can introduce undesirable high switching frequencies when it is not properly tuned. Therefor there is a high switching frequency protection implemented, the *HF*-protection as seen in the upper right corner of block diagram 1 in the attachments. There are two identical blocks for this purpose, one for each leg in the bridge. The only thing that differs is the *S1* and the *S2* in the names.

The desired leg position comes from *Use both zero vectors* and if it is okay to switch it is directly forwarded to *S1*. The protection uses a timer that starts counting when a switching occur to prevent that the same transistor is turned on again, in a certain time. This means for example that the transistor could be turned on, and immediately off again, but then the transistor can not be turned on again before the timer has counted to the desired limit that defines the highest switch frequency. The same thing applies for next turn off. The minimum time between switches is sent to the block in ticks to the *Min ticks* input. The output signals from the two *HF-protection* blocks are sent to the *Digital out* block.

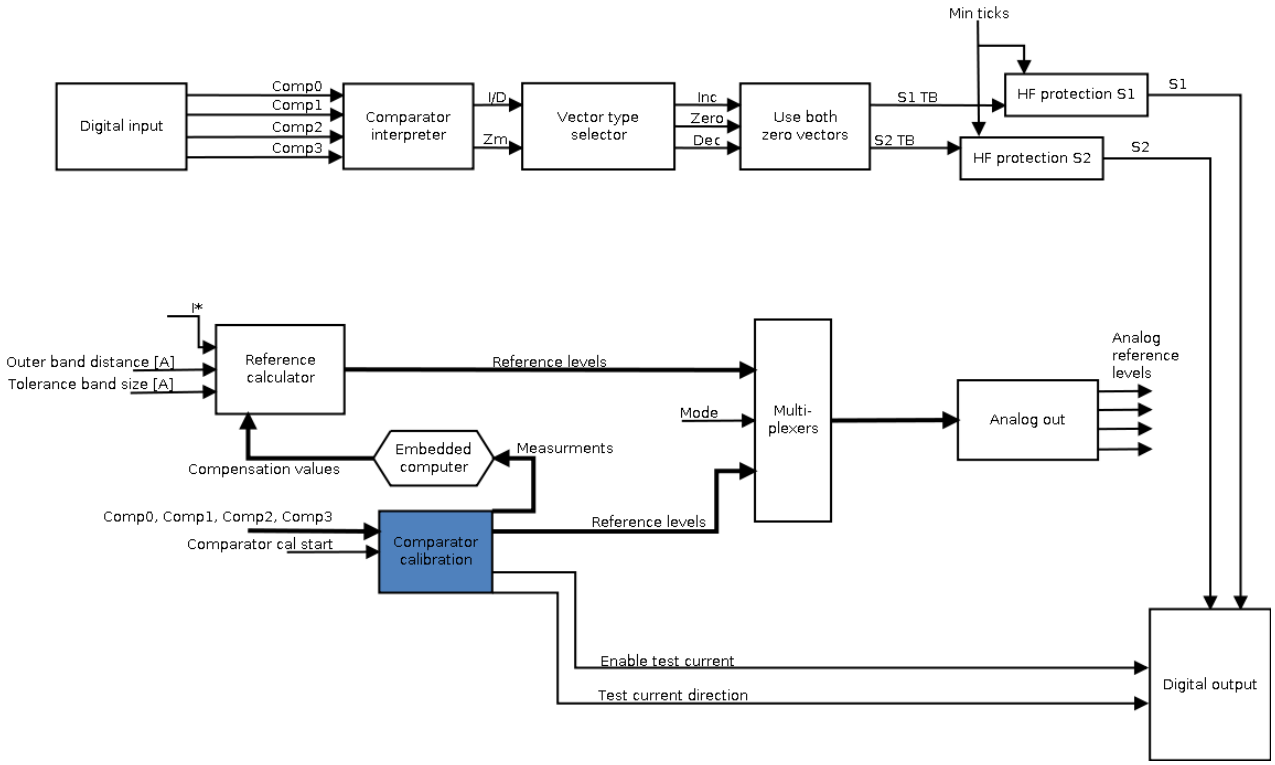
4.4.3 Generation of tolerance bands



Block diagram 2: FPGA code

In the block diagram above blocks involved in the analog reference levels has been added to *Block diagram 1*. To control the tolerance bands the FPGA program uses four analog voltage output signals called *Analog reference levels* and is seen to the right of the *Analog out*. It is the rightmost block of the blue colored blocks. The levels are calculated by the *Reference calculator* which is the leftmost of the blue colored blocks. It uses the *Outer band distance [A]*, *Tolerance band size [A]* and the current reference, *I**, to calculate the ideal value for the reference levels. These are then recalculated within the *Reference calculator* with the *Compensation values* from the embedded computer before they are sent to the *Multiplexers*. The *Multiplexers* chooses which reference levels to send to the *Analog output* block. So far there is only one block that generates reference levels, namely the *Reference calculator* block.

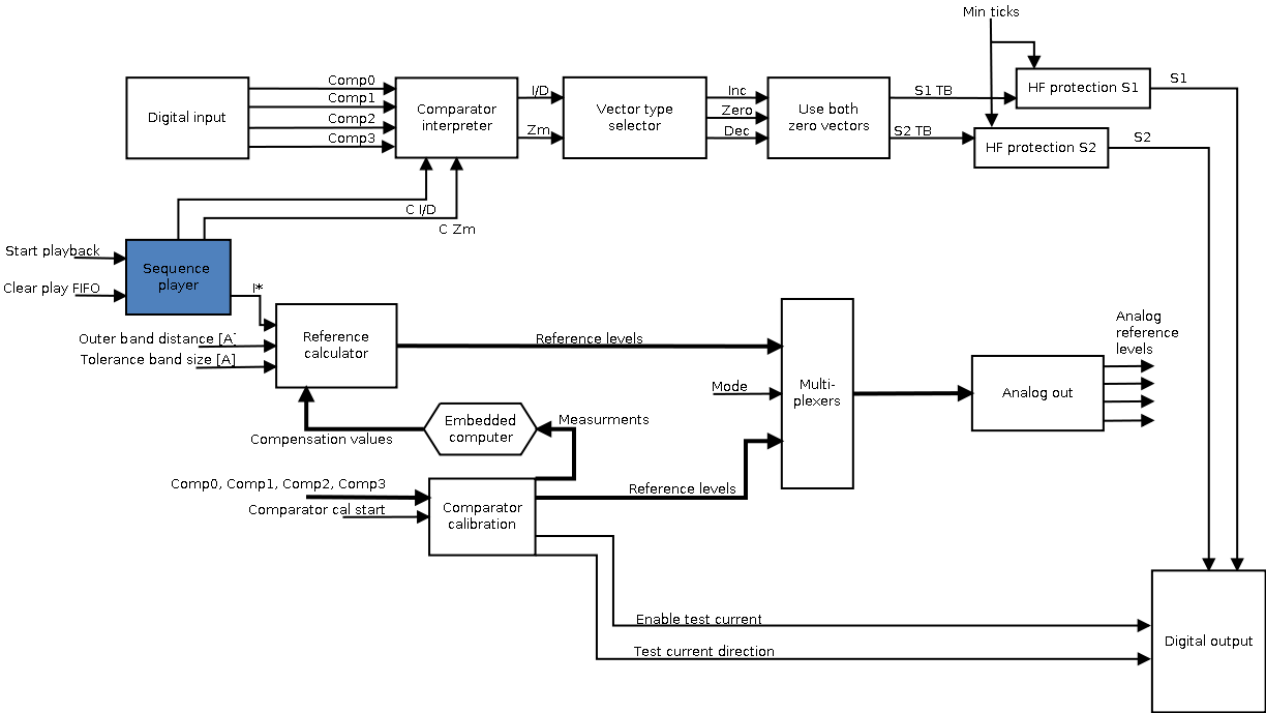
4.4.4 Comparator calibration



Block diagram 3: FPGA code

When the *Comparator calibration* is added the resulting block diagram is seen above. The *Comparator calibration* performs a calibration by sweeping the *Reference levels* and check when the comparators change. To do this the *Reference levels* it generates needs to be sent to the *Analog out* block, here the *Multiplexers* block comes in handy. With the input *Mode* it can choose to use the *Reference levels* from the *Reference calculator* or the *Comparator calibration* block. When the calibration is started the *Comparator calibration* block will as said sweep the *Reference levels* and check when the comparators change. It does this for two different test currents, one positive and one negative. The measurements are then processed by the embedded computer which calculates the *Compensation values*.

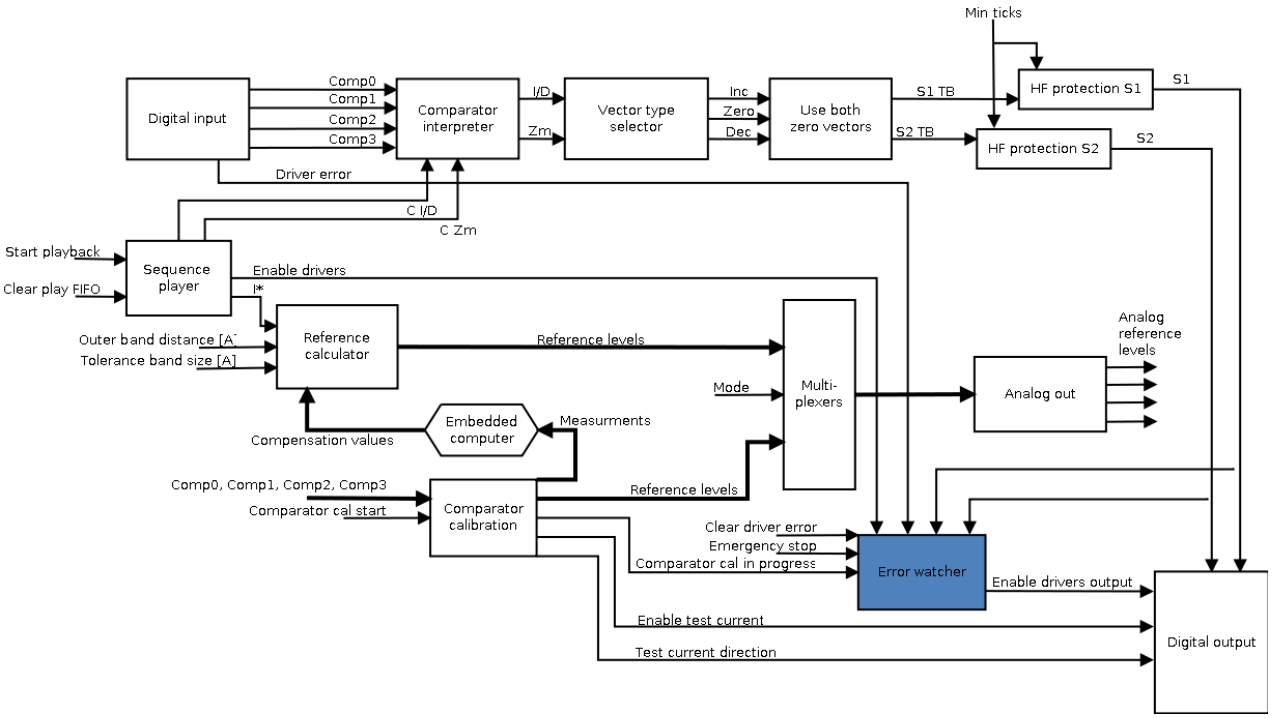
4.4.5 Current pulse generation



Block diagram 4: FPGA code

To generate a current pulse the *Sequence player* is added to the block diagram and the resulting block diagram is seen above. The current reference, *I**, is changed by the *Sequence player* to generate a current pulse. It gets the data points for the current pulse from a FIFO-queue called *Current to play* which the embedded computer puts the data points into. When the *Start playback* signal is activated the *Sequence player* starts to consume the data points at a constant rate and uses the value as the present current reference, *I**. During a period of time this will create a current pulse. The *Sequence player* is also responsible for changing the values of the *I/D* and the *Zm* signals with the *C I/D* and *C Zm* signals before it starts to generate the current pulse.

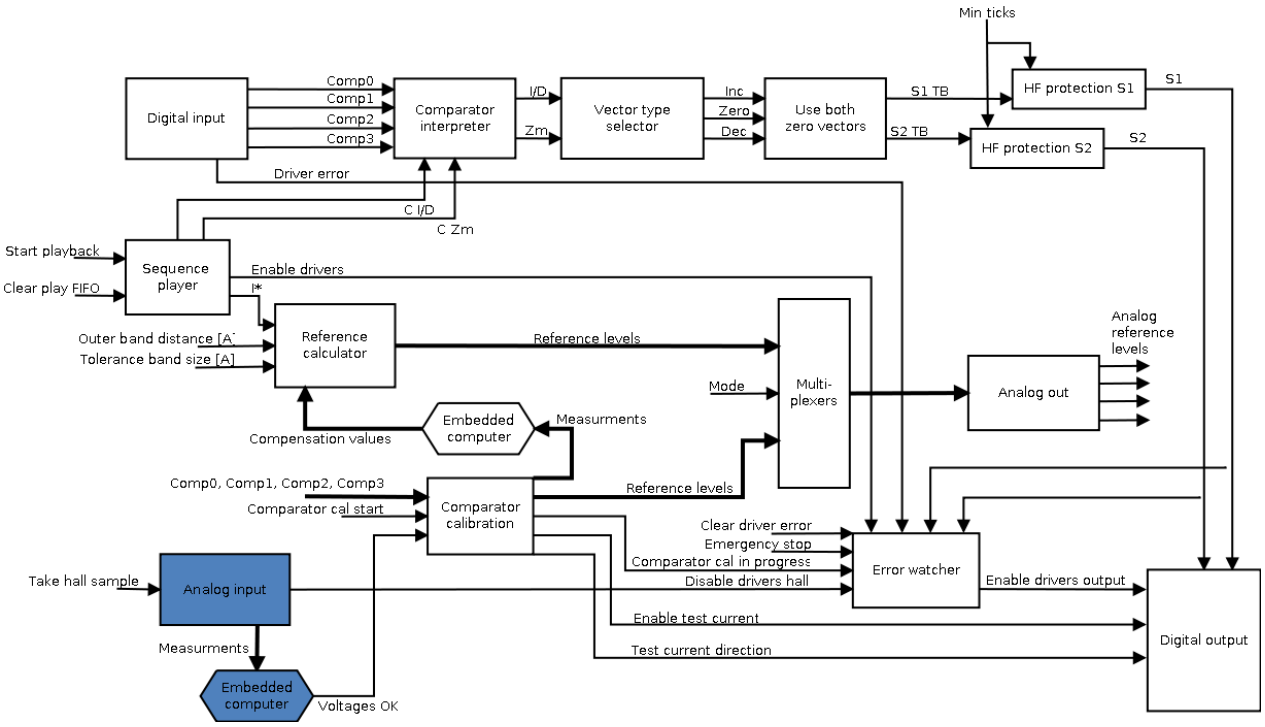
4.4.6 Error watcher



Block diagram 5: FPGA code

In the block diagram above the *Error watcher* block has been added. It ensures that the IGBT drivers is only enabled when it is needed it is also responsible for shutting down the IGBT driver if an errors occurs. It the driver itself that detects an error the *Error watcher* gets to know this by the signal *Driver error*. If driver causes the error the *S1* and *S2* signals are saved to help the error search afterwards.

4.4.7 Data sampling

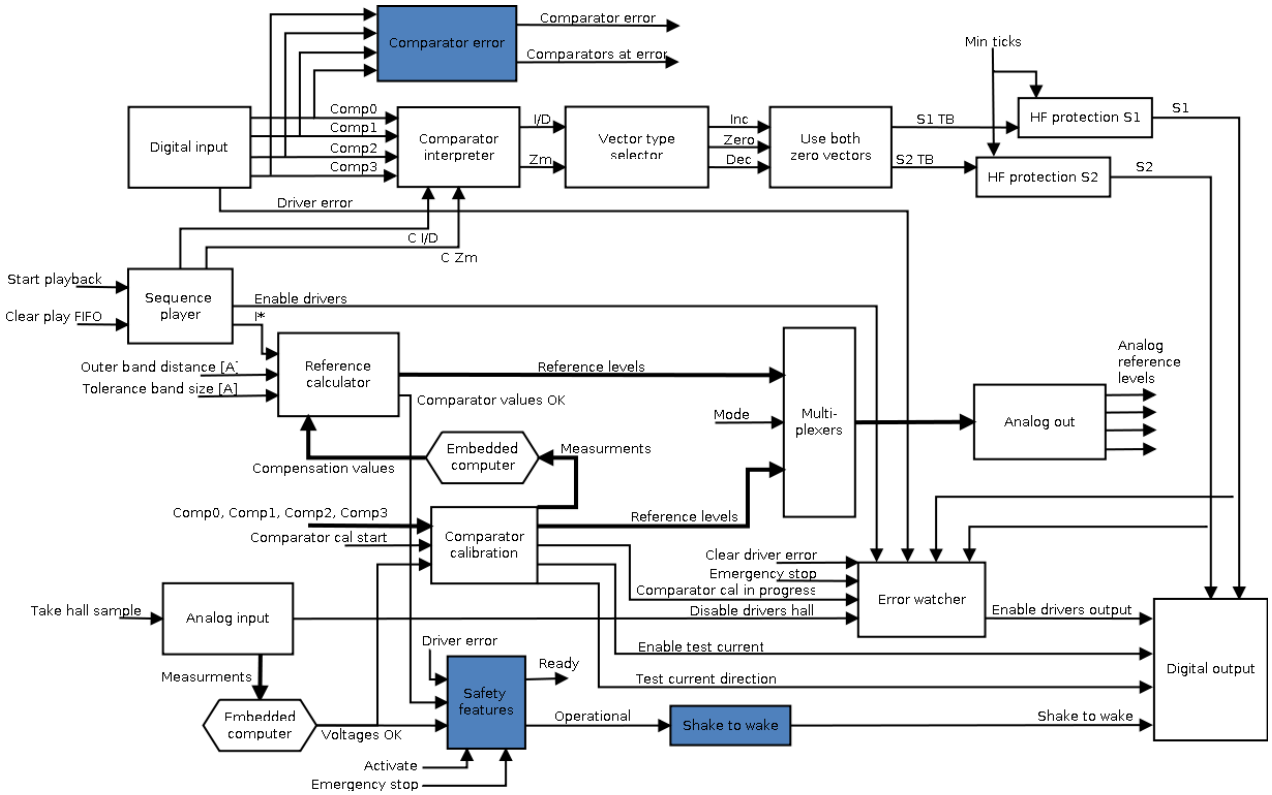


Block diagram 6: FPGA code

In the block diagram above the *Analog input* block has been added. It samples the analog power supplies and sends the measured data to the embedded computer. The embedded computer analyzes the samples and returns the *Voltages OK* signal to the FPGA program. When the *Take hall sample* signal is activated the *Analog input* block changes the sampling tactics and only samples the hall sensors for a while along with the supply voltage to the hall sensors. The samples are sent to the embedded computer which uses them to take a mean value of the magnetization level. When the hall sensors are sampled the driver is disabled with the *Disable drivers hall* signal. This is only a safety precaution because the driver should not be enabled when the hall sensors is sampled.

The Sequence player also takes analog samples. That is samples of the current in the flux providing coils and the DC link voltage when a current pulse is generated. The comparator calibration also samples current when it is doing the calibration procedure.

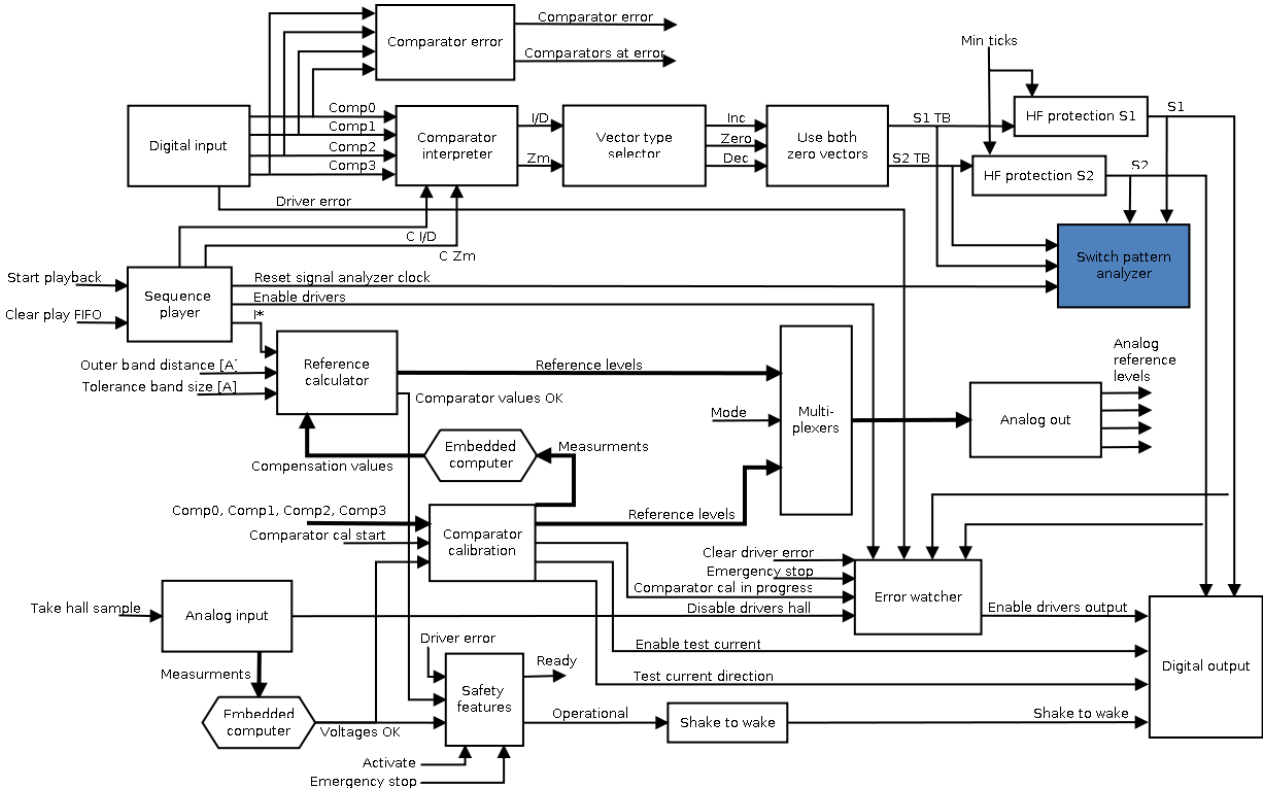
4.4.8 Safety in software



Block diagram 7: FPGA code

In the block diagram above the *Safety features*, *Shake to wake* and *Comparator error* blocks has been added. These two first is responsible for turning on the DC link voltage when the *Activate* signal is activated and everything is okay. The *Comparator values OK* signal should indicate that they are okay, the software controlled *Emergency stop* should not be activated and there should not be any *Driver error*. The *Shake to wake* block will provide a 1 kHz signal to the *Shake to wake electronics* when the *Operational* signal is true. The *Comparator error* block is also added in block diagram 5. It looks at the comparator signals to detect if there is any illegal combination and stores it if one found. An illegal combination could be that the comparators indicates that the current is both higher and lower than the reference at the same time. This is a tool that could come in handy to detect if there is problem with noise in the analog electronics.

4.4.9 Switch pattern analyzer



Block diagram 8: FPGA code

In the block diagram above the *Switch pattern analyzer* block is added. This is the final block in the FPGA code and is used to analyze the switch pattern of the IGBTs but also the desired switching instances. This block stores which variable that where changed, to which value it was changed and on which clock cycle it changed into the FIFO-queue called *Digital samples*. This allows the embedded computer to analyze the data and reconstruct the switching pattern both of the IGBT and the desired values from the current controller logic. This means that is also can detect when the HF protection was engaged.

4.5 MATLAB programs

The purpose of the programs in MATLAB is to compile the results into information that could be analyzed by the user. The result is presented as a surface with the test conditions on the x- and y-axis and the analyzed parameter on the z-axis. The analyzed parameters are the maximum resulting magnetization and width of the magnetized segment. The width is from 50% on the positive edge to 50% of the negative edge.

The first m-script downloads files from the cRIO to the working directory of the computer it is running on. It does this by presenting a list of the files in the folder *Surface results* in the cRIO. When the script runs the user can then choose a file to download and when done the script can be stopped. The script is called *cRIO_result_files_getter.m* and can be found in the attachment MATLAB code.

The next m-script loads a file from the working directory into a matrix in the MATLAB workspace. It also interprets the file name that has the format presented in table 1 in the attachments, and saves the values from segment 2 to 7 and 10 into variables. The user interface for this script is used in the same way as for the previous script. The script is called *MATLAB_file_loader.m* and can be found in the attachment MATLAB code.

The analysis is done with the third m-script. First of all the user needs to enter what type of test that is analyzed, if it is a performance test with different currents and number of pulses or with different currents and slopes. The user can also specify which of the sensor to use. First the script extracts the used positions from the data. Then it starts to divide the rest of the loaded array into smaller arrays that each one contains the data from one scanning round of the band. In this process the reset data is denoised. The number of test positions that has been used in every one of the scanning rounds is also extracted and saved in variables. Note that there are two scans for each test round, one from the reset scan and one from the pulse or slope scan. The scanned rounds are then iterated through and analyzed by a MATLAB function that has been created, it is called *PeakNDeltFinderOneRound*. The results from *PeakNDeltFinderOneRound* are added up to a resulting matrix. After this the script takes the data corresponding to the chosen sensor from the matrix and plots three different plots. The first is a surface plot with the test conditions on the x- and y-axis and the maximum resulting magnetization on the z-axis. The second surface plot has the maximum resulting magnetization relative to the magnetization for the reset at the z-axis. The third surface plot has the width of the magnetized segment on the z-axis. The script is called *Data_divider.m* and can be found in the attachment MATLAB code.

The function *PeakNDeltFinderOneRound* mentioned earlier uses the reset data and result data from one round along with conditions of the tests. It goes through every tested position and analyzes the data with a MATLAB function called *PeakNDeltaFinder* for every sensor. When it is finished it returns the result. It also returns matrix with the invalid results that is used to make the grayed area in the surface plots. The code for *PeakNDeltFinderOneRound* can be found in the attachment MATLAB code.

The *PeakNDeltaFinder* function takes two vectors, one containing data with a peak in and one containing the data from the reset scan. It then finds the peak value in the data and calculates the width of the peak. It also returns the peak value the data relative to the reset. The code for *PeakNDeltaFinder* can be found in the attachment MATLAB code.

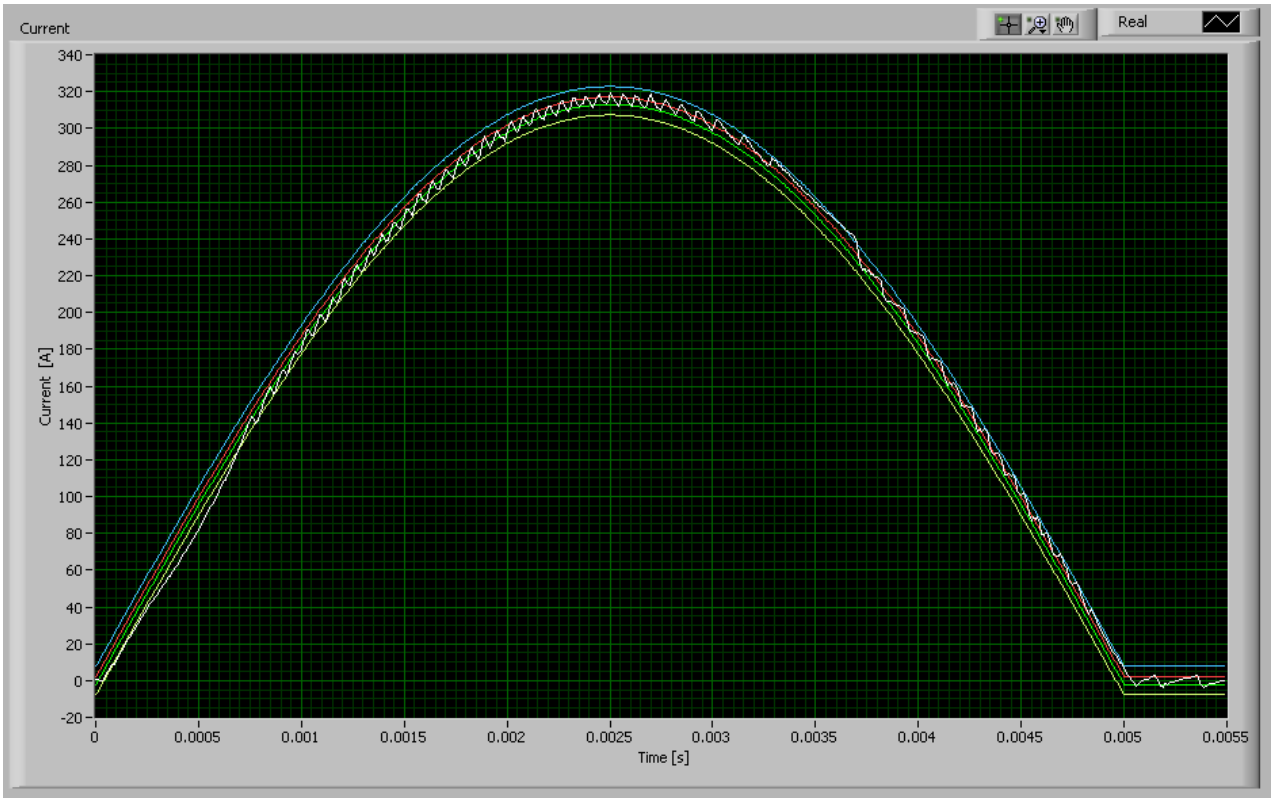
If the user wants to study the pulse that analyzed to get the data point in a surface there is a m-script that does that. When an interesting data point has been found the x and y values is entered in the script. The script finds the round containing that pulse and plots it. It also tells which of the pulse that is the interesting in the command window in MATLAB. The script is called peakCurrentPlotter.m and can be found in the attachment MATLAB code.

5 Results

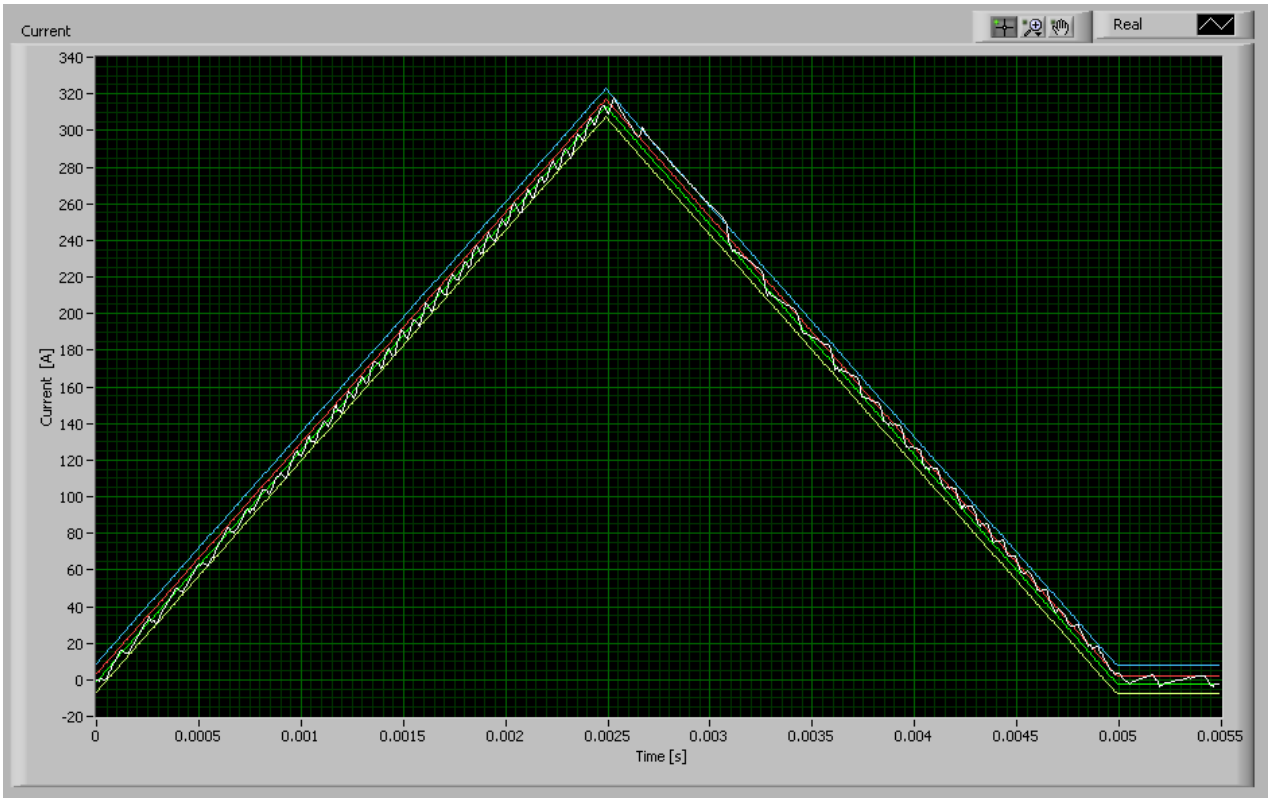
5.1 Current control

One of the objectives in this thesis was to develop a current controller for the flux providing coils. In order to facilitate the tuning of the controller the current is sampled by the cRIO and plotted on the front panel during the test shots. The same plot tool is used to show these results.

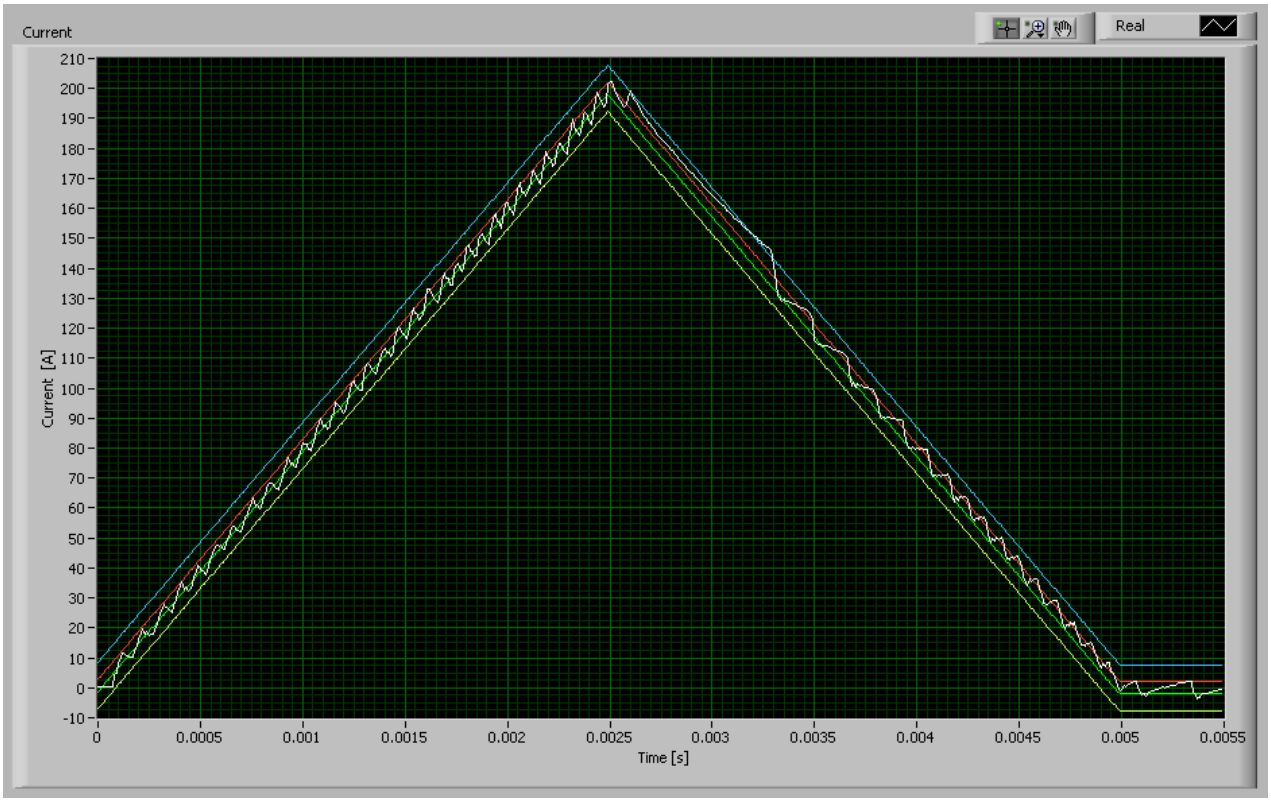
Several different currents were tested to show the performance. The results will begin with tests at the rated current for the machine, 315 A and then gradually decrease to 5 A. The tests at the rated current will be shown for both a half sinusoidal pulse and a triangular pulse while the rest of the currents only will be shown for triangular pulses. These results are shown in following eight graphs.



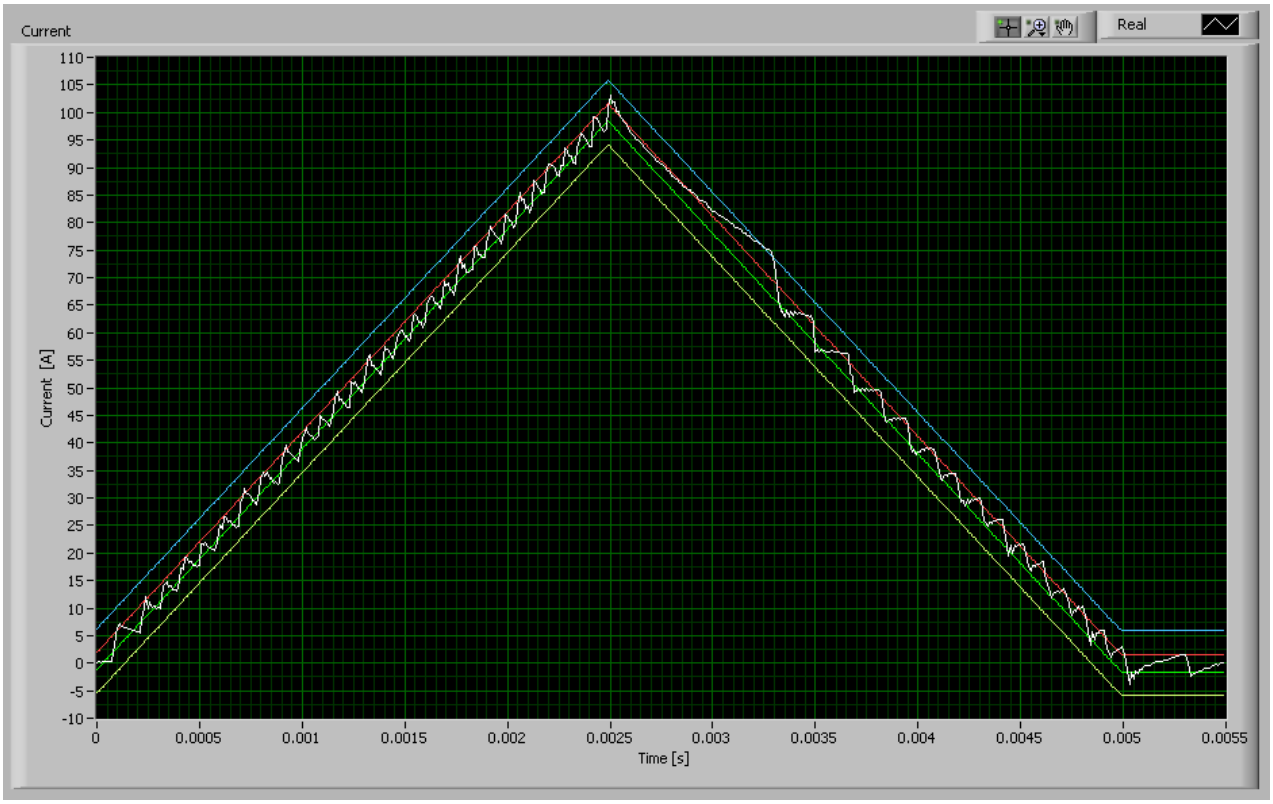
Graph 1: Current response for a sinusoidal reference with a peak value of 315 A



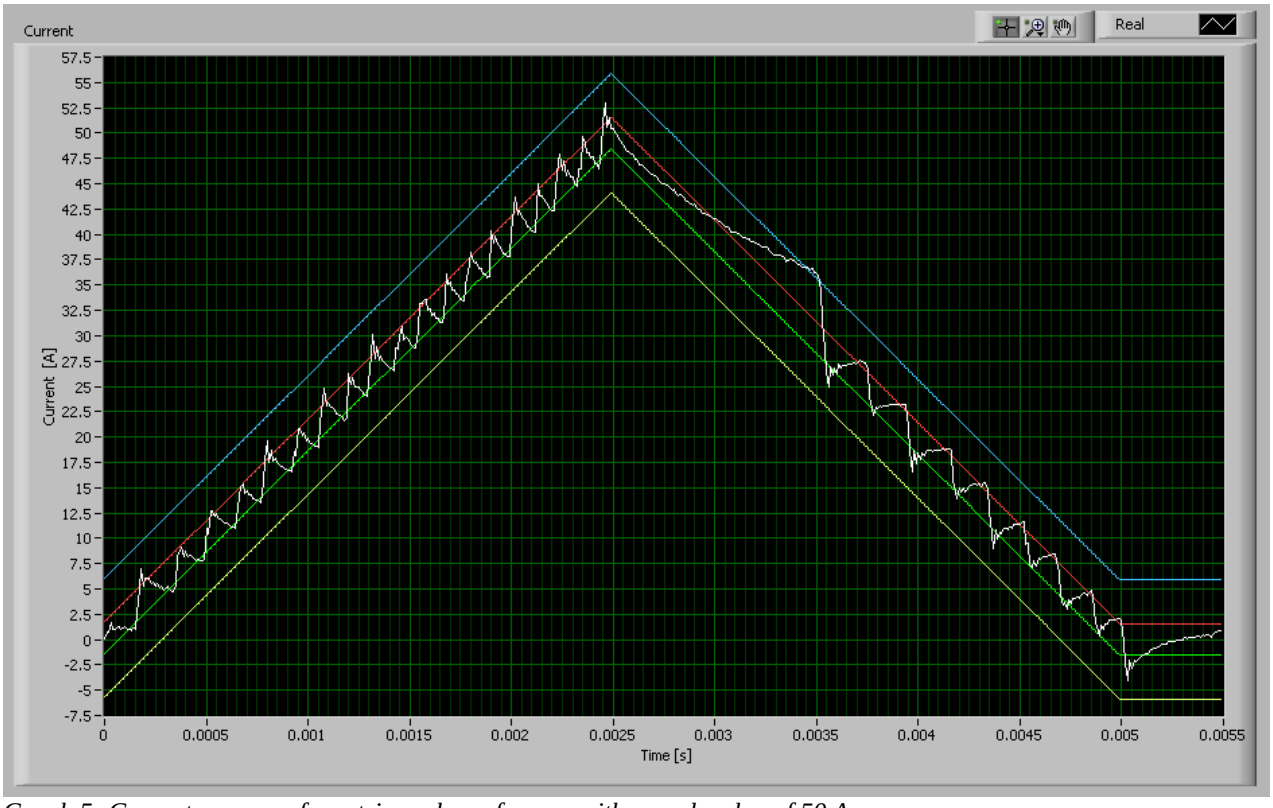
Graph 2: Current response for a triangular reference with a peak value of 315 A



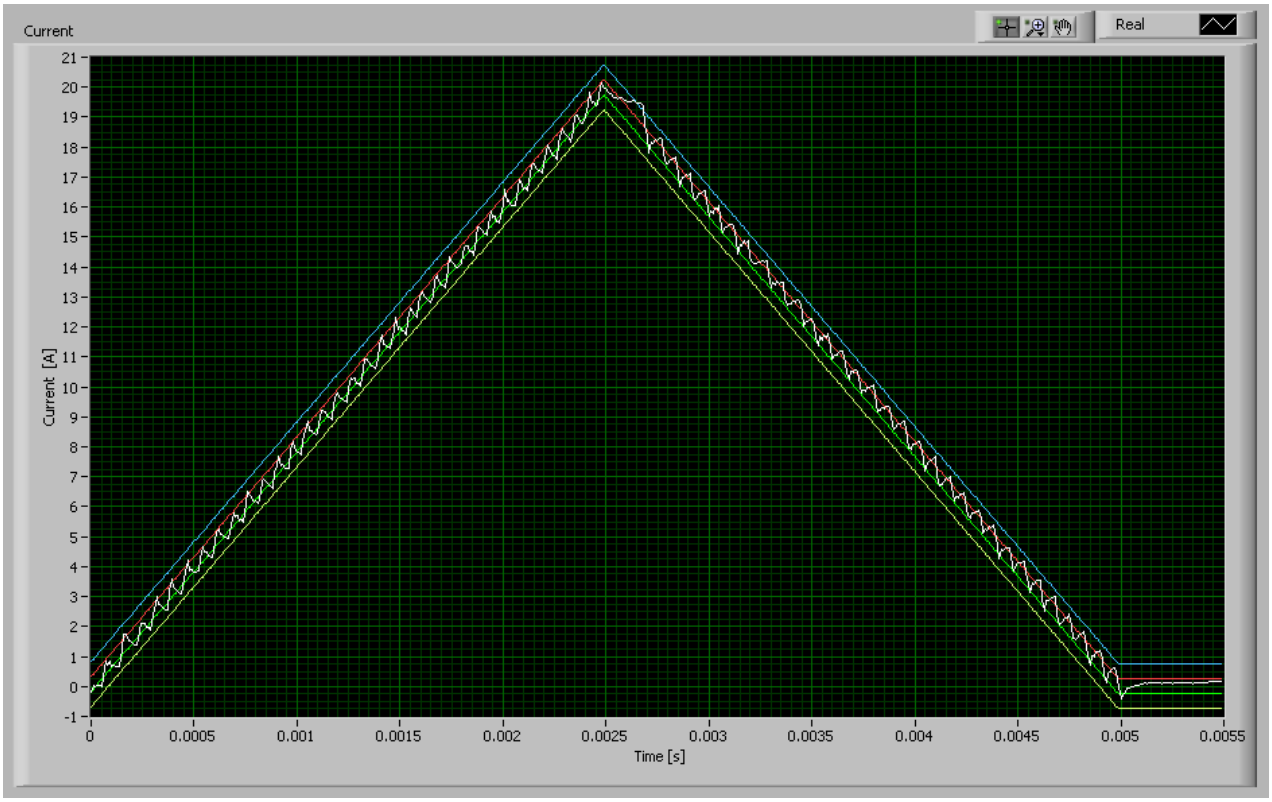
Graph 3: Current response for a triangular reference with a peak value of 200 A



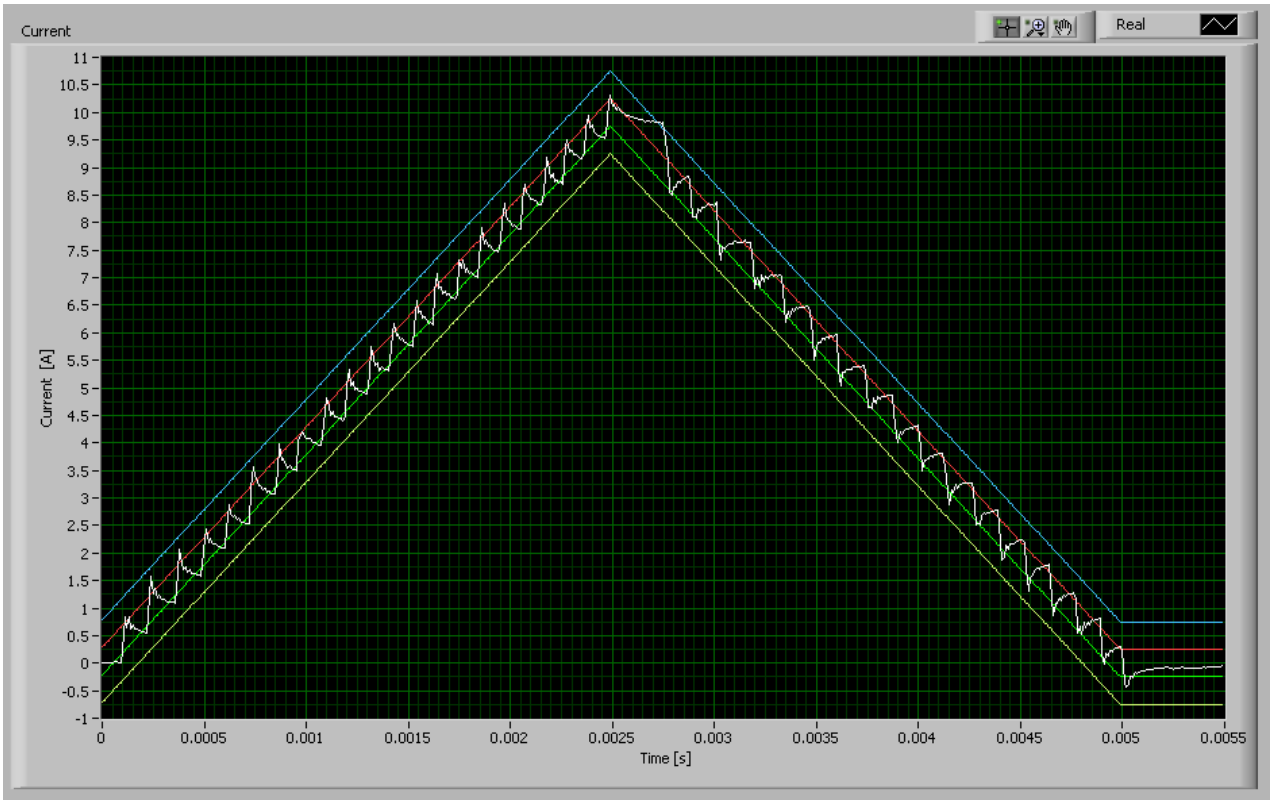
Graph 4: Current response for a triangular reference with a peak value of 100 A



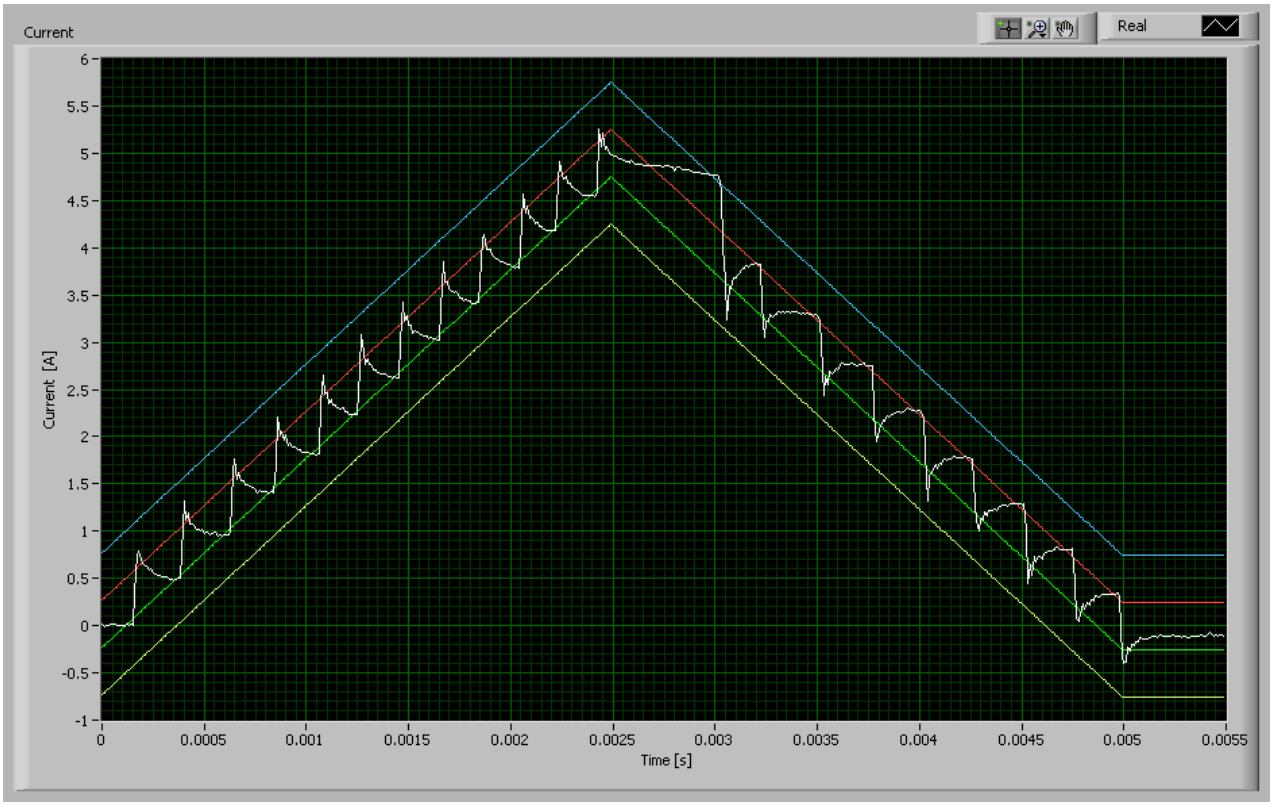
Graph 5: Current response for a triangular reference with a peak value of 50 A



Graph 6: Current response for a triangular reference with a peak value of 20 A

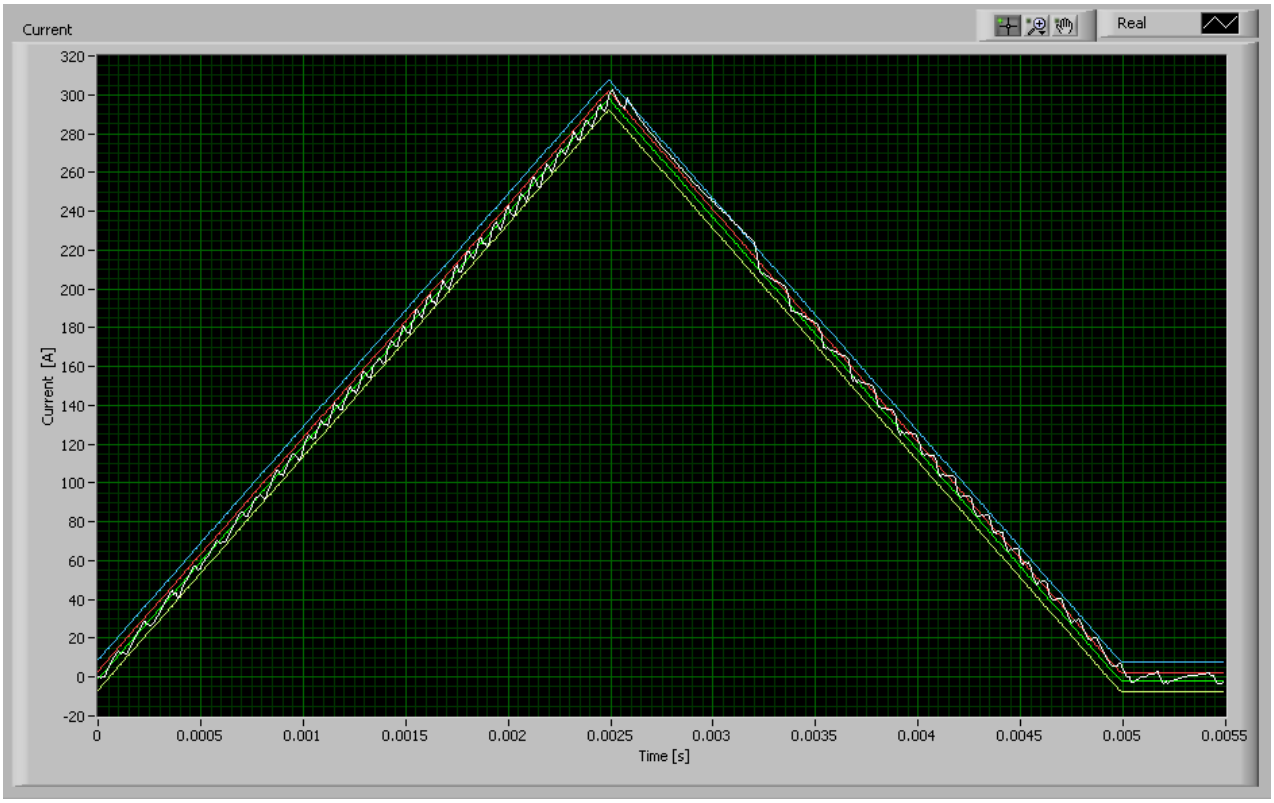


Graph 7: Current response for a triangular reference with a peak value of 10 A

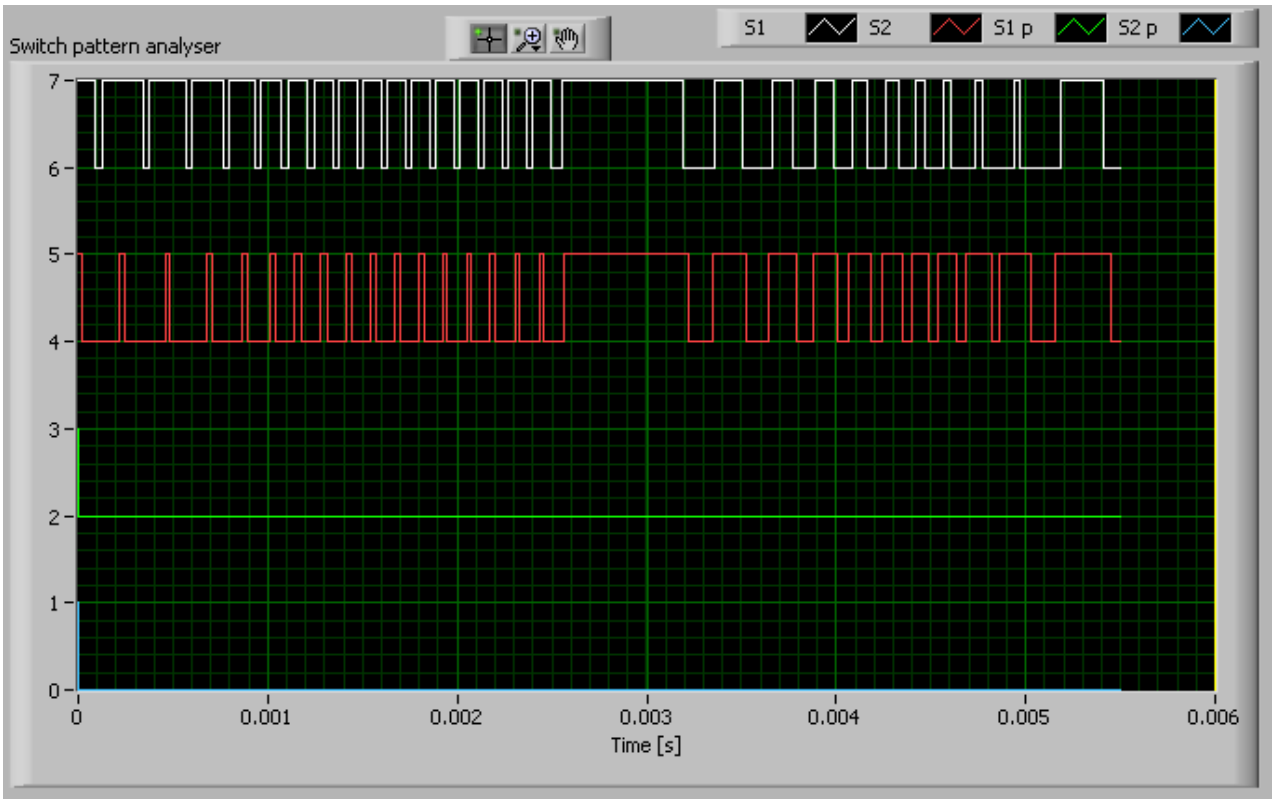


Graph 8: Current response for a triangular reference with a peak value of 5 A

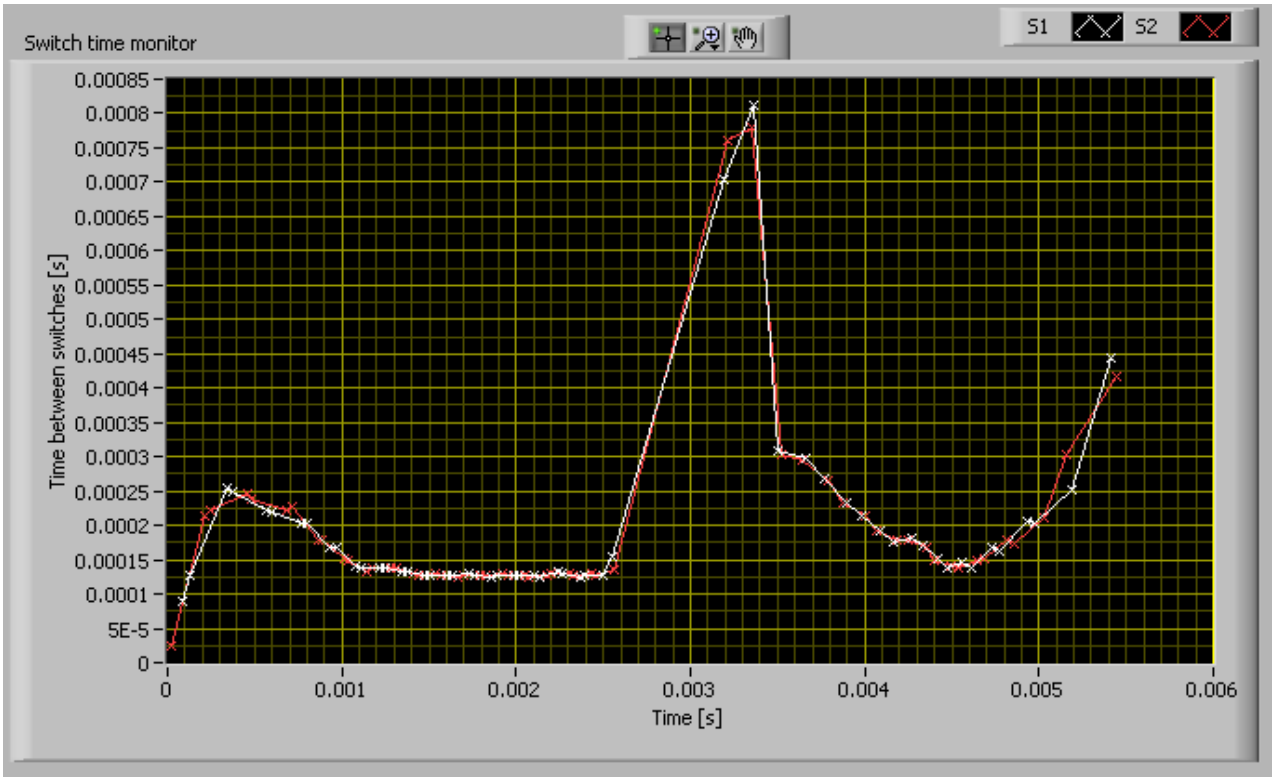
To show the work of the high frequency protection a current shot of 300 A is used, first with a correctly tuned controller and then with a controller where the tolerances is a little too small. There will be three graphs showing the result of each setting. The first one is the current response, as in the earlier graphs. The second graph is showing the switch pattern and the high frequency protection activity during the shot. The third graph is showing switch to switch time of each IGBT. These results of the correctly tuned controller are shown in the three graphs below.



Graph 9: Current response for a triangular reference with a peak value of 300 A, correctly tuned controller

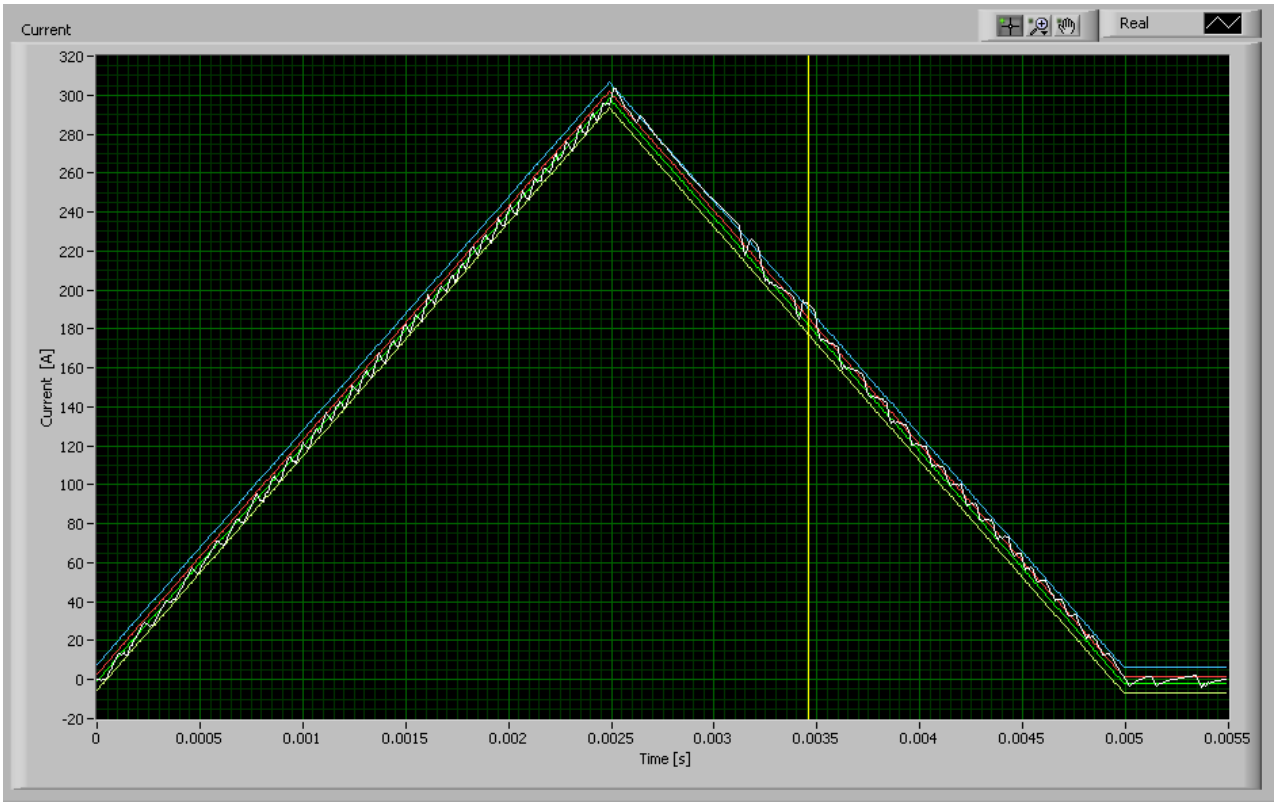


Graph 10: Switch pattern during the triangular pulse of 300 A, correctly tuned controller

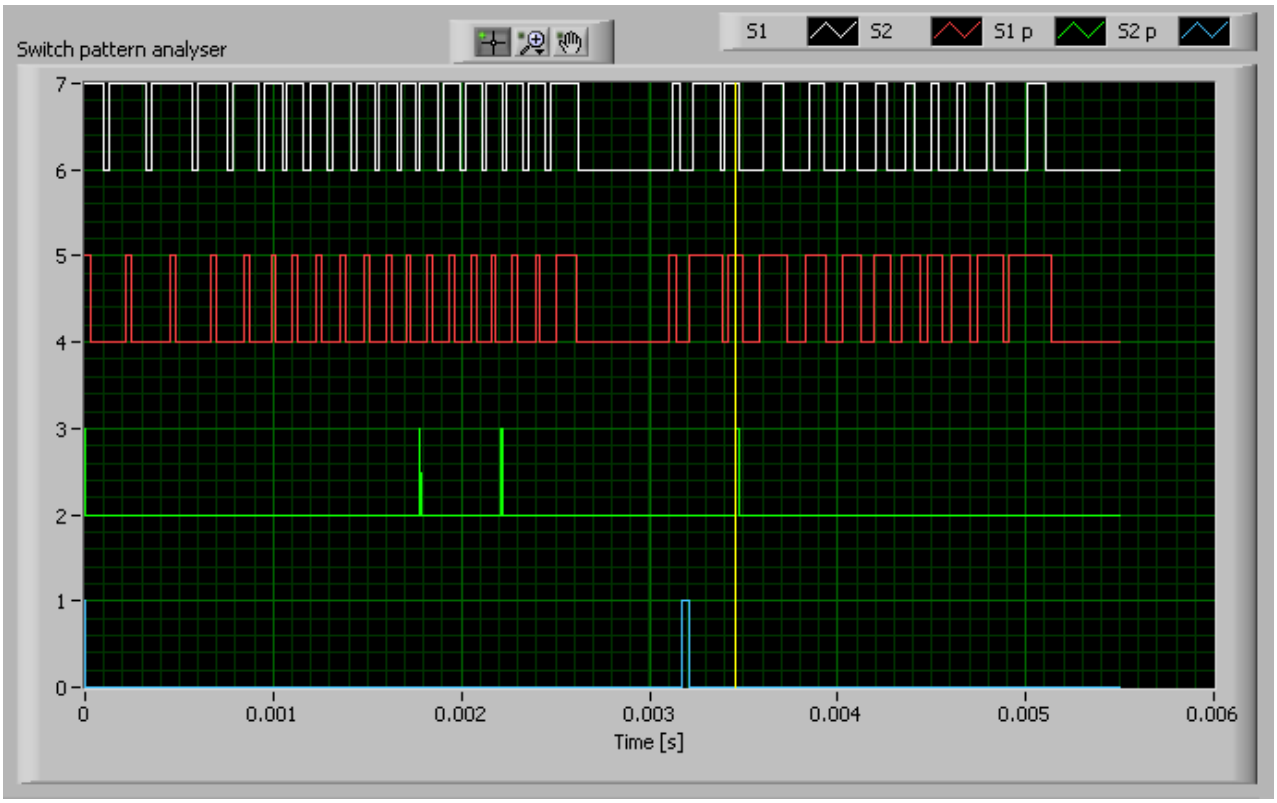


Graph 11: Switch times during the triangular pulse of 300 A, correctly tuned controller

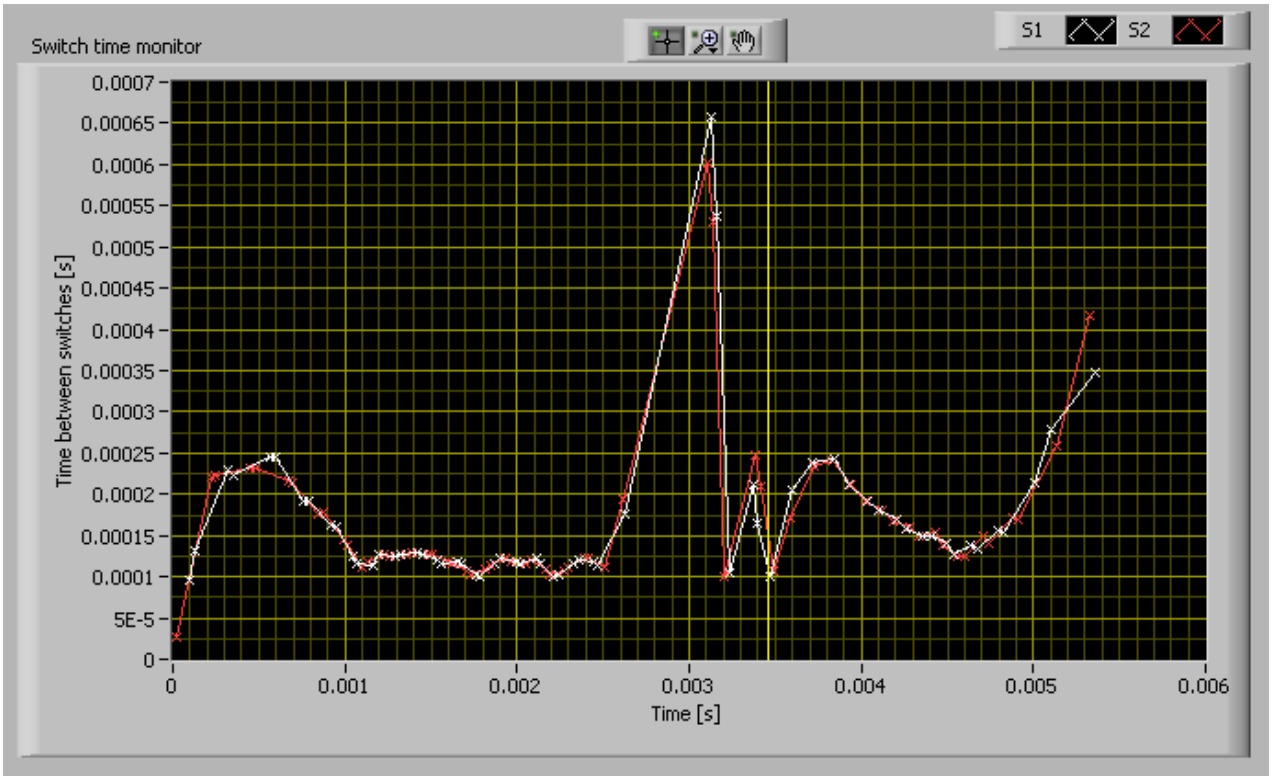
These next three graphs shows the behavior of controller where the tolerances are a little too tight. The interference of the high frequency protection are shown by the two lower lines in the switch pattern graph.



Graph 12: Current response for a triangular reference with a peak value of 300 A, incorrectly tuned controller

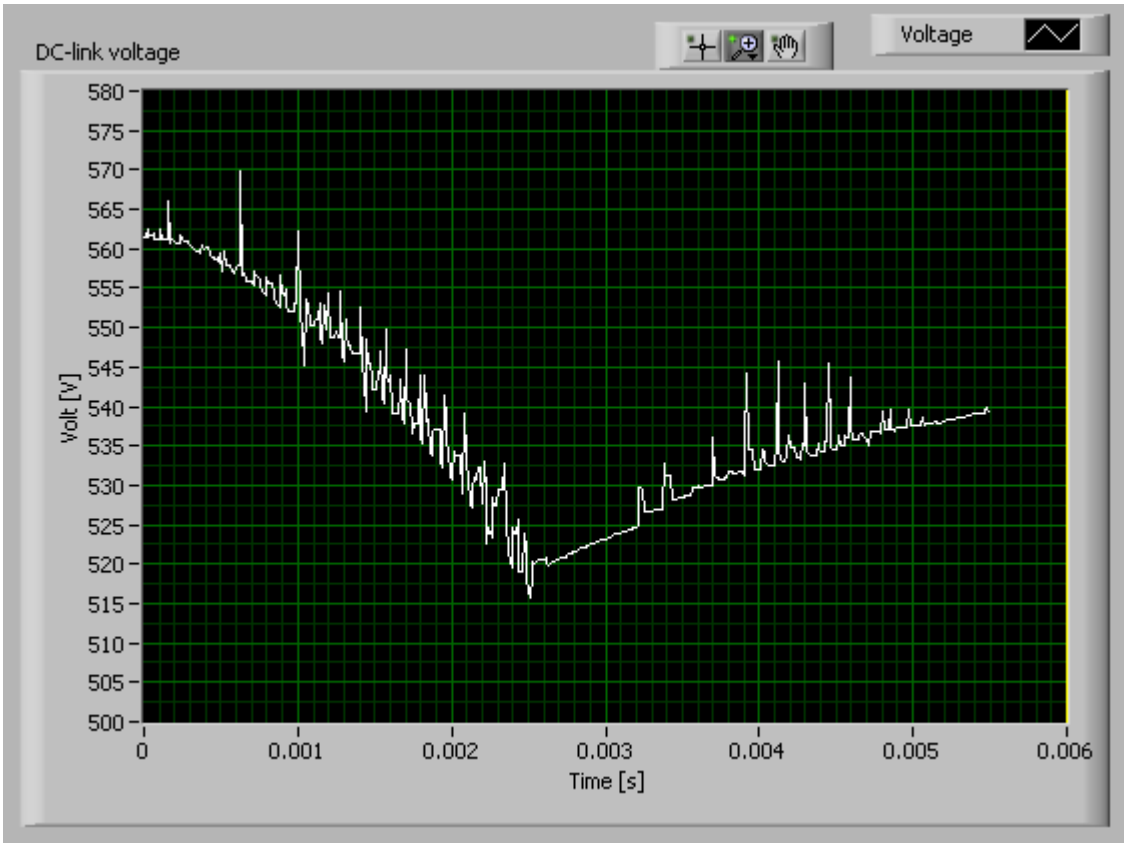


Graph 13: Switch pattern during the triangular pulse of 300 A, incorrectly tuned controller



Graph 14: Switch times during the triangular pulse of 300 A, incorrectly tuned controller

At last a graph showing the DC link voltage during a 300 *A* triangular current shot is shown in the graph below.



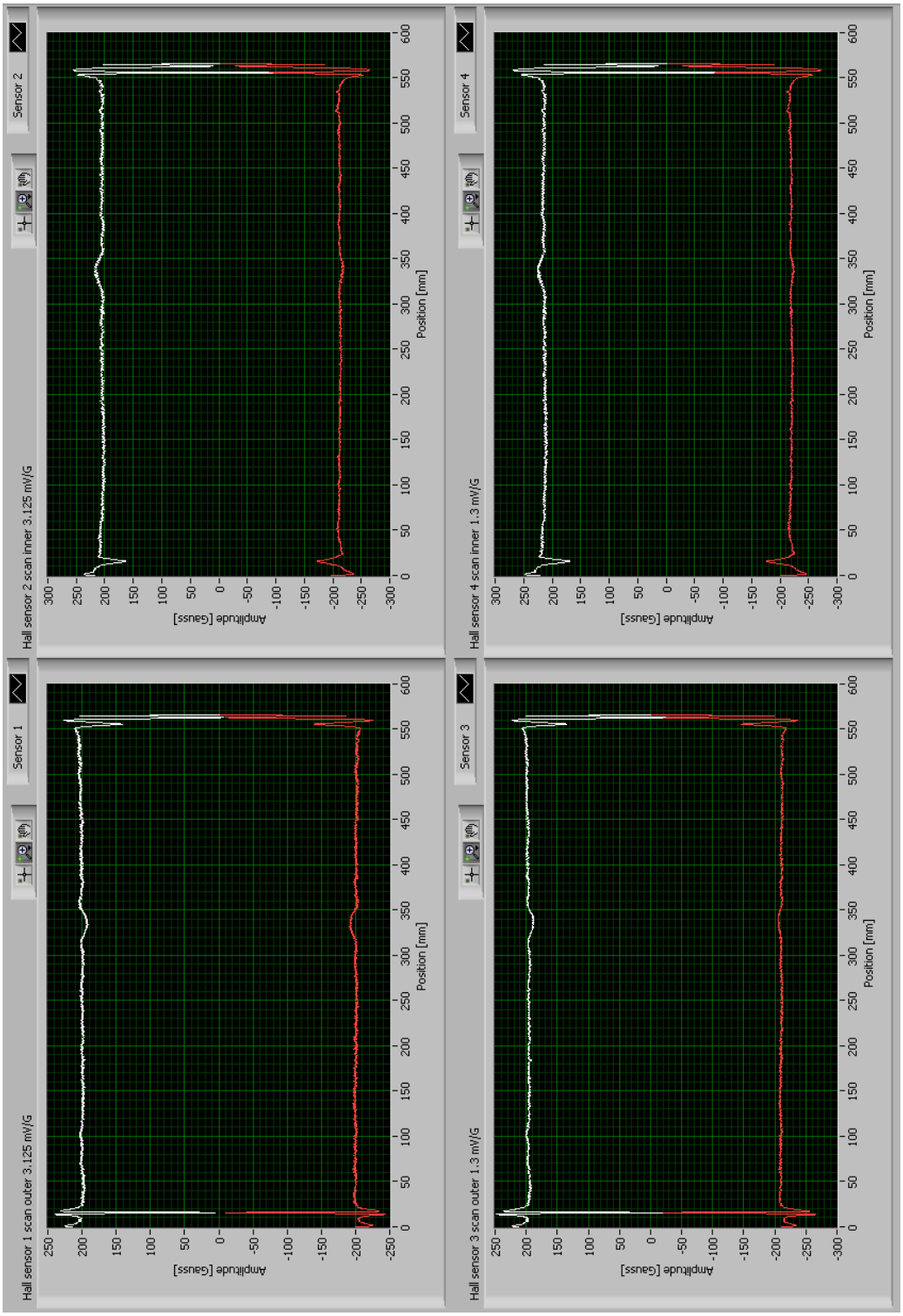
Graph 15: DC link voltage during the triangular pulse of 300 A

5.2 Magnetizing performance

As mentioned, the magnetizing performance of the machine was tested. These tests were focused on the ability to magnetize small spots of the magnet band. The studied parameters were the peak magnetization and the spread around the magnetization peak, called magnetization width. These parameters were studied as a function of different current magnitudes, shapes and different pulse times. There will also be some graphs on some of the accomplished magnetizing pulses.

5.2.1 Reset results

To make these tests possible the band was restored to fairly uniform magnetization every time all positions of the band were used. The method of this restoration, called *reset* in the program was found by trial and error, and the result is shown in reset result below.

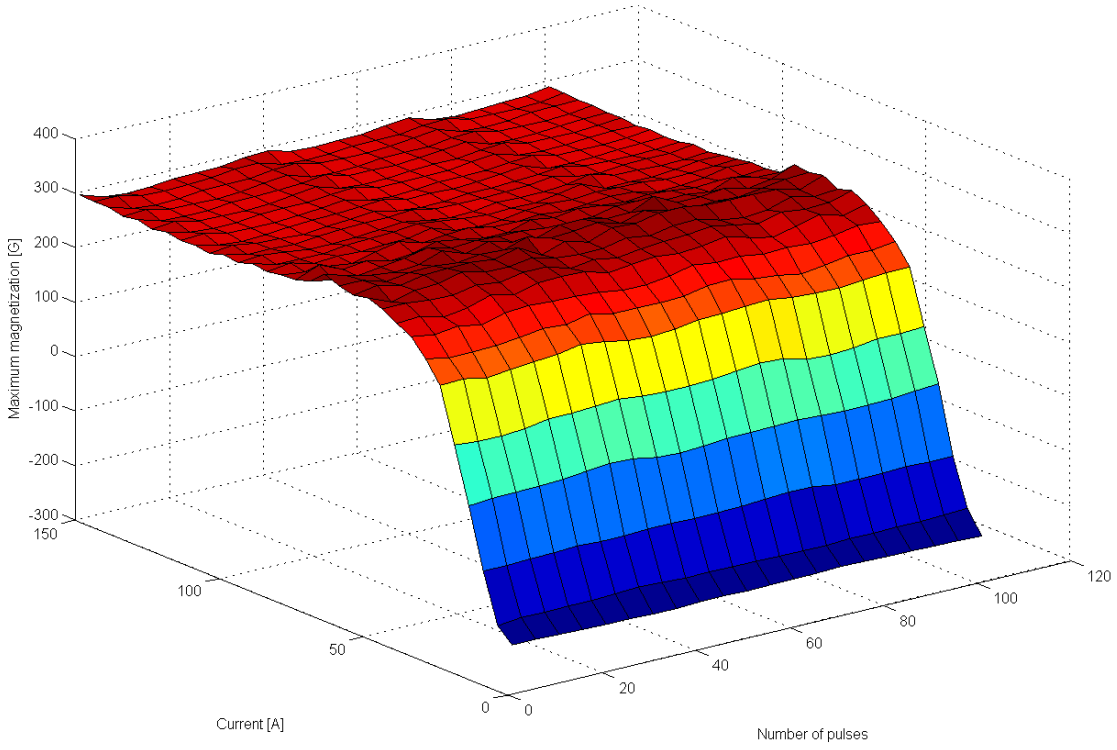


Reset result

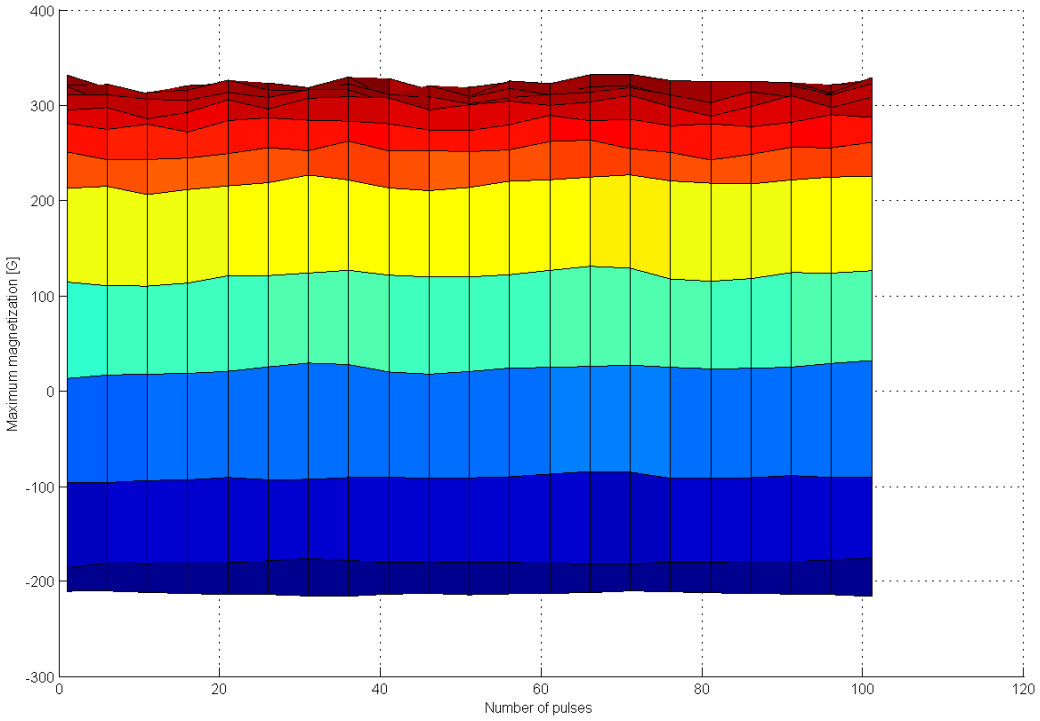
5.2.2 Surfaces

For each set of settings there are two different surfaces showing the peak magnetization respectively the magnetization width and all surfaces is shown in three different angles

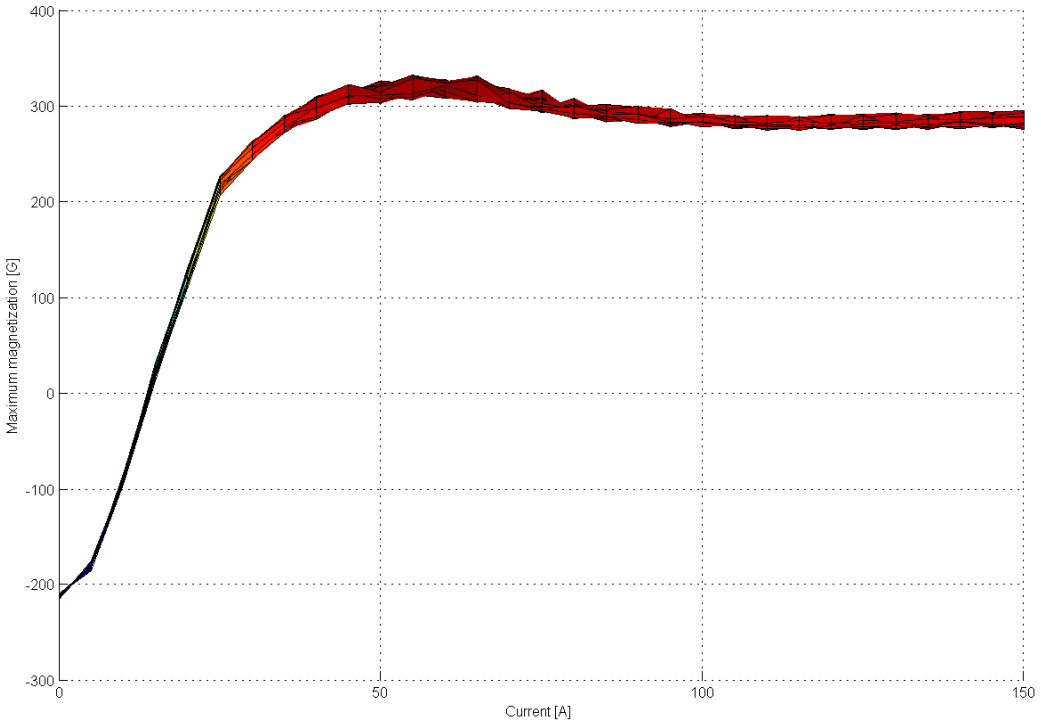
To begin with two measurements with identical settings, except for the pulse shape was made. The first measurement is done with half sinusoidal pulses and the second is made with triangular pulses. The current is starting a 0 A and is increasing by 5 up to 150 A. The number of pulses is starting at 1 pulse and is increasing by 5 up to 101 pulses. The pulse time is fixed to 5 *ms*. The resulting surfaces for the half sinusoidal current pulses are shown in the six surfaces below.



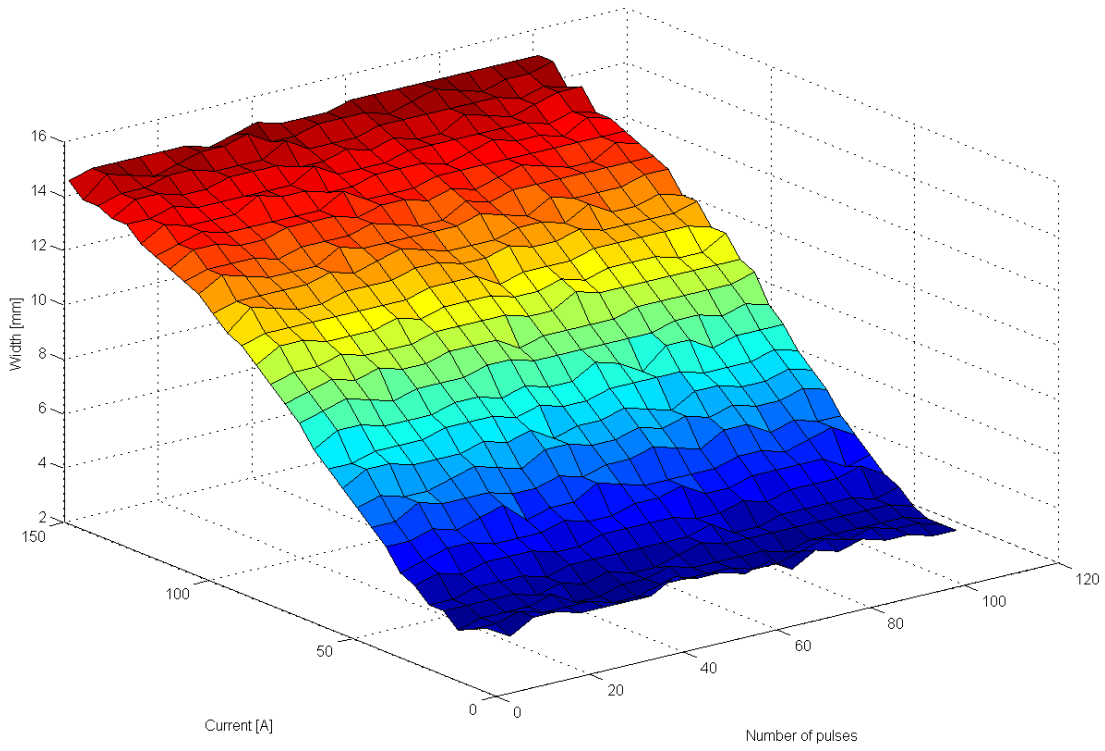
Surface 1: Peak magnetization with half sinusoidal shaped current pulses and with pulse time fixed to 5 ms



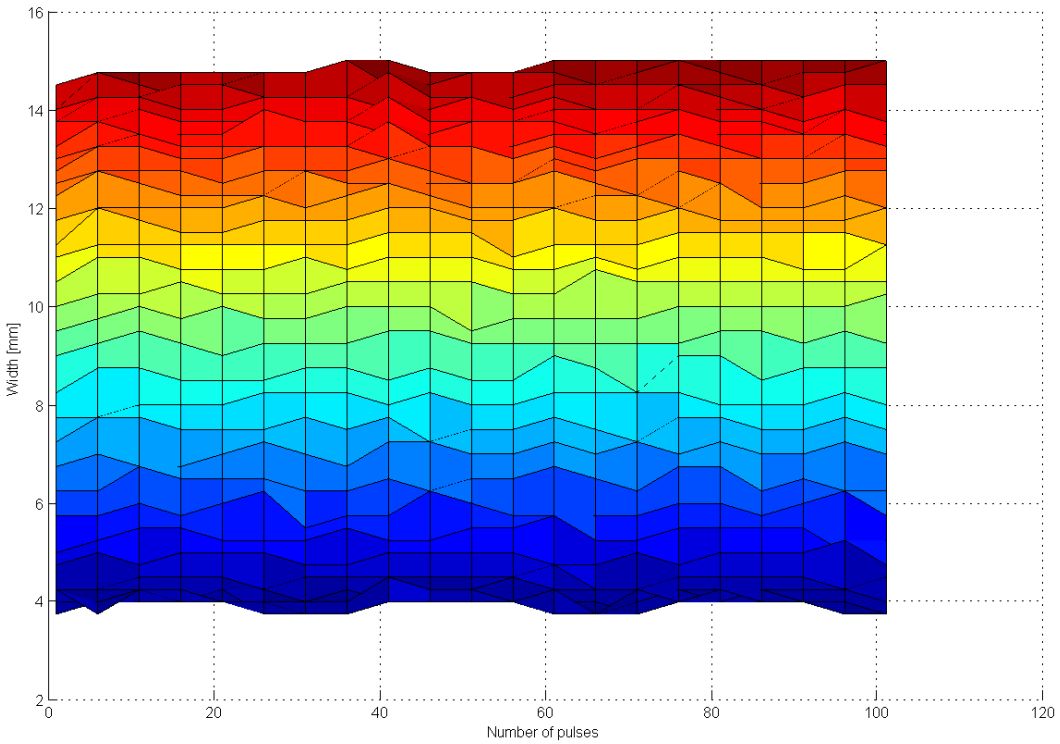
Surface 2: Peak magnetization with half sinusoidal shaped current pulses and with pulse time fixed to 5 ms. Seen from the front



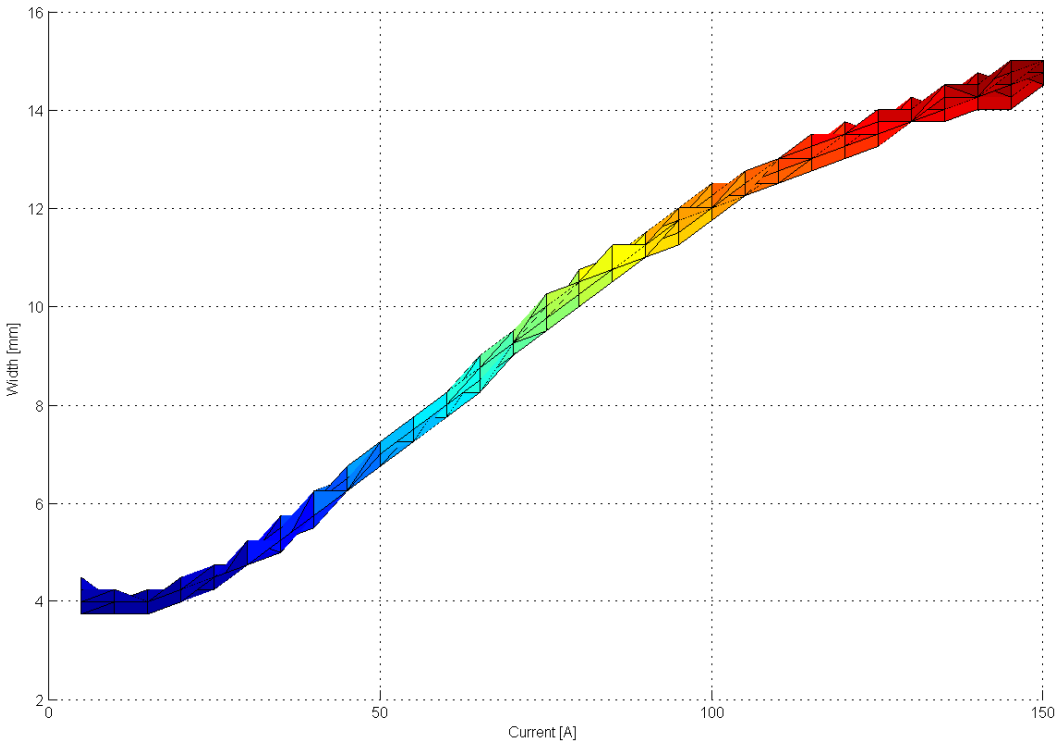
Surface 3: Peak magnetization with half sinusoidal shaped current pulses and with pulse time fixed to 5 ms. Seen from the right



Surface 4: Pulse width with half sinusoidal shaped current pulses and with pulse time fixed to 5 ms

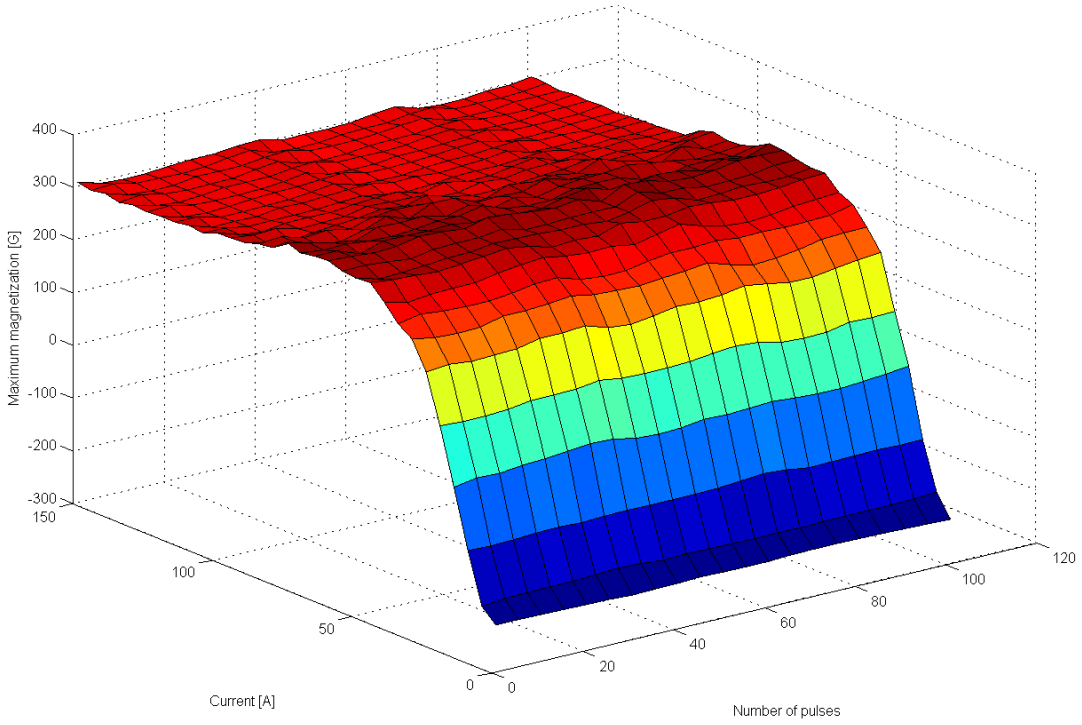


Surface 5: Pulse width with half sinusoidal shaped current pulses and with pulse time fixed to 5 ms. Seen from the front

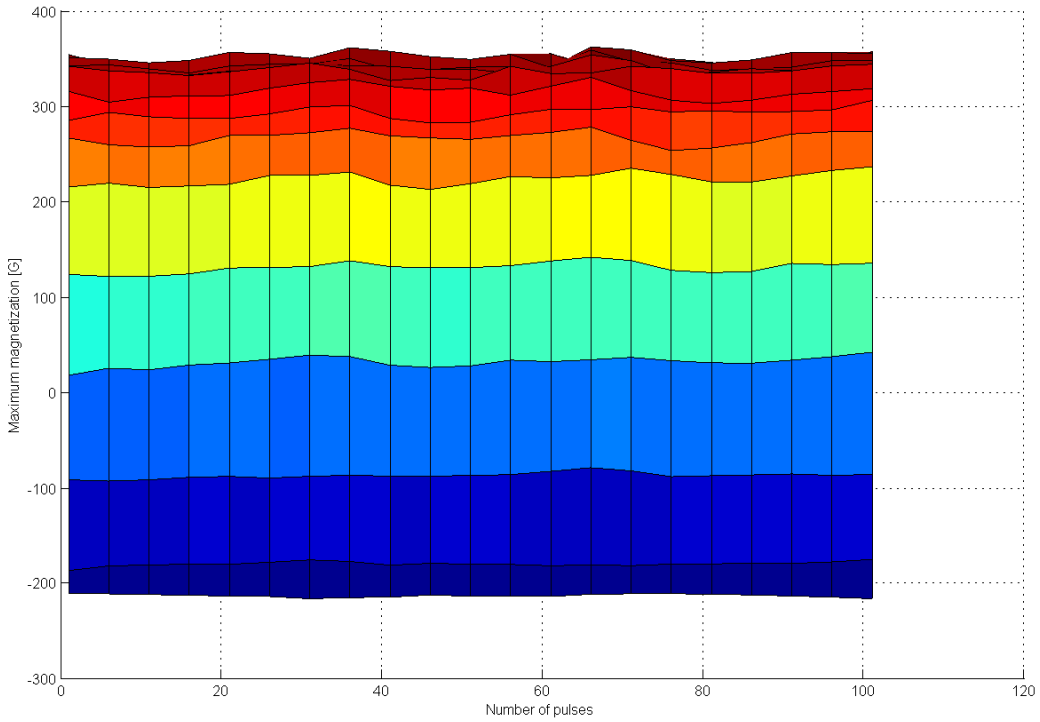


Surface 6: Pulse width with half sinusoidal shaped current pulses and with pulse time fixed to 5 ms. Seen from the right

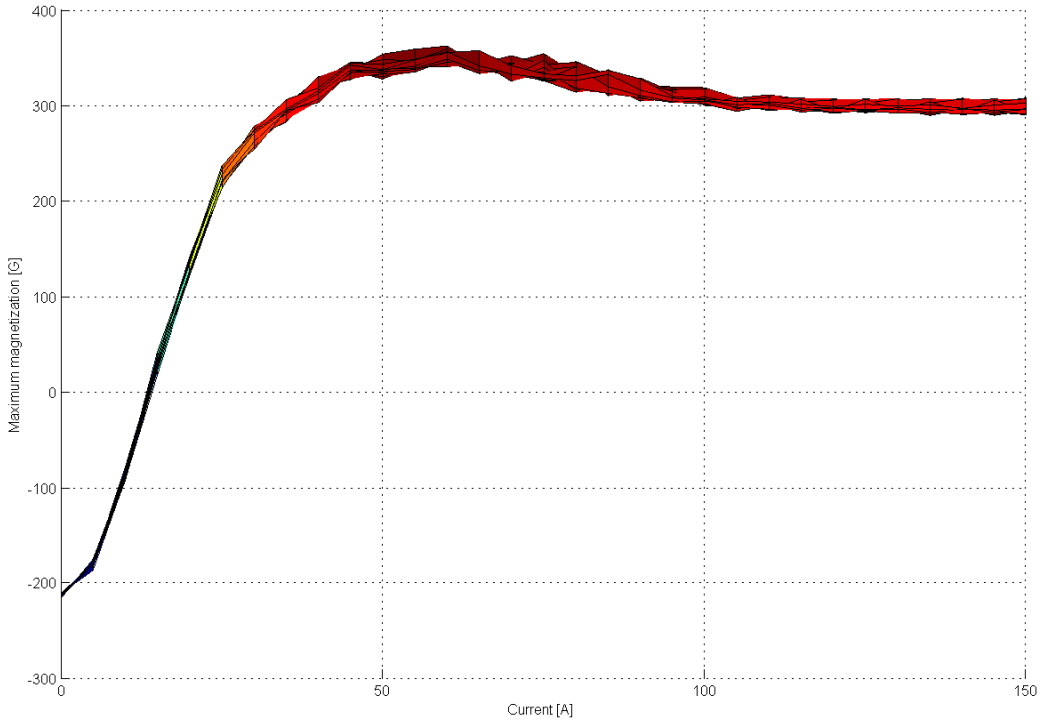
The resulting surfaces for the triangular current pulses are shown in the six surfaces below.



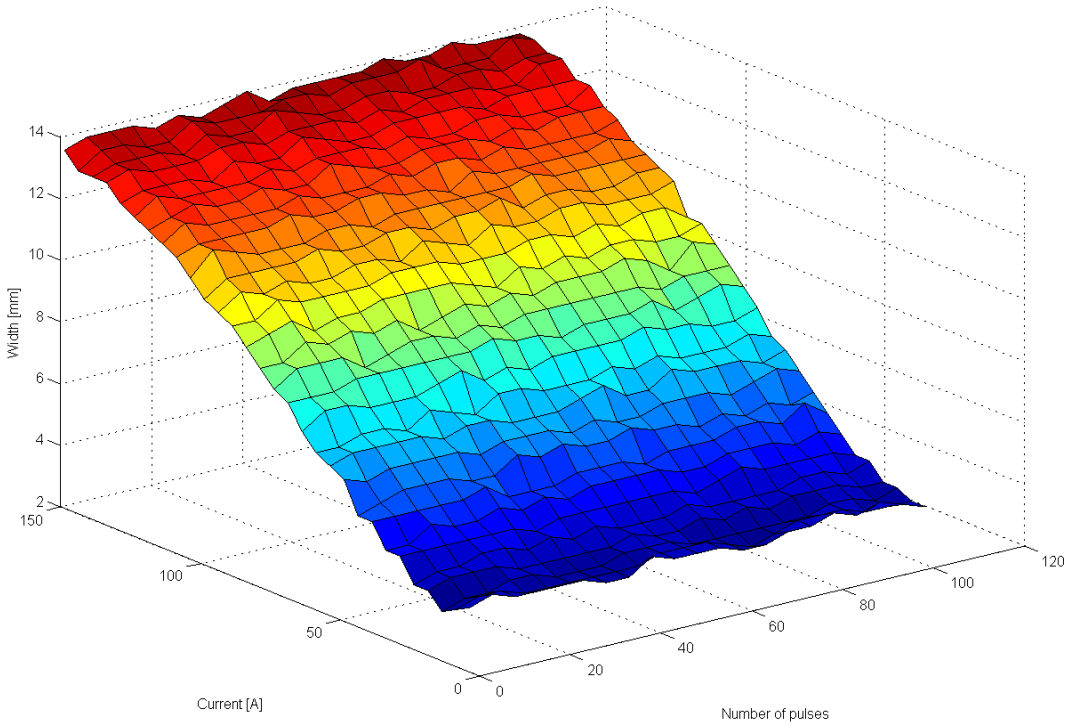
Surface 7: Peak magnetization with triangular shaped current pulses and with pulse time fixed to 5 ms



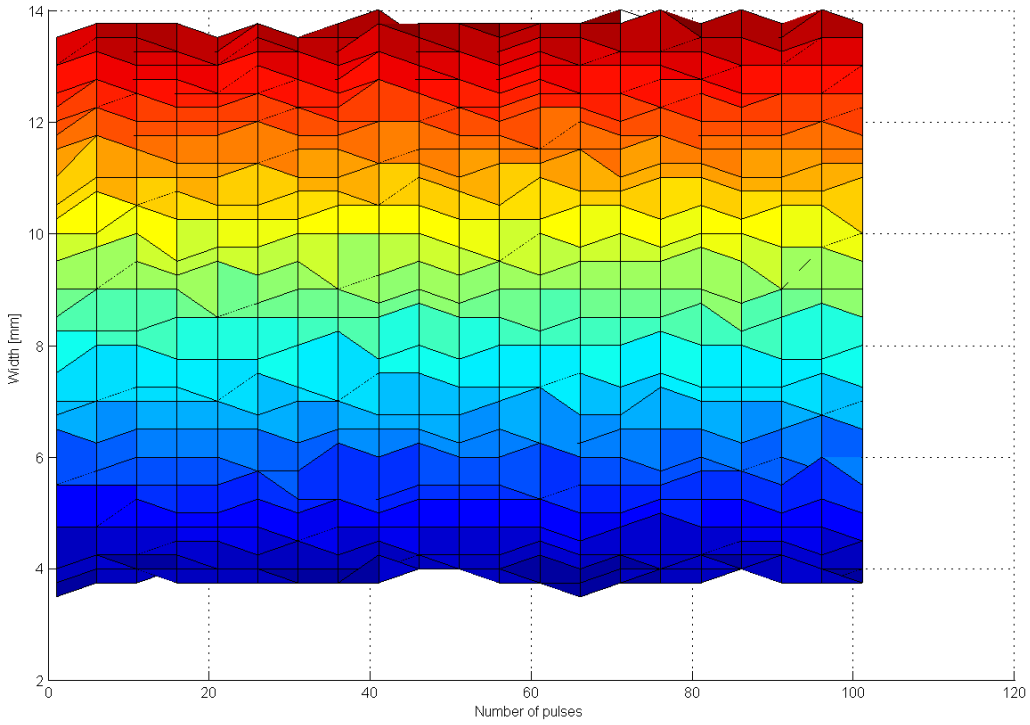
Surface 8: Peak magnetization with triangular shaped current pulses and with pulse time fixed to 5 ms. Seen from



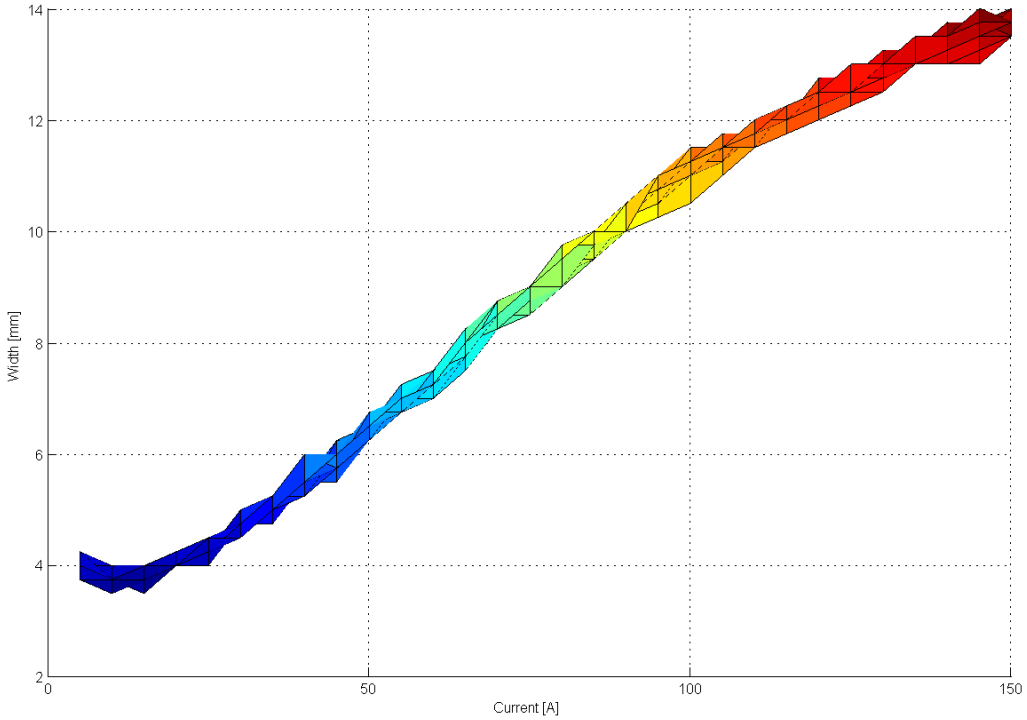
Surface 9: Peak magnetization with triangular shaped current pulses and with pulse time fixed to 5 ms. Seen from the right



Surface 10: Pulse width with triangular shaped current pulses and with pulse time fixed to 5 ms

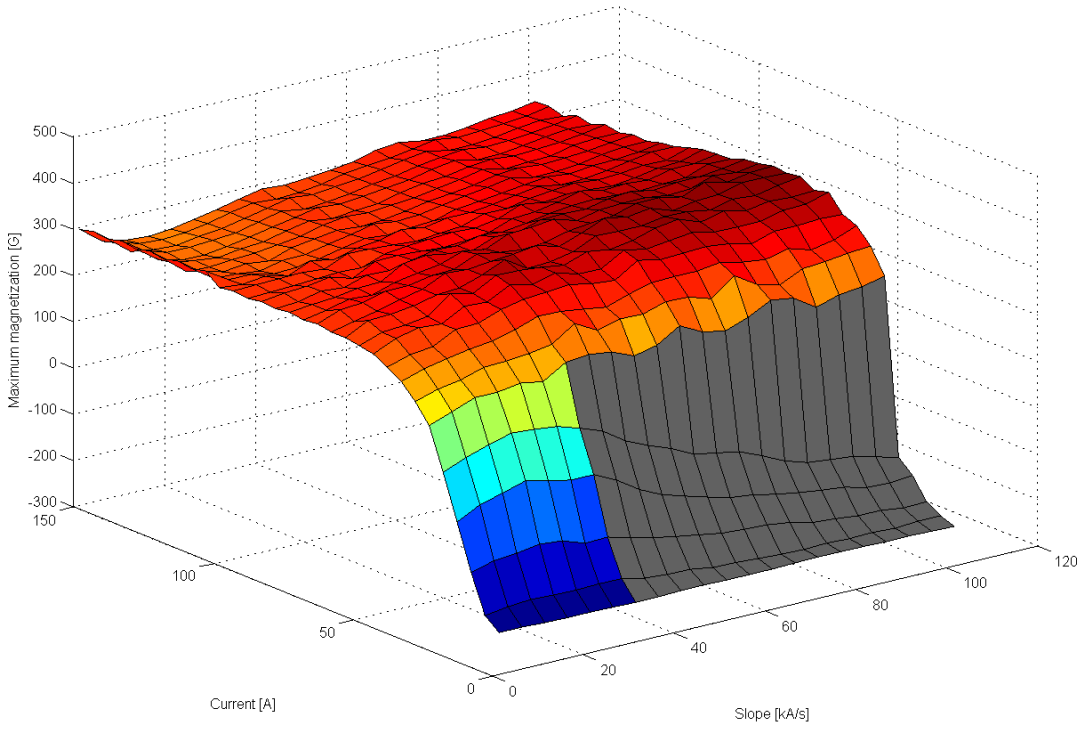


Surface 11: Pulse width with triangular shaped current pulses and with pulse time fixed to 5 ms. Seen from the front

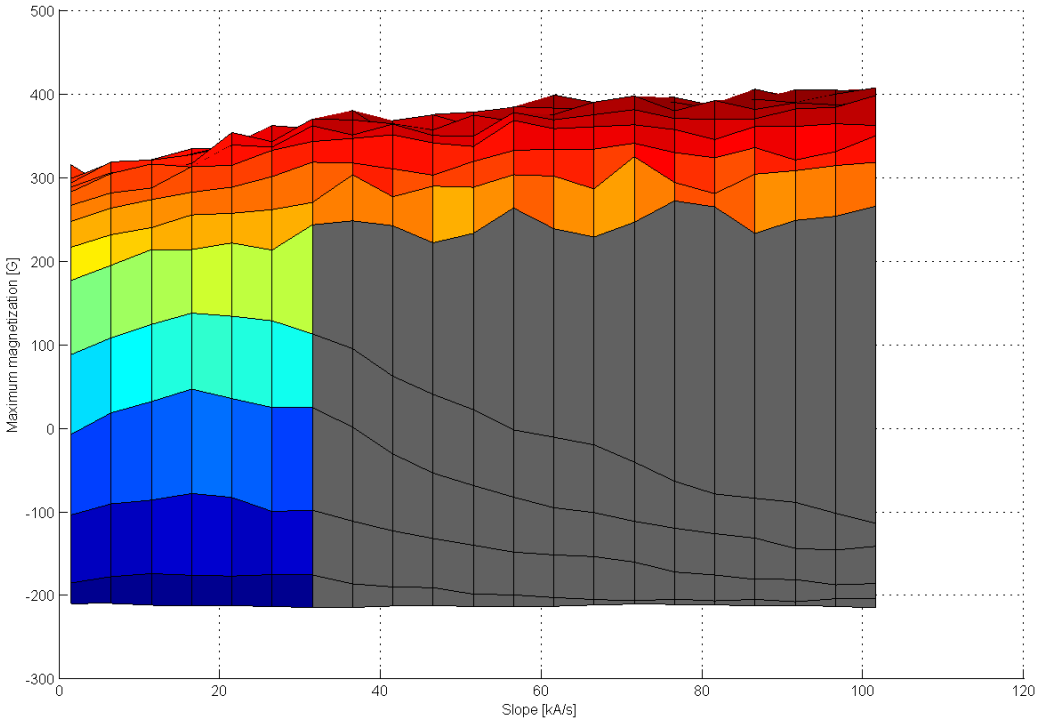


Surface 12: Pulse width with triangular shaped current pulses and with pulse time fixed to 5 ms. Seen from the right

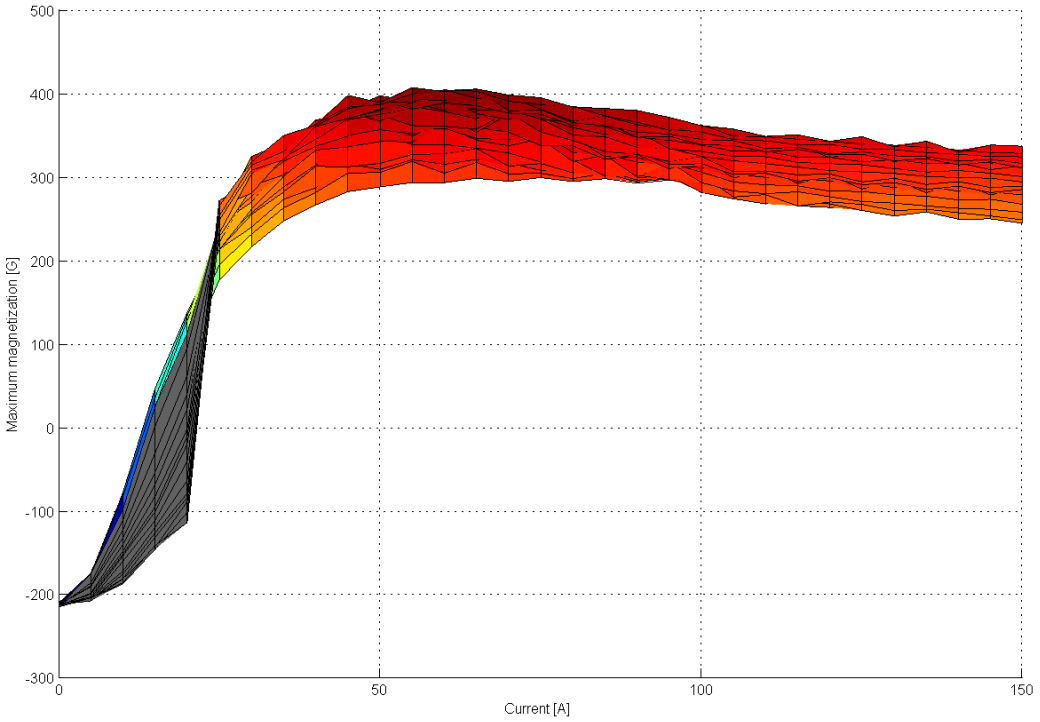
The last measurement was made in a different way. Triangular pulses with the same current magnitudes were used. But this time the pulse time was altered in correlation to the current magnitude to obtain a constant slope of the triangular shape. Hence the axis earlier used for number of pulses was used for current slope instead, and only one current pulse was shot. The current slope was varied from $1{,}5kA/s$ to $101{,}5kA/s$ in steps of $5kA/s$. The resulting surfaces six surface in presented below. A piece of each of these surfaces is grayed to show were the requested current slope could not be maintained due to the request of current magnitude.



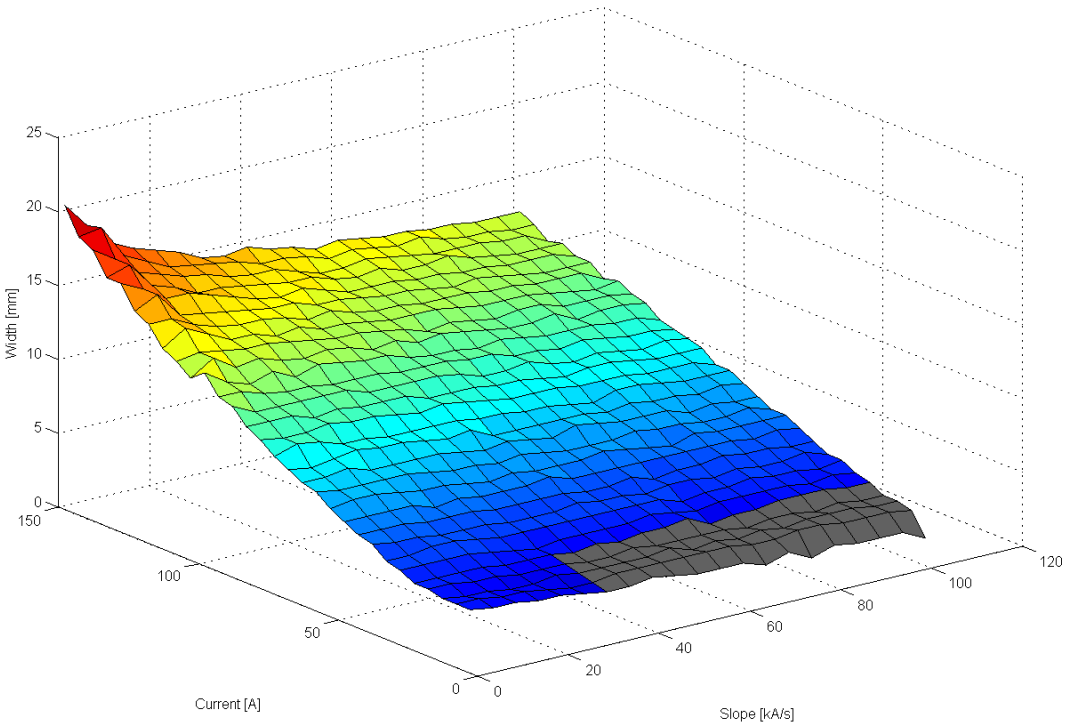
Surface 13: Peak magnetization with triangular shaped current pulses with varied pulse time to obtain current slopes according to the slope axis



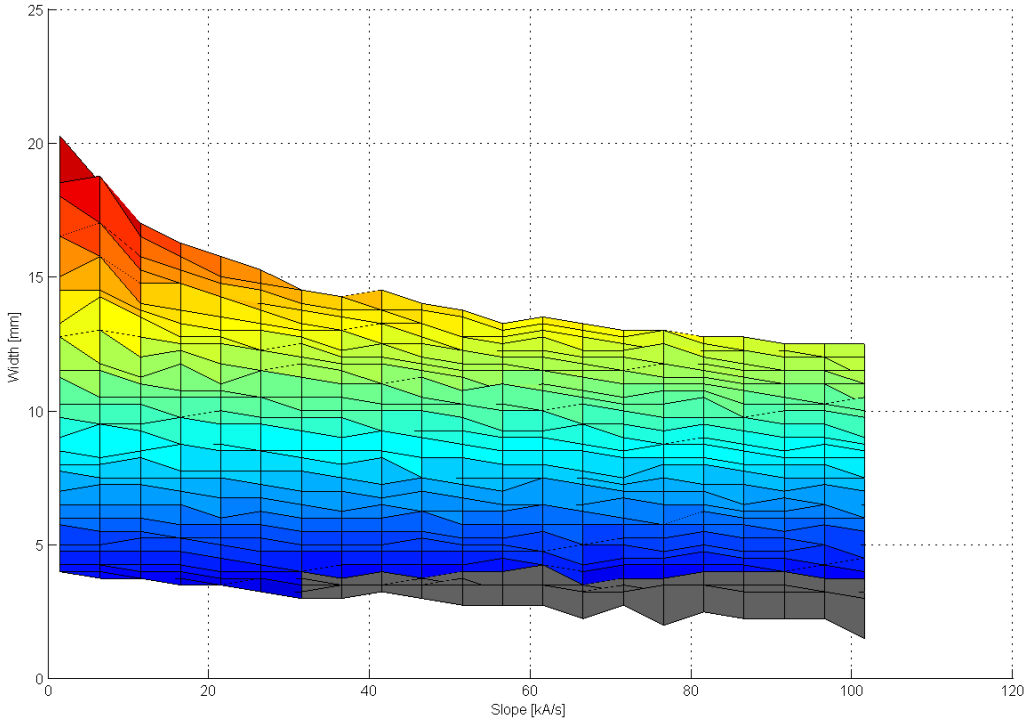
Surface 14: Peak magnetization with triangular shaped current pulses with varied pulse time to obtain current slopes according to the slope axis. Seen from the front



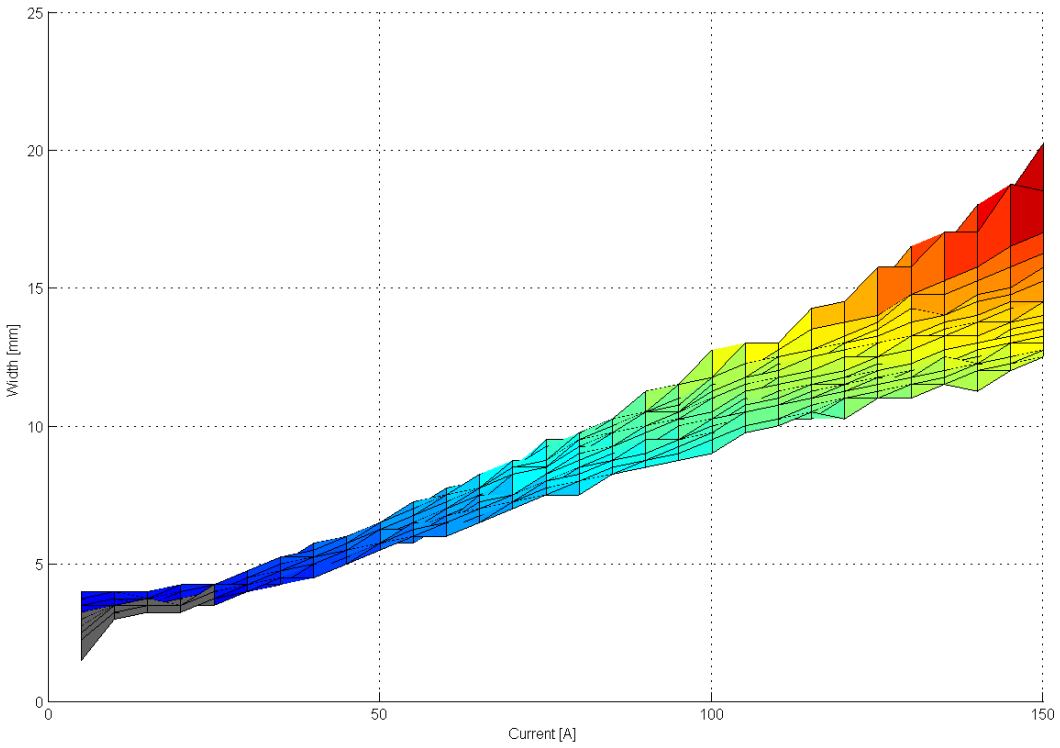
Surface 15: Peak magnetization with triangular shaped current pulses with varied pulse time to obtain current slopes according to the slope axis. Seen from the right



Surface 16: Pulse width with triangular shaped current pulses with varied pulse time to obtain current slopes according to the slope axis

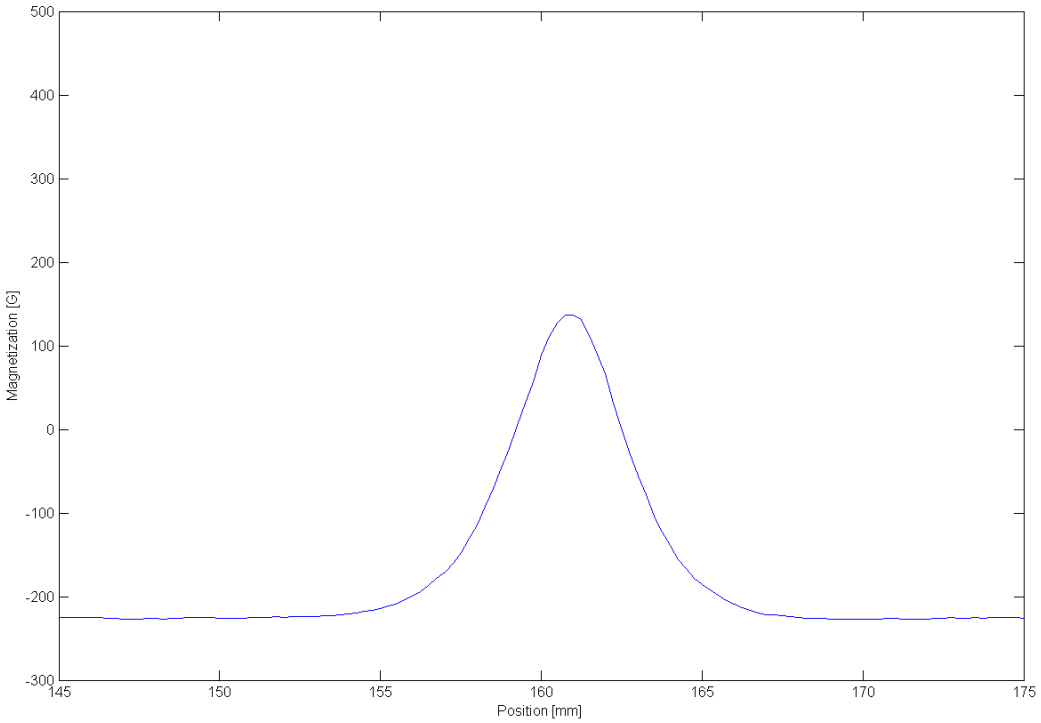


Surface 17: Pulse width with triangular shaped current pulses with varied pulse time to obtain current slopes according to the slope axis. Seen from the front

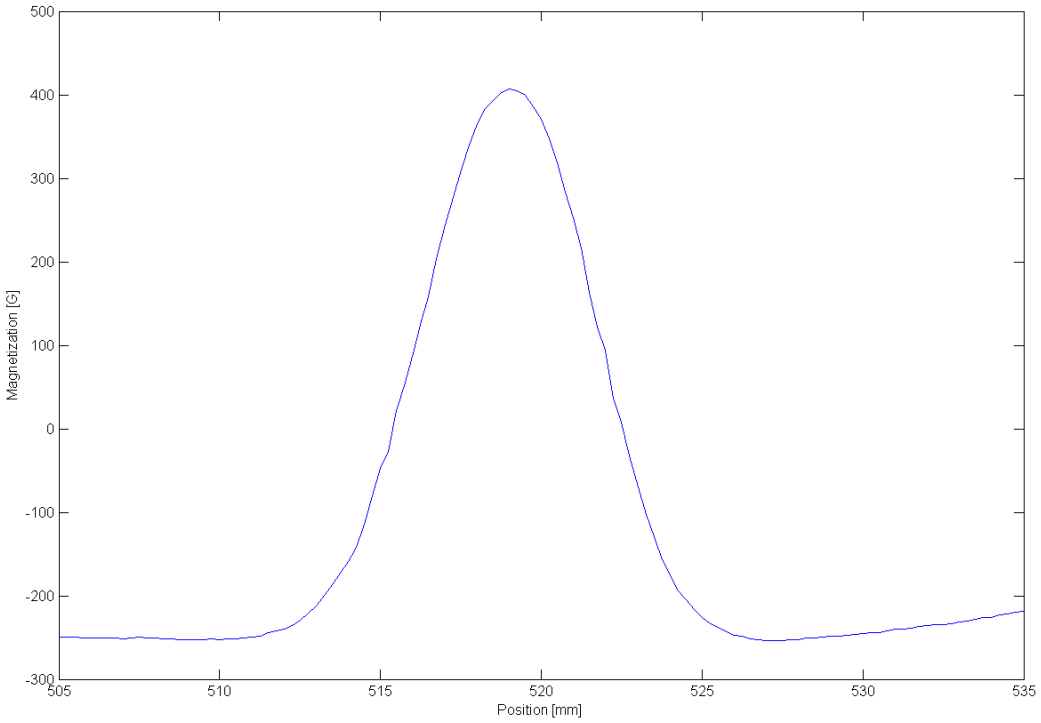


Surface 18: Pulse width with triangular shaped current pulses with varied pulse time to obtain current slopes according to the slope axis. Seen from the right

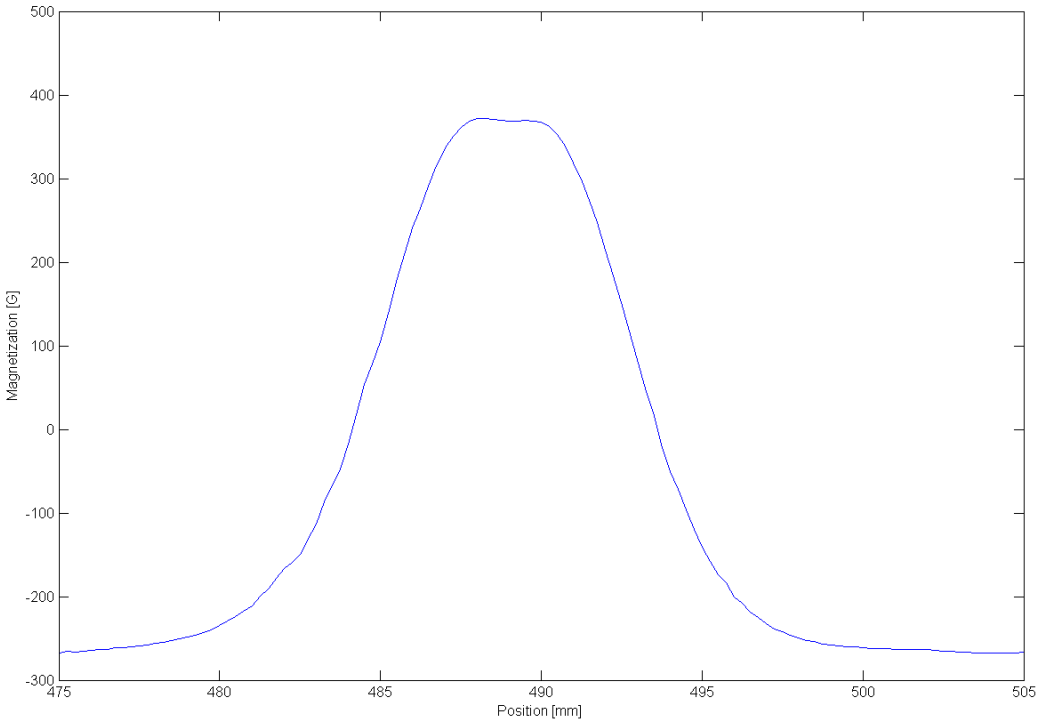
To facilitate an attempt to explain the shapes of these surfaces here are six pictures on carefully selected magnetizing pulses.



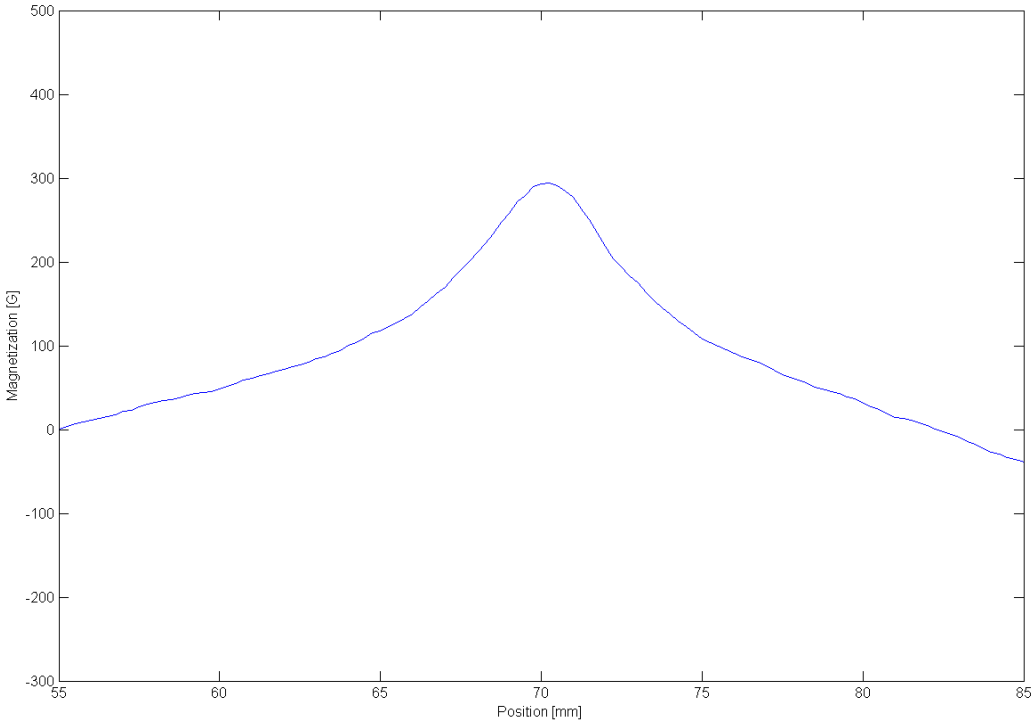
Pulse 1: The accomplished magnetization of triangular pulse with an amplitude of 20 A and a current slope of 16,5 kA/s



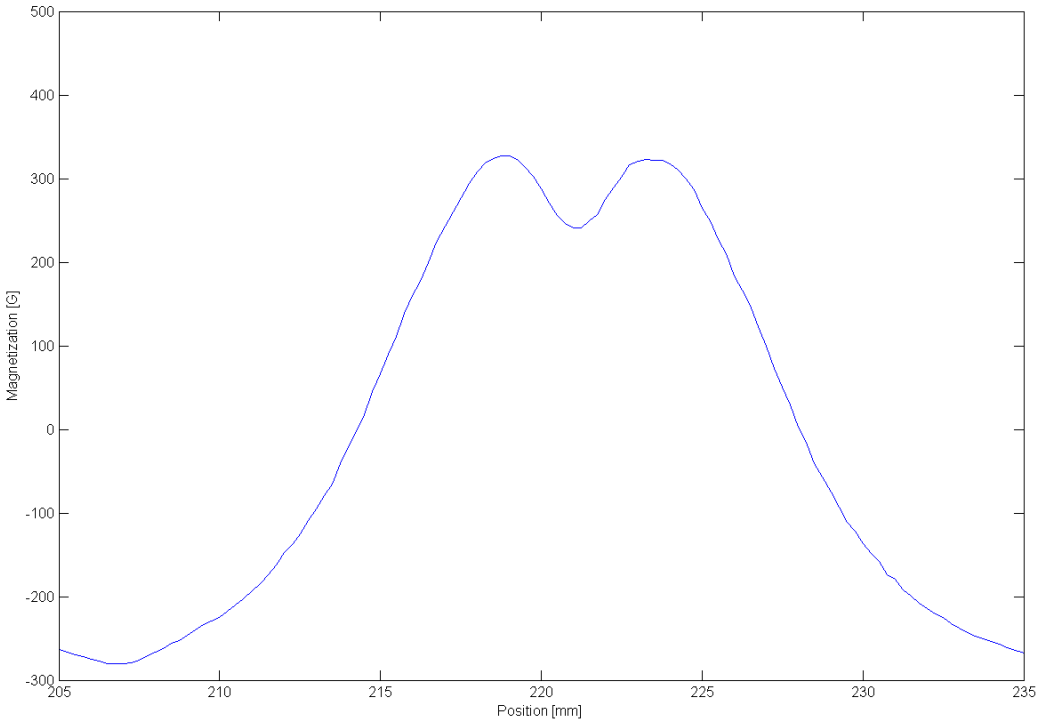
Pulse 2: The accomplished magnetization of triangular pulse with an amplitude of 55 A and a current slope of 101,5 kA/s



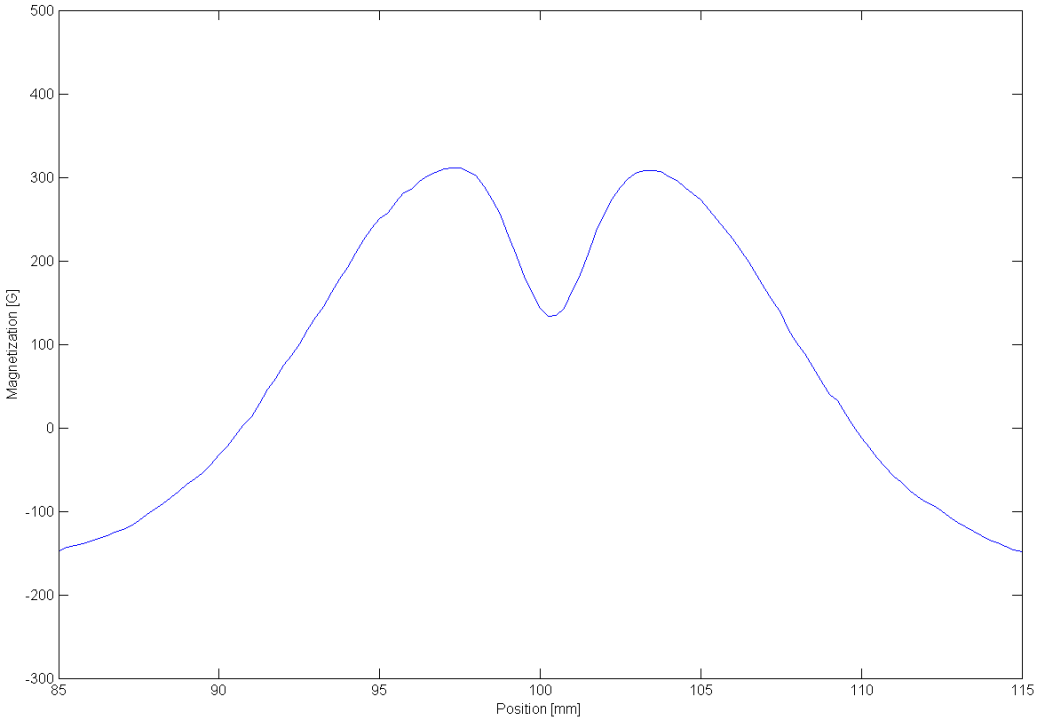
Pulse 3: The accomplished magnetization of triangular pulse with an amplitude of 85 A and a current slope of 96,5 kA/s



Pulse 4: The accomplished magnetization of triangular pulse with an amplitude of 150 A and a current slope of 1,5 kA/s



Pulse 5: The accomplished magnetization of triangular pulse with an amplitude of 150 A and a current slope of 96,5 kA/s



Pulse 6: The accomplished magnetization of triangular pulse with an amplitude of 250 A and a current slope of 100 kA/s

5.3 Time usage

The time to perform a magnetization pulse is less than 1 *s*, the exception is when the pulse time is close to or more than 1 *s*. That includes calculating the current reference, shooting the pulse and transferring the data to the embedded computer. When the current controller is tuned the embedded computer makes an analysis of the resulting current and plots it. The analysis is also done within this second for pulses with a pulse time less than a tens of *ms*. In cases with a longer pulse time the calculation time for the analysis makes it take longer time.

The time to position the servo depends on the distance to travel. It basically consists of two parts, the time it takes to communicate with the servo and the time it takes for the servo to rotate. The time of the communication differs from time to time depending on if the data is intact at arrival or not. To turn rotate the magnet band 180º (which is the worst case) it takes barely 6 *s*. To scan the whole magnet band with the highest resolution that the equipment allows it takes barely 30 *min* to perform the scan. The highest resolution that the equipment allows is 0.25 *mm* and with that resolution there is more than 2000 points on the magnet band to scan. This means that is takes less than 1 s to move the magnet band 0.25 *mm* and to take a measurement with the hall sensors.

6 Discussion and conclusions

6.1 Current control

6.1.1 The work of the controller

As one can see the controller is keeping the current within tolerances when it is possible. At graph 1 the current is falling behind in the beginning of the half period. This is because the voltage is not high enough in comparison with the inductance to obtain a sufficient current slope, the controller could not possibly do more.

For the triangular pulse of the same magnitude in graph 2 is the current slope on the way up no problem. In Graphs 3 – 5 one can clearly see that on the way down zero output voltage is not enough to make the current fall in the desired way. The current crosses the outer upper band and the controller changes negative output voltage to make the current fall faster. Furthermore, the ripple on the current becomes more and more significantly due to the decreasing magnitude of the references. Where the current slope is steep one can see that the current actually is crossing the reference. This is due to the delay in the power electronics.

In graph 6 one can see that the ripple performance is improved. This is due to the variable inductance which has increased the inductance.

In graph 9 is a triangular current shot of 300 A, and in graph 10 is the corresponding switch pattern. On the switch pattern one can see that both output combinations resulting in zero output voltage is used to distribute the switching load. On graph 11 the corresponding time between each switch with each IGBT is shown. Around 1 –2,5 ms at the time axis the times between the switches are close to 10 μs which corresponds to 10 kHz which in turn is the threshold for the high frequency protection.

Graph 12 – 14 shows to the same thing as graph 9 – 11, but with an incorrectly tuned controller, the tolerances are too tight. This means that the switching frequency will be too high which trips the high frequency protection. The green and the blue line show where the high frequency protection is engaged. A cursor is showing one of the interventions and cursors are found at the corresponding time in the other graphs. At the time where the high frequency is active the switch time is down to 10 μs which as mentioned is the threshold of it. It is also clear that to tight tolerances result in more current ripple than necessary.

6.1.2 Suggestions of improvements

The overall current performance could be improved a little more if the tolerance bands where shaped progressively to always utilize the highest possible switching frequency. However, it would not improve the maximum ripple level of a given current pulse with a correctly tuned controller.

A more sophisticated solution of the variable inductance with a bigger variety of inductances could be implemented, but faster power electronics would probably be a better solution.

Another approach is to control the actual flux instead. This could be done by for example a time integration of the voltage applied on the flux proving coils, which will be proportional to the provided flux if the resistive voltage drop is subtracted.

6.2 Magnetizing results

First of all, when reasoning about these measurements, the reader should keep in mind that the used magnet material is bonded ferrite. This means that no significant eddy current should occur in the magnetic material.

6.2.1 Reset

There is not much to say about the reseting results. It was obtained by trial and error to find something to make further tests from. The method is as one can see working well and it is in practical use very time effective. The big variations at the beginnings and the ends of each measurements corresponds to the ends of the magnet band and the small variations corresponds to mechanical unevennesses.

6.2.2 Discussion about the surfaces

The Surfaces 1 – 12, especially 2 and 8 tells us that the number of pulses does not affect the magnetizing result in any significant way. Another obvious conclusion is that the resulting flux density is correlated with the current magnitude until the magnet is saturated. By trying to magnetize the magnet more, the resulting flux density is decreasing, which invites to discussion.

As one can see the magnetizing width is consequently which could be explained by that the leakage flux will increase with the total flux. Another interesting trend is that triangular shaped current pulses results in both higher resulting flux and narrower magnetizing pulses, only benefits in other words! Likely it depends on that the flux collecting lenses is doing a better work when flux derivative and hence the eddy currents in them are kept at a more constant level.

The foregoing reasoning is supported by for example surface 16 where one can see that steeper current slope results in narrower pulses. In the same way the maximum achievable flux in surface 14 increases with steeper current slopes.

A set of magnetizing pulses are shown in attachment Magnetizing results as Pulses 1-6. Pulse 1 shows the result of a relatively small current pulse while pulse 2 shows the result of a bigger pulse, but still in the linear area of magnetization. Pulse 3 shows the beginning of the saturation of the magnet. The pulses 5 and 6 show a rather interesting phenomenon which in a way explains the look on the surfaces at higher currents. The widening of the pulse is continuing while flux density is decreasing at the location where it should be peaking.

A proposal to an explanation of why is that it is due to unexpected eddy currents in the air gap where the magnet is located. This theory is supported by surface 13 where one can see that the extremely flat slopes which of course results in less eddy current does not suffer from the same peak flux reduction at high currents. This is further supported by pulse 4 which is done with a small current slope and a big current. Of course it will result in an extreme pulse width to.

References

[1] Joseph J. Stupak Jr. “Methods magnetizing permanent magnets” Oersted Technology corporation. pp. 1 - 8, October 2000.

[2] Mats Alaküla and Per Karlsson, “Power Electronics – Devices, Converters, Control and Applications”, Lund University, Department of Industrial Electrical Engineering and Automation, pp. 33 – 106.

[3] National Instruments Corporation, “Operating instructions and specifications – ComapctRIO NI cRIO-9022”, pp. 5 - 17.

[4] National Instruments Corp., “Operating instructions and specifications – NI 9205”, pp. 1 – 25.

[5] National Instruments Corp., “Operating instructions and specifications – NI 9215”, pp. 1 – 21.

[6] National Instruments Corp., “Operating instructions and specifications – NI 9263”, pp. 1 – 15.

[7] National Instruments Corp., “Operating instructions and specifications – NI 9401”, pp. 1 – 14.

[8] LEM, Datasheet for: “Current Transducer LA 306-S/SP1”, pp. 1 - 3, July 2007.

[9] LEM, Datasheet for: “Voltage transducer LV 25-P/PS2”, pp. 1 - 2, Mars 2006.

[10] National Semiconductor, Datasheet for: “LF347”, pp. 1 – 2, August 2000.

[11] National Semiconductor, Datasheet for: “LM339”, pp. 1 - 4, March 2004.

[12] Semikron, Datasheet for: “SKHI 23/17 (R)”, pp. 1-10, June 2006.

[13] Philips Semiconductor, Datasheet for: “74HCU04” pp. 3 – 5, September 1993.

[14] Toshiba, Datasheet for: “TC4049”, pp. 1 – 3, February 1998.

[15] Philips Semiconductor, Datasheet for: “HEF4081”, pp. 2 - 3, January 1995.

[16] VERO POWER, Datasheet for: “EPLAX PK-serie, PK60”, pp. 10- 11.

[17] XP POWER, Datasheet for: “VCS Series – VCS50US15”, pp. 1 - 2, May 2011.

[18] Philips Semiconductor, Datasheet for: “HEF4030”, pp. 2 – 3, January 1995.

[19] National Instruments Corporation, “LabVIEW Core 1 Course Manual”, pp. 1-1 – 9-24, August 2010.

[20] National Instruments Corporation, “CompactRIO and LabVIEW Development Fundamentals - Course Manual”, pp. 1-1 – 9-49, September 2008.

[21] Cooper PowerTools, “User Manual – DIS-2 48/10 IC”, Metronix Messgeräte und Elektronik GmbH, pp. 13 – 138, 2006

Attachments

Hardware

Connection lists

cRIO

NI 9205

AI0	Diagnostics X1-1
AI1	Diagnostics X3-1
AI2	Diagnostics X3-2
AI3	Diagnostics X3-3
AI4	Diagnostics X3-4
AI5	NC
AI6	NC
AI7	NC
AI8	Diagnostics X1-2
AI9	NC
AI10	NC
AI11	NC
AI12	NC
AI13	NC
AI14	NC
AI15	NC
AI16	Hall sensor supply, X2-1
AI17	Hall sensor 1
AI18	Hall sensor 2
AI19	Hall sensor 3
AI20	Hall sensor 4
AI21	NC
AI22	NC
AI23	NC
AI24	NC
AI25	NC
AI26	NC
AI27	NC
AI28	NC
AI29	NC
AI30	NC
AI31	NC
COM	Screening box ground, variable inductance electronics
DO0	Variable inductance electronics
AISENSE	Diagnostics circuit, X5-1

PFI0	NC

NI 9215

AI0 +	Current and voltage measuring electronics, X3-1
AI0 -	Current and voltage measuring electronics, X3-2
AI1 +	Current and voltage measuring electronics, X3-3
AI1 -	Current and voltage measuring electronics, X3-2
AI2 +	Current and voltage measuring electronics, X3-2
AI2 -	Current and voltage measuring electronics, X3-2
AI3 +	Current and voltage measuring electronics, X3-2
AI3 -	Current and voltage measuring electronics, X3-2
NC	NC
COM	Screening box ground

NI 9263

AO0	Current and voltage measuring electronics, X4-2
COM	Current and voltage measuring electronics, X4-5
AO1	Current and voltage measuring electronics, X4-1
COM	Current and voltage measuring electronics, X4-5
AO2	Current and voltage measuring electronics, X4-3
COM	Current and voltage measuring electronics, X4-5
AO3	Current and voltage measuring electronics, X4-4
COM	Current and voltage measuring electronics, X4-5
NC	NC
COM	Screening box ground

NI 9401 (1)

COM	Current and voltage measuring electronics, X1-5
NC	NC
COM	Current and voltage measuring electronics, X1-5
COM	Current and voltage measuring electronics, X1-5
NC	NC
COM	Current and voltage measuring electronics, X1-5
COM	Calibrating electronics, X1-1
NC	NC
COM	Calibrating electronics, X1-1
COM	NC
NC	NC
COM	NC
COM	NC
DIO0	Current and voltage measuring electronics, X1-4
NC	NC
DIO1	Current and voltage measuring electronics, X1-3
DIO2	Current and voltage measuring electronics, X1-1

NC	NC
DIO3	Current and voltage measuring electronics, X1-2
DIO4	Calibrating electronics, X1-3
NC	NC
DIO5	Calibrating electronics, X1-4
DIO6	NC
NC	NC
DIO7	NC

NI 9401 (2)

COM	Level converter electronics, X4-2
NC	NC
COM	Level converter electronics, X4-2
COM	Level converter electronics, X4-2
NC	NC
COM	Level converter electronics, X3-6
COM	Level converter electronics, X3-6
NC	NC
COM	Level converter electronics, X3-6
COM	Level converter electronics, X3-6
NC	NC
COM	Level converter electronics, X3-6
COM	NC
DIO0	Level converter electronics, X4-2
NC	NC
DIO1	Level converter electronics, X4-2
DIO2	Level converter electronics, X4-2
NC	NC
DIO3	Level converter electronics, X3-1
DIO4	Level converter electronics, X3-5
NC	NC
DIO5	Level converter electronics, X3-4
DIO6	Level converter electronics, X3-3
NC	NC
DIO7	Level converter electronics, X3-2

Interconnections

Level converter electronics, X6-2 – Shake to wake electronics, X1-1
Level converter electronics, X1-1 – IGBT driver, supply voltage
Level converter electronics, X1-2 – IGBT driver, ground
Level converter electronics, X1-3 – IGBT driver, S1 lower
Level converter electronics, X1-4 – IGBT driver, S1 upper
Level converter electronics, X1-5 – IGBT driver, S2 lower
Level converter electronics, X1-6 – IGBT driver, S2 upper

IGBT driver, error out – Level converter electronics, X1-7

Calibration electronics, X3-1 – Diagnostics electronics, X1-1
Calibration electronics, X3-2 – Diagnostics electronics, X1-2

Analog supply voltage (+15) – Diagnostics electronics, X4-1
Analog supply voltage (-15) – Diagnostics electronics, X4-2

Digital supply voltage (+5) – Diagnostics electronics, X4-3
Digital supply voltage (+15) – Diagnostics electronics, X4-4

Shake to wake electronics, X2-1 – Control panel, Shake to wake electronics
Shake to wake electronics, X2-2 – Control panel, Shake to wake electronics

MATLAB code

cRIO_result_files_getter.m

```
cRIO = ftp('130.235.80.52')
cd(cRIO, 'Surface results');
fileslist = dir(cRIO);

for n = 1:length(fileslist)
    disp( strcat([num2str(n) ': ' fileslist(n).name]) )
end

file = 1;
while file > 0
    file = input('Select file, enter 0 to close:');
    if(file > 0)
%         fileformat = fileslist(file).name;
        disp(mget(cRIO, fileslist(file).name))
    end
end

close(cRIO)
clear cRIO
clear fileslist
clear n
clear file
```

MATLAB_file_loader.m

```
fileslist2 = ls;
ps = size(fileslist2);
n=1;
while n <= ps(1)
    if strfind(fileslist2(n,:), '.xls')
        disp( strcat([num2str(n) ': ' fileslist2(n,:)]) )
        n = n+1;
    else
        fileslist2(n,:) = [];
        ps(1) = ps(1)-1;
    end
end

file = 1;
while file > 0
    file = input('Select file, enter 0 to close:');
    if(file > 0)
        filesformat = strread(fileslist2(file,:), '%s');
        current0 = str2double(filesformat(2));
        delta_current = str2double(filesformat(3));
        number_of_pulses = str2double(filesformat(4));
        delta_number_of_pulses = str2double(filesformat(5));
        max_number_of_pulses = str2double(filesformat(6));
        pulse_width = str2double(filesformat(7));
        time = 1000*str2double(filesformat(9));
        workname = cell2mat(filesformat(10));
        workname = workname(1:(length(workname)-4));
        workname = genvarname(workname);
        plotname  =  strcat([cell2mat(filesformat(8))  '  '  num2str(time)  'ms  '
workname]);
        eval([workname '=load(fileslist2(file,:));']);
    end
end

clear fileslist2
clear ps
clear n
clear filesformat
clear file
clear time
```

Data_divider.m

```
% ------------------------------------------------------------------------ %
% These variables should be changed by the user to fit the measurment that
% is analyzed

  slope = 1;         % 0 - curent and pulse
  sensor = 1;        % Which sensor to look at, 1, 2, 3 or 4

  figure_start = 1; % Figure number to start at when generatong the 4 plots

% ------------------------------------------------------------------------ %

% create the variable used positions
eval(['usedpositions = ' workname '(1:32,1:2);']);

% Clear unused positions from usedpositions
n = 1;
while n <= length(usedpositions)
    if usedpositions(n,1) == 0
        usedpositions(n,:) = [];
    else
        n = n+1;
    end
end
usedpositions = usedpositions(:,2);

% create a vairiable containing the scanning resoulution
eval(['scaningres = ' workname '(34,1) - ' workname '(33,1);']);
nbr_of_index = round(180*pi/scaningres);


% divides the loaded datafile inso smaller parts that contain one scan of
% the band
divide_index = 33;
n = 0;
eval(['datalength = length(' workname ');']);
while divide_index < datalength
    n = n + 1;
    resetname = genvarname([workname '_reset_' num2str(n)]);
    dataname = genvarname([workname '_data_' num2str(n)]);
    datanumbername = genvarname([workname '_datanumber_' num2str(n)]);
    eval([resetname            '            =            '            workname
'(divide_index:divide_index+nbr_of_index,:);']);
    divide_index = divide_index + nbr_of_index + 1;
    eval([dataname             '            =            '            workname
'(divide_index:divide_index+nbr_of_index,:);']);
    eval([datanumbername ' = ' workname '(divide_index+nbr_of_index+1,2);']);

    eval([resetname      '(:,2)      =      wden('      resetname      '(:,2),
''sqtwolog'',''s'',''one'',4,''sym4'');']);
    eval([resetname      '(:,3)      =      wden('      resetname      '(:,3),
''sqtwolog'',''s'',''one'',4,''sym4'');']);
    eval([resetname      '(:,4)      =      wden('      resetname      '(:,4),
''sqtwolog'',''s'',''one'',4,''sym4'');']);
    eval([resetname      '(:,5)      =      wden('      resetname      '(:,5),
''sqtwolog'',''s'',''one'',4,''sym4'');']);
```

```
    divide_index = divide_index + nbr_of_index + 2;
end

rounds = n;
current = current0;
pulses = number_of_pulses;
result = zeros(0,14);
invalid_result = NaN(0,14);
invalid_current = ceil((20.001-current0)/delta_current)*delta_current;
invalid_pulse                                =                                ceil((300-
number_of_pulses)/delta_number_of_pulses)*delta_number_of_pulses;
for n = 1:rounds

    resetname = genvarname([workname '_reset_' num2str(n)]);
    eval(['reset_data = ' resetname ';']);
    dataname = genvarname([workname '_data_' num2str(n)]);
    eval(['pulse_data = ' dataname ';']);
    datanumbername = genvarname([workname '_datanumber_' num2str(n)]);
    eval(['iterations = ' datanumbername ';']);
    [result_part,      invalid_result_part,      current,      pulses]      =
PeakNDeltaFinderOneRound( ...
    reset_data, pulse_data, usedpositions, iterations, scaningres, ...
    pulse_width, current, delta_current, ...
    pulses, delta_number_of_pulses, number_of_pulses, max_number_of_pulses, ...
    invalid_current, invalid_pulse);
    result = [result; result_part];
    invalid_result = [invalid_result; invalid_result_part];
end

max_current = current; % this is used in peakCurrentPlotter.m

nbr_of_pulse_types                =                ceil((max_number_of_pulses-
number_of_pulses+1)/delta_number_of_pulses);
if nbr_of_pulse_types == Inf
    nbr_of_pulse_types = 1;
end
if slope == 1
    x = result(1:nbr_of_pulse_types, 2)./10;
else
    x = result(1:nbr_of_pulse_types, 2);
end
y = result(1:nbr_of_pulse_types:end, 1);


if y(1) < 2
    cut = 1
else
    cut = 0
end

sensor = sensor*3;
z1 = vec2mat([result(:,sensor)], length(x));
z1i = vec2mat([invalid_result(:,sensor)], length(x));
z2 = vec2mat([result(:,sensor+1)], length(x));
z2i = vec2mat([invalid_result(:,sensor+1)], length(x));
tmp = result(:,sensor+2);
tmpi = invalid_result(:,sensor+2);
if cut >= 1
    y3 = y(2:length(y));
```

```
    z3 = vec2mat([tmp(length(x)+1:length(result))], length(x));
    z3i = vec2mat([tmpi(length(x)+1:length(invalid_result))], length(x));
else
    y3 = y;
    z3 = vec2mat(tmp, length(x));
    z3i = vec2mat(tmpi, length(x));
end
if slope == 1
    xlabel('Slope [kA/s]')
else
    xlabel('Number of pulses')
end
ylabel('Current [A]')
zlabel('Maximum magnetization [G]')

figure(figure_start)
surf(x,y,z1)
hold on
h = surf(x,y,z1i);
set(h, 'FaceColor', [0.3804    0.3804    0.3804])
hold off
if slope == 1
    xlabel('Slope [kA/s]')
else
    xlabel('Number of pulses')
end
ylabel('Current [A]')
zlabel('Maximum magnetization [G]')

figure(figure_start+1)
surf(x,y,z2)
hold on
h = surf(x,y,z2i);
set(h, 'FaceColor', [0.3804    0.3804    0.3804])
hold off
if slope == 1
    xlabel('Slope [kA/s]')
else
    xlabel('Number of pulses')
end
ylabel('Current [A]')
zlabel('Maximum magnetization [G]')

figure(figure_start+2)
surf(x,y3,z3)
hold on
h = surf(x,y3,z3i);
set(h, 'FaceColor', [0.3804    0.3804    0.3804])
hold off
if slope == 1
    xlabel('Slope [kA/s]')
else
    xlabel('Number of pulses')
end
ylabel('Current [A]')
zlabel('Maximum magnetization [G]')

if slope == 1
    % Slope
    mx = x(1):15:x(end);
```

```
    my = (y(1):2.5:y(end))';
else
    % Pulse
    mx = x(1):2:x(end);
    my = (y(1):2:y(end))';
end

[mxi,myi] = meshgrid(mx, my);
zi = interp2(x,y,z1,mx,my,'linear');
figure(figure_start+3)
surf(mx,my',zi)
if slope == 1
    xlabel('Slope [kA/s]')
else
    xlabel('Number of pulses')
end
ylabel('Current [A]')
zlabel('Maximum magnetization [G]')

clear n
clear nbr_of_index
clear divide_index
clear resetname
clear dataname
clear datanumbername
```

PeakNDeltFinderOneRound.m

```
function [result, invalid_result, current_out, pulses_out] =
PeakNDeltaFinderOneRound( ...
    reset_data, pulse_data, usedpositions, iterations, scaningres, ...
    pulse_width, current, delta_current, ...
    pulses, delta_number_of_pulses, number_of_pulses, max_number_of_pulses, ...
    invalid_current, invalid_pulse)

result = zeros(iterations, 14);
invalid_result = NaN(iterations, 14);
half_width = floor((pulse_width/scaningres)/2);
for n = 1:iterations
    index = usedpositions(n)/scaningres;
    result(n,:) = [current pulses result(n,3:14)];

    pd = pulse_data(index-half_width:index+half_width, 2);
    rd = reset_data(index-half_width:index+half_width, 2);
    if current > 1
        [PeakValue, RelPeakValue, FirstIndex, SecondIndex, DeltaX] =
PeakNDeltaFinder(pd, rd);
    else
        mid = floor(pulse_data(length(pd/2)));
        PeakValue = pd(mid);
        RelPeakValue = pd(mid) - rd(mid);
        DeltaX = 0;
    end

    result(n,:) = [result(n,1:2) PeakValue RelPeakValue DeltaX*scaningres
result(n,6:14)];
    if current <= invalid_current
        if pulses >= invalid_pulse
            invalid_result(n,:) = [invalid_result(n,1:2) PeakValue RelPeakValue
DeltaX*scaningres invalid_result(n,6:14)];
        end
    end

    pd = pulse_data(index-half_width:index+half_width, 3);
    rd = reset_data(index-half_width:index+half_width, 3);
    if current > 1
        [PeakValue, RelPeakValue, FirstIndex, SecondIndex, DeltaX] =
PeakNDeltaFinder(pd, rd);
    else
        mid = floor(pulse_data(length(pd/2)));
        PeakValue = pd(mid);
        RelPeakValue = pd(mid) - rd(mid);
        DeltaX = 0;
    end
    result(n,:) = [result(n,1:5) PeakValue RelPeakValue DeltaX*scaningres
result(n,9:14)];
    if current <= invalid_current
        if pulses >= invalid_pulse
            invalid_result(n,:) = [invalid_result(n,1:5) PeakValue RelPeakValue
DeltaX*scaningres invalid_result(n,9:14)];
        end
    end
```

```
    pd = pulse_data(index-half_width:index+half_width, 4);
    rd = reset_data(index-half_width:index+half_width, 4);
    if current > 1
        [PeakValue,   RelPeakValue,   FirstIndex,   SecondIndex,   DeltaX]   =
PeakNDeltaFinder(pd, rd);
    else
        mid = floor(pulse_data(length(pd/2)));
        PeakValue = pd(mid);
        RelPeakValue = pd(mid) - rd(mid);
        DeltaX = 0;
    end
    result(n,:)  =  [result(n,1:8)  PeakValue  RelPeakValue  DeltaX*scaningres
result(n,12:14)];
    if current <= invalid_current
        if pulses >= invalid_pulse
            invalid_result(n,:) = [invalid_result(n,1:8) PeakValue RelPeakValue
DeltaX*scaningres invalid_result(n,12:14)];
        end
    end

    pd = pulse_data(index-half_width:index+half_width, 5);
    rd = reset_data(index-half_width:index+half_width, 5);
    if current > 1
        [PeakValue,   RelPeakValue,   FirstIndex,   SecondIndex,   DeltaX]   =
PeakNDeltaFinder(pd, rd);
    else
        mid = floor(pulse_data(length(pd/2)));
        PeakValue = pd(mid);
        RelPeakValue = pd(mid) - rd(mid);
        DeltaX = 0;
    end
    result(n,:) = [result(n,1:11) PeakValue RelPeakValue DeltaX*scaningres];
    if current <= invalid_current
        if pulses >= invalid_pulse
            invalid_result(n,:)     =     [invalid_result(n,1:11)     PeakValue
RelPeakValue DeltaX*scaningres];
        end
    end

    pulses = pulses + delta_number_of_pulses;
    if pulses > max_number_of_pulses
        pulses = number_of_pulses;
        current = current + delta_current;
    end
end

current_out = current;
pulses_out = pulses;
```

PeakNDeltaFinder.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                              %
% Pulse magnetizer                                                             %
% 2001-08-17                                                                   %
%                                                                              %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [PeakValue, RelPeakValue, FirstIndex, SecondIndex, DeltaX] = ...
    PeakNDeltaFinder(PeakData, ResetData)

NbrOfElements = length(PeakData);
NormData = PeakData - ResetData;
ResetMean = mean(ResetData);

if(ResetMean < 0)
    [PeakValue, I] = max(PeakData);
else
    [PeakValue, I] = min(PeakData);
end

if(ResetMean < 0)
    [RelPeakValue, I] = max(NormData);
else
    [RelPeakValue, I] = min(NormData);
end


FirstHalf = NormData(1:I);

[Moonshine, FirstIndex] = min(abs(FirstHalf - ((PeakValue-ResetMean)/2)*...
    ones(length(FirstHalf), 1)));

SecondHalf = NormData((I+1):NbrOfElements);

[Moonshine, SecondIndex] = min(abs(SecondHalf - ((PeakValue-ResetMean)/2)*...
    ones(length(SecondHalf), 1)));

SecondIndex = SecondIndex + length(FirstHalf);
DeltaX = SecondIndex - FirstIndex;

end
```

peakCurrentPlotter.m

```
current = current0;
pulses = number_of_pulses;

% ------------------------------------------------------------------------ %
  current_goal = 150; % Y in a surface plot
  pulse_goal = 965;  % X in a surface plot
% ------------------------------------------------------------------------ %

test_point_nbr = 1;
round_nbr = 1;
while current < current_goal
    if pulses >= max_number_of_pulses
        pulses = number_of_pulses;
        current = current + delta_current;
    else
        pulses = pulses + delta_number_of_pulses;
    end
    test_point_nbr = test_point_nbr + 1;
    datanumbername = genvarname([workname '_datanumber_' num2str(round_nbr)]);
    eval(['temp = ' datanumbername ';']);
    if test_point_nbr > temp
        test_point_nbr = 1;
        round_nbr = round_nbr + 1;
    end

    if current > max_current
        disp('This was bad 1 !')
        break
    end
end

datanumbername = genvarname([workname '_datanumber_' num2str(round_nbr)]);
eval(['temp = ' datanumbername ';']);
while pulses < pulse_goal
    pulses = pulses + delta_number_of_pulses;
    test_point_nbr = test_point_nbr + 1;
    if test_point_nbr > temp
        test_point_nbr = 1;
        round_nbr = round_nbr + 1;
        datanumbername       =       genvarname([workname       '_datanumber_'
num2str(round_nbr)]);
        eval(['temp = ' datanumbername ';']);
    end

end

dataname = genvarname([workname '_data_' num2str(round_nbr)])
eval(['temp_data = ' dataname ';']);

if pulses > max_number_of_pulses
    disp('This was bad 2 !')
else
    interresting_pulse = test_point_nbr
end
```

```
figure(figure_start+4)
plot(temp_data(:,1), temp_data(:,1+sensor/3))
xlabel('Position [mm]')
ylabel('Magnetization [G]')
center = 220;
axis([center-15 center+15 -300 500])
```