TECHNISCHER BERICHT

TECHNICAL REPORT

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1. INTRODUCTION

I have performed my third year Summer Practice in Liebherr - Aerospace Lindenberg GmbH, which is one of the worlds leading manufacturer's in the field of aircraft equipment. My practice lasted totally 11 weeks, starting from 1.7.2003 and ending in 12.9.2003. The division at which I have performed my work was the motion control division, which is a part of the Pre - Development Department. I have performed my work under the supervision of Dipl.-Ing. (FH) Frank Kronburger and Ing.-grad. Georg Ried.

I have been involved in a project which dealt with the design and test of a driver circuitry for a switched reluctance motor, which is desired to be controlled by a digital signal processor. The usage purpose of this actuator can not be explained here due to company confidentiality.

This report includes a detailed description of everything that has been done and observed during the summer practice, including the design procedure of every single part of the main circuitry and test environment. The report starts with the description of the company, in which the organizational structure of the company is explained. The main report includes the subject related to the work done in the company, including the design procedure and the tests made. At the end, an appendix is included as a reference text.

2. DESCRIPTION OF THE COMPANY

2.1 Company Name

Liebherr - Aerospace Lindenberg GmbH

2.2 Company Location

Pfänderstraße 50-52
D-88161 Lindenberg/Allgäu
GERMANY

2.3 Organizational Structure of the Company

The Liebherr Group is a decentralized company, comprising moderately sized autonomous companies. The parent company is Liebherr - International AG, based in Bulle, Switzerland, with a share capital of 500 million Swiss Francs. All shareholders are members of the Liebherr family.

Liebherr- Aerospace Lindenberg GmbH is a subcompany of the Liebherr Aerospace SAS group. It has been founded in 1960 and is located at the southern part of Germany. The following figure 2.3-1 shows the organization of Liebherr Aerospace SAS and the activities of Liebherr - Aerospace Lindenberg GmbH, along with other subcompanies that belong to the Liebherr Aerospace SAS group.

LIEBHERR Board

Isolde Liebherr & Willi Liebherr

LIEBHERR-AEROSPACE (AER) SAS

F. Beyer	**President**
F. Niss	**Managing Director**
J. Mündelein	**Executive V.P. Sales & Marketing**
G. Kowal	**Executive V.P. Customer Services**
A. Benhamou	**V.P. Environmental Control Systems**

LIEBHERR-AEROSPACE LINDENBERG	LIEBHERR-AEROSPACE TOULOUSE	LIEBHERR-AEROSPACE SALINE	LIEBHERR-AEROSPACE SINGAPORE	LIEBHERR-AEROSPACE CANADA	LIEBHERR-AEROSPACE SHANGHAI	EMBRAER-LIEBHERR BRAZIL*	LIEBHERR VERKEHRS-TECHNIK
Actuation and Flight Control Systems Landing Gear Air Conditioning Systems Hydraulics System Electronics	Integrated Air Management Systems Engine Bleed Air Systems Anti-Icing Systems Cabin Pressure Control Systems Air Conditioning Systems	Customer Support	Customer Support	Service Engineering	Electronic Support via Airbus Industrie Beijing	Landing Gear Hydraulic Components High Precision Parts for Aerospace Industry	Transport Technology Air Cycle Air Conditioning Systems Vapour Air Conditioning Syst. Hydraulic Actuation Systems

* 40% share held by Liebherr Group

Fig. 2.3-1 Organization of Liebherr Aerospace SAS Group

The Liebherr - Aerospace Lindenberg’s organizational schematic is as shown in the following figure (Fig. 2.3-2).

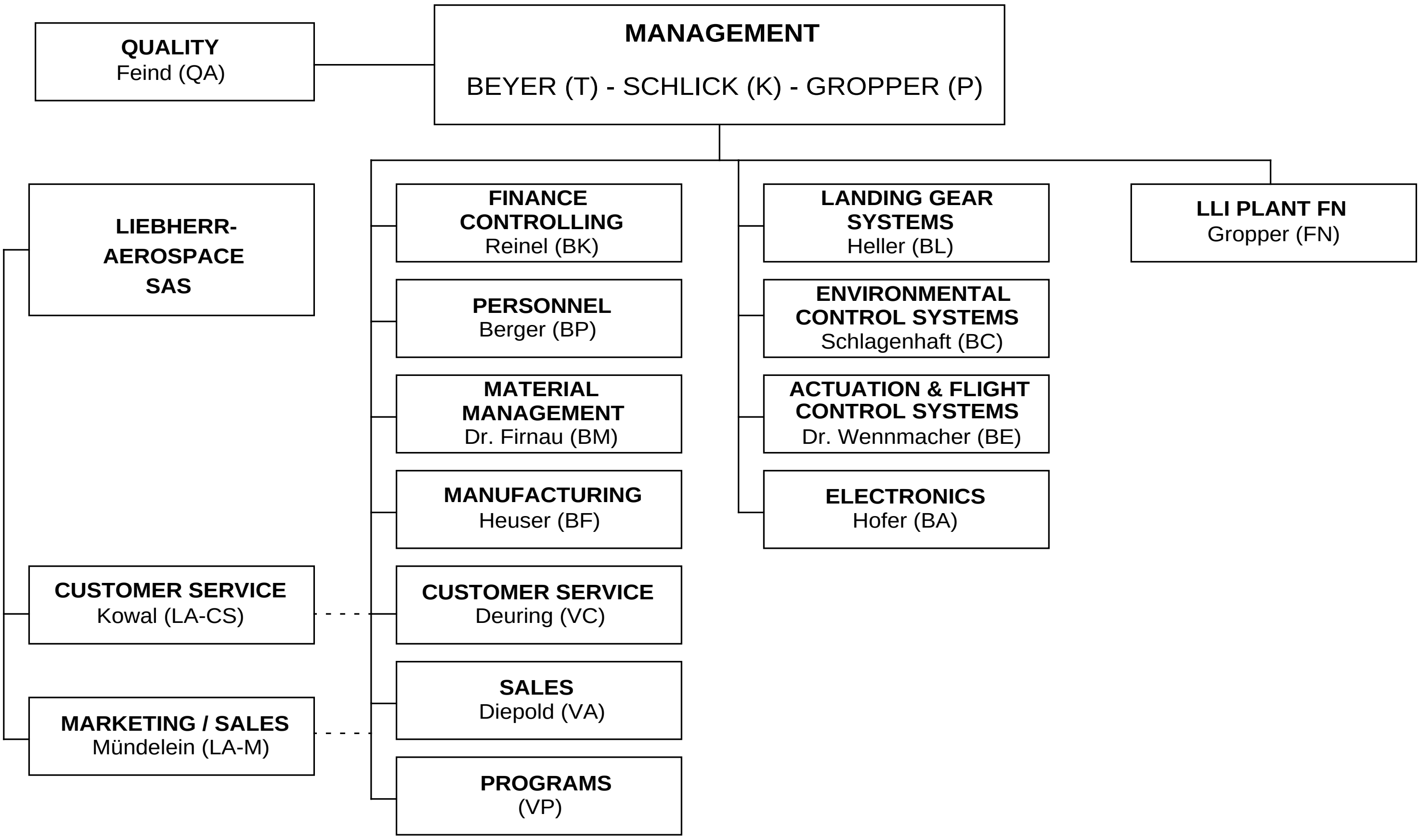


Fig. 2.3-2 Organization of Liebherr - Aerospace Lindenberg GmbH

The organization of the Product Line Electronics Division, which includes the Pre - Development department is shown in figure 2.3-3.

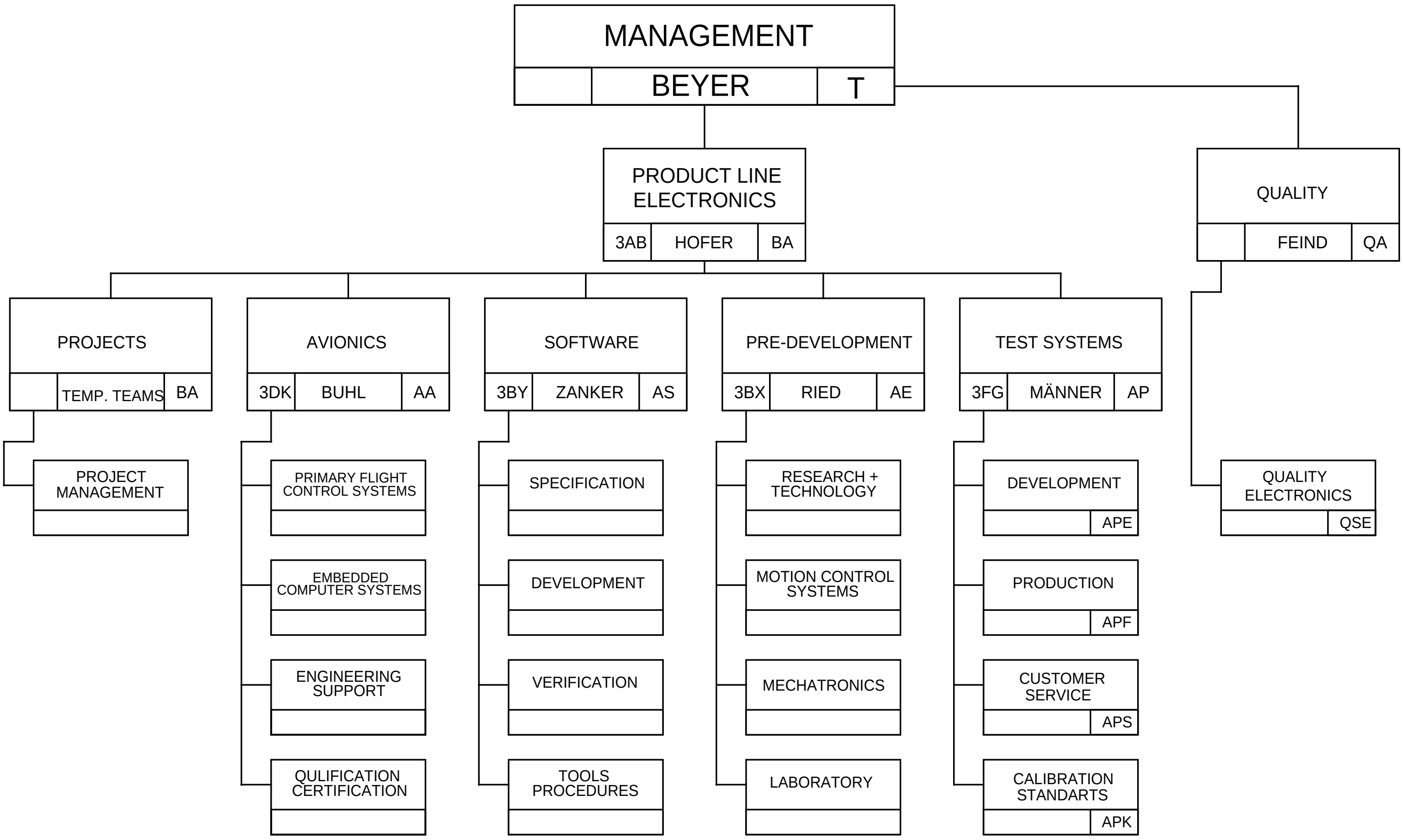


Fig. 2.3-3 Organization Schematic; Product Line Electronics

2.4 Number and Duties of Engineers Employed

The statistical data for the exact numbers of engineer employees is not found. However, the approximate values for the number and duties of the engineers are:

Total number of employees: 1600
Total number of engineers: 500
Electronics/Informatics Engineers: 80
Physics Engineers: 80
Mechanical Engineers: 200
Hydraulics - Pneumatics Engineers: 40
Aeronautical Engineers: 20
Production Engineers: 100

2.5 Main Area of Business

Liebherr - Aerospace Lindenberg develops, manufactures and services actuation systems, landing-gears and air supported air conditioning systems.

2.6 Brief History of Company

Liebherr - Aerospace Lindenberg GmbH was found by Dr. Hans Liebherr in 1960 having the name „Liebherr-Aero-Technik GmbH“. Becoming unified with ABG-SEMCA group in 1984, the company has later on gotten the name „Liebherr Aerospace Lindenberg GmbH“. Today it is one of the world’s leading manufacturers in the field of Aerospace industry.

Liebherr - Aerospace Lindenberg GmbH equips a wide variety of different aircraft with its products. This spectrum includes commercial transport aircraft, commuter and regional aircraft, business jets, fighter, military transport and trainer aircraft, and civil and combat helicopters.

Examples of participation are the flight controls for the Airbus aircraft family in which Liebherr is the system leader for the flap/slat operating system in most of these aircraft versions.

Liebherr Aerospace Lindenberg GmbH has also share in the EMB145, Global Express, Eurofighter and NH90 complete nose landing gear systems. Some other examples of participation in air systems are the integrated air systems for the Global Express and CRJ-700, bleed air conditioning systems for Airbus A319/A320/A321/A330/A340, air conditioning systems for the Super Puma and Tiger Helicopters, the fighter aircraft Mirage 2000 and commuter aircraft, as well as cabin pressure control systems for different Airbus versions and commuters.

3. PROJECT DESCRIPTION

The project that I was involved in deals with the design of a driver circuitry to drive a switched reluctance motor. The control of such a driver circuitry is desired to be done by pulse width modulated signals that are created by a digital signal processor. After the design was completed, the driver circuitry has been manufactured. Another part of my task was to test the operation of the driver, as explained in the next chapter.

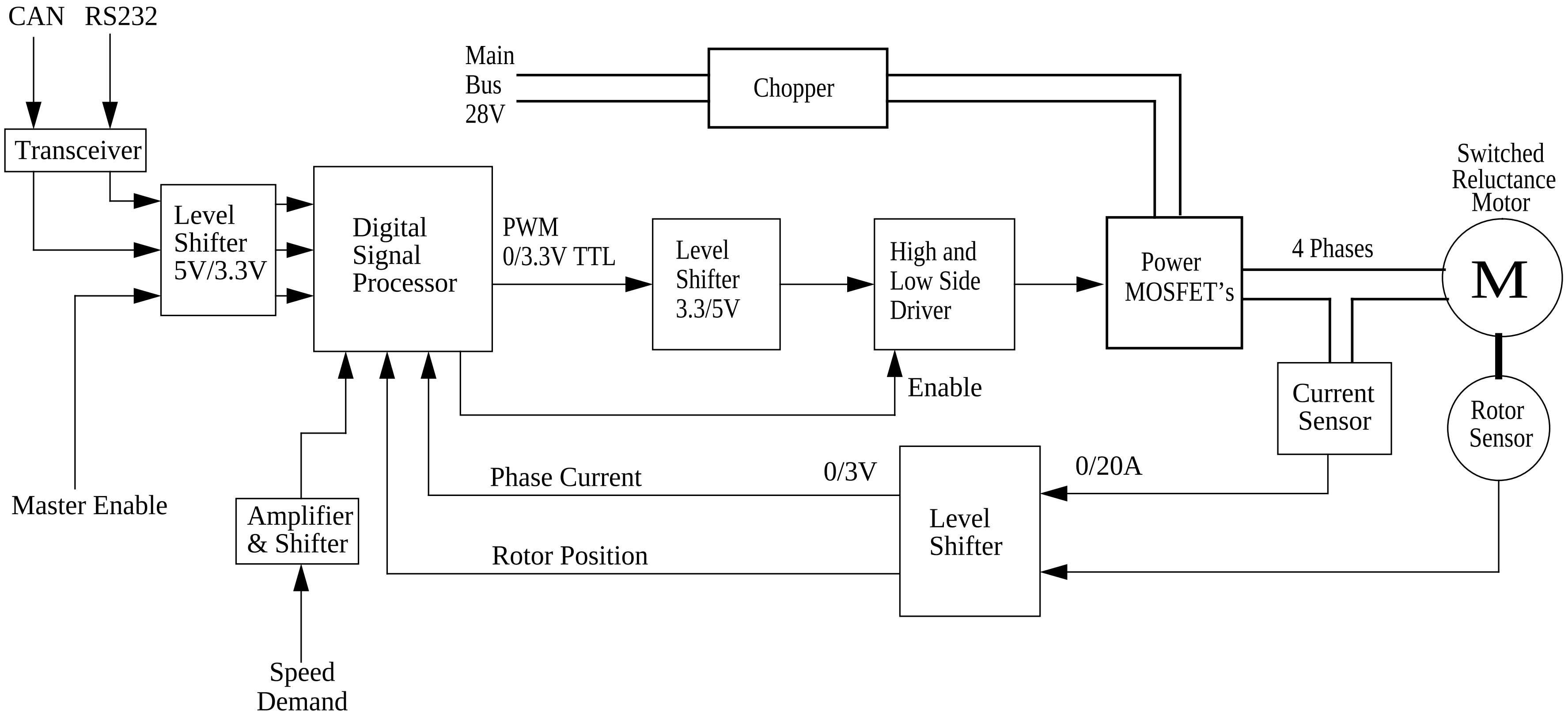
Before the explanation of each individual part of the design, it would be helpful to make a general overview of it. The system model of the desired circuitry is shown on the next page.

The main control action is done by the digital signal processor. There are several input signals to the DSP by which the DSP sets the output signals accordingly. The external output signals are the speed demand signal, the master enable signal, Control Area Network (CAN) interface signals and RS232 interface signals. There are also internal feedback signals that are set as inputs to the DSP. These are the phase current signals and the rotor position signals.

By the use of the input signals through pre determined algorithms built in the DSP, the output pulse width modulated signals are created. In addition to the PWM signals, an enable signal is created in order to stop the operation of the circuitry in an emergency condition.

The following sections include further details of each individual part of the circuitry.

FUNCTIONAL SCHEMATIC



3.1 The Switched Reluctance Motor

The switched reluctance (SR) motor is a doubly salient machine with independent phase windings on the stator and a solid laminated rotor. The stator windings are on diametrically opposite poles and are connected in series to form one phase of the motor. The number of stator and rotor poles of a switched reluctance motor is often described in an abbreviation as stator poles divided by rotor poles, i.e., a 8/6 switched reluctance motor is a motor having 8 stator poles and 6 rotor poles. Figure 3.1-1 shows a four phase 8/6 switched reluctance motor. When a stator phase is energized, the most adjacent rotor pole-pair is attracted towards the energized stator in order to minimize the reluctance of the magnetic path. By energizing consecutive phases in succession it is possible to develop constant torque in either direction of rotation.

(Reference Text 1)

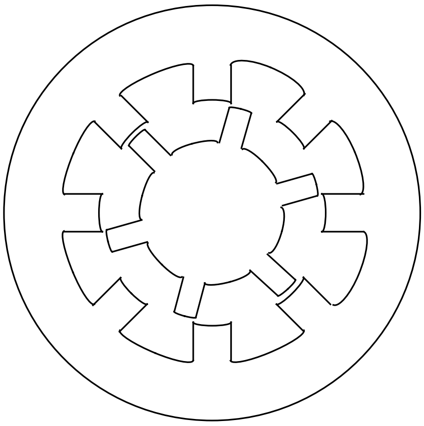


Fig. 3.1-1 8/6 Switched Reluctance Motor

Theoretically, it is possible to have a number of stator and rotor pole combinations. However, certain combinations, such as 4/4, would have problems during start up, since it would be impossible to produce a starting torque with this combination when the stator and rotor poles are exactly aligned. Although the configurations with higher numbers of stator/rotor poles have less torque ripples and do not have the problem of developing starting torque, 6/4 or 8/6 combinations are typically used.

A well designed switched reluctance motor would minimize the core losses, would offer good starting capabilities, and would also minimize the unwanted effects due to varying flux distributions and saturation. The choice of the number of phases is open but increasing the number of phases would increase the number of power devices needed for the motor driver circuitry. Moreover, higher number of poles will decrease the maximum inductance ratio obtainable for a good torque per ampere ratio. These practical issues limit stator and pole ratio to 8/6 or 6/4 in most applications of switched reluctance motors.

In this particular project, a 8/6 switched reluctance motor having a power rating of 300 watts is being used (Manufacturer: Maccon GmbH, type SR90 Appendix 7.2).

3.2 Half Bridge Configuration

Each phase of the motor is driven by two power MOSFETs (IRF2805, Appendix 7.1.b), each of them at one side, that when they are on (conducting) they supply current through the phase. However this structure is not enough for driving one phase. Since the motor phase is nothing but a coil having a high (and also variable) inductance, due to the high *di/dt* ratio that would occur when the driving MOSFETs are turned off, a high voltage is produced on the coil. This high voltage can easily cause the power MOSFET's to burn out. In order to prevent this happening, two diodes (60APU02, Appendix 7.1.c) are used forming another path that the current can flow through. When either transistor is turned off, the current commutates from the transistors to the diodes. This structure is often referred to Half Bridge inverter, and is as shown below:

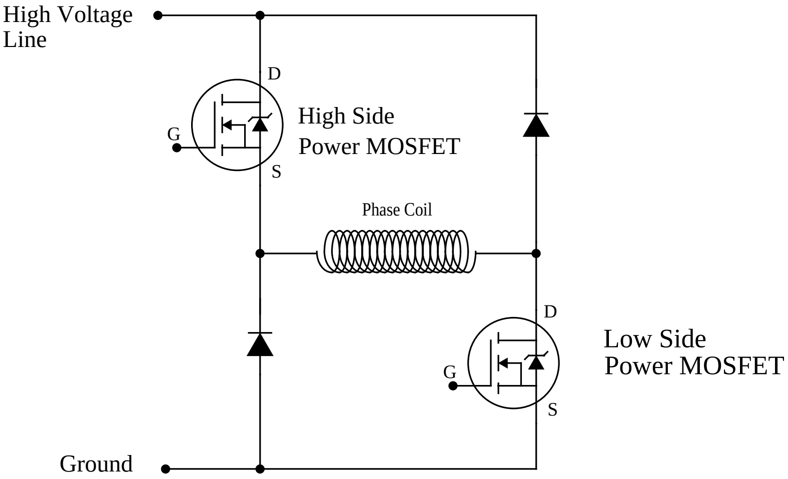


Fig. 3.2-1 Half Bridge Configuration

3.3 High and Low Side Driver

One of the most critical issues in a high power motor driver is to construct a circuitry that will be able to drive the high side power MOSFET. Since the source of this device is connected to one end of the phase coil, the voltage level of this node is floating due to the induced voltage on the phase coil. So, the gate voltage of the high side power MOSFET must be set accordingly to provide proper operation of this device.

To provide such a source that would set a voltage level according to a floating node, a high and low side MOSFET driver IC is being used (IR2113S, Appendix 7.1.a). This driver IC can control both high and low side transistor of a half bridge inverter. One significant property of a MOSFET is its capacitive input characteristics, i.e., the fact that they are turned on by supplying a charge to the gate rather than a continuous current. Such charge can be supplied by a capacitor (called the bootstrap capacitor), which establishes a voltage level between the floating node (connected to the source of the high side power MOSFET) and a node that would provide charge to the gate of the power MOSFET. The schematic of this configuration is shown below:

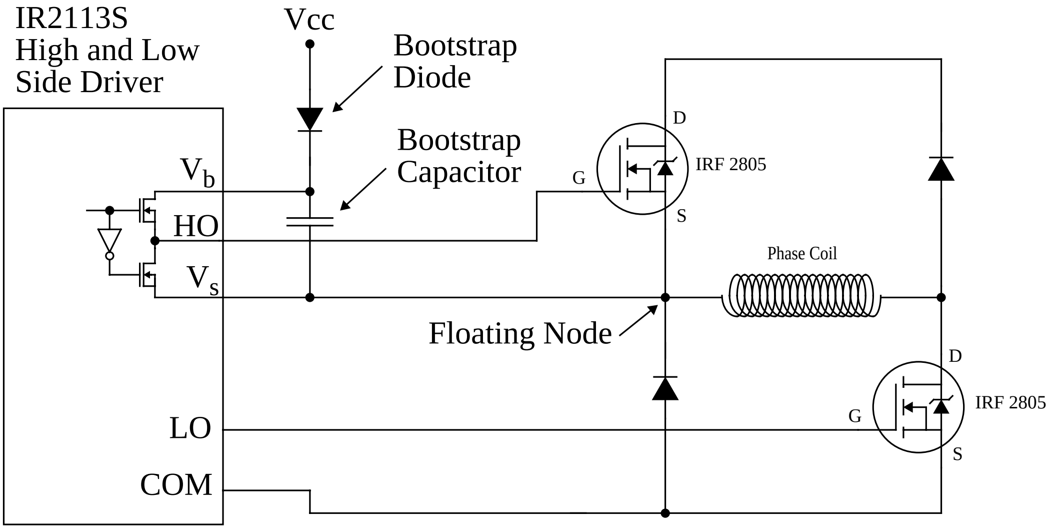


Fig. 3.3-1 High and Low side Driver Configuration

The bootstrap capacitor is charged by an external voltage source over a diode (so called bootstrap diode) (1n4148, Appendix 7.1.j) during the time when the power MOSFET is off. The operation of the circuit is as follows: when V_s is pulled down to ground (through the load) the bootstrap capacitor charges through the bootstrap diode, thus providing a level between V_b and V_s.

3.3.1 Selection of the Bootstrap Capacitor:

(Reference Text 2,3)

The bootstrap diode and the capacitor are the only external components that are strictly required for operation in a standard PWM application. Local decoupling capacitors on the V_{cc} (and digital) supply are useful in practice to compensate for the inductance of the supply lines.

The voltage seen by the capacitor is the V_{cc} supply only. The minimum bootstrap capacitor value can be calculated from the following equation:

$$C \geq \frac{2\left[2Q_g + \frac{I_{qbs(max)}}{f} + Q_{ls} + \frac{I_{cbs(leak)}}{f}\right]}{V_{cc} - V_f - V_{LS}}$$

Where;

Q_g = Gate charge of high side FET
$I_{qbs(max)}$ = Quiescent current for the high side driver circuitry (max)
$I_{cbs(leak)}$ = Bootstrap capacitor leakage current
V_{cc} = Driver's supply voltage

V_f = Forward voltage drop across the bootstrap diode
Q_{ls} = Level shift charge required per cycle = $5nC$ (for 500V/600V IC’s)
f = frequency of operation
V_{LS} = Voltage drop across the low side FET or load

The typical values for the components selected are:

IR2805 (Power MOSFET): $Q_g = 150nC$ (Typ.)
IR2113 (High and Low Side Driver): $I_{qbs(max)} = 230\ microA$, $V_{cc} = 12V$, $Q_{ls} = 5nC$
1N4148 (Diode): $V_f = 1V$
$f = 20\ kHz$.

$$C \geq \frac{2\left[2 \times 150 \times 10^{-9} + \dfrac{125 \times 10^{-6}}{20 \times 10^{3}} + 5 \times 10^{-9} + \overset{\text{negligiable}}{\cancel{\dfrac{I_{cbs(leak)}}{f}}}\right]}{12 - 1 - 10}$$

$$\longrightarrow \quad C \geq 620nF$$

Since bootstrap capacitor selected for this particular application is a non-electrolytic type which has a very small leakage current, the term $I_{cbs(leak)}/f$ can be ignored. In addition, the capacitor value obtained by the equation above is the absolute minimum required, however due to the nature of the bootstrap circuit operation, a low value capacitor can lead to overcharging, which could in turn damage the IC. Therefore to minimize the risk of overcharging and further reduce the ripple on the Vbs voltage, the C value obtained from the above equation should be increased. The actual value used in the design is $1microF$.

3.4 Chopper (Regeneration Clamp)

In most motor drive applications, a chopper circuit is needed to prevent high voltage accumulation on the main bus capacitors that occurs due to the power generation at the phases when the main driving path of the phase is closed. As it is shown in figure 3.4-1, the magneto static energy stored in the coil is released in the form of current through the diodes when the high and low side drivers of the phase A coil are closed, and thus the main bus line capacitor is being charged. Therefore, the voltage level of the main bus line may increase to a certain level that may cause damage and result in a malfunction of the circuit.

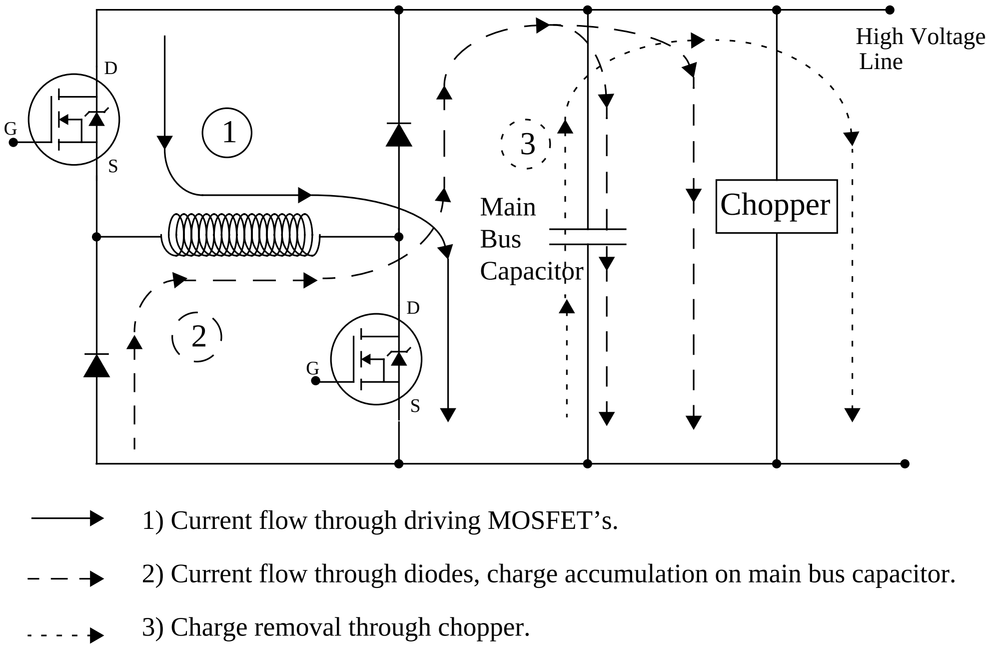


Fig. 3.4-1 Schematic of Chopper Operation

The chopper circuit that is to be used to prevent this effect is shown below. Here, by the use of a reference voltage and a comparator, an additional current path is being opened for this excessive power to be removed. When, due to regeneration, the main bus voltage reaches a level of 45V (this level is determined by the designer), the output voltage level of the comparator becomes high, and thus the power MOSFET connected to that node (over a driver/buffer) is switched on. Then, the main bus voltage starts to decrease as the charge is now removed from the main bus capacitor through this new path. The chopper circuit is designed in such a way that when the bus voltage reaches a certain level of 35V, the comparator output voltage level becomes low, and the additional path is again closed.

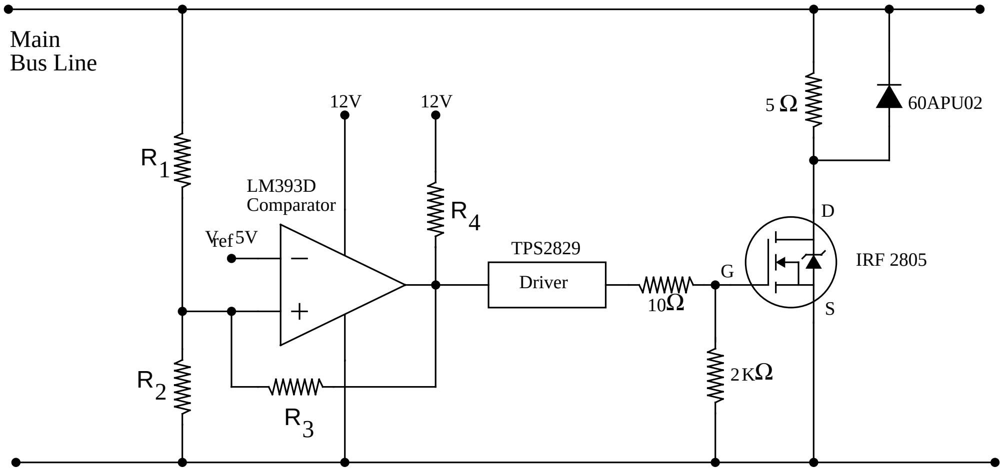


Fig. 3.4-2 The Chopper

For the chopper circuit, 5V reference voltage is used in order to determine the opening and closing voltage levels of power transistor which is at the output stage of the chopper, instead of the 12V analog voltage level. This is because that the 12V voltage level is not precise enough that there may occur ripples (noise) at this voltage level due to the high speed logic circuit operation. The 5V reference voltage is being created by a high precision voltage regulator, implemented as ADR02AR.

3.4.1 Chopper Calculations

In order to set the desired opening and closing points for the comparator, the resistance values must be set accordingly. Calculations governing the operation of the chopper circuit are shown below. The input/output characteristics of the chopper circuit is desired to have a hysteretic form as shown:

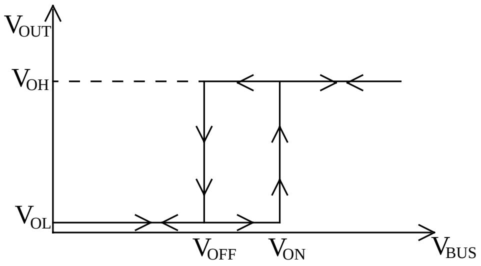


Fig. 3.4-3 Desired Input/Output Characteristics for the Chopper Comparator

As discussed earlier, the opening level is set to 45V and the closing Voff level is set to 35V.

When the output of the comparator is LOW, the equation for the operating point, where the comparator output is just turned to HIGH, can be written as:

$$V_{ON} \times \frac{R_2 \parallel R_3}{R_1 + (R_2 \parallel R_3)} = V_{REF} \qquad ①$$

The equation above is valid under this assumption: the output stage of the comparator is open collector type (LM393, Appendix 7.1.h), so it is assumed that the output sink current of the comparator is high enough to maintain the output stage BJT in saturation (In OFF case), so that the output voltage of the comparator is equal to V_{CESAT} which is around 0,2 Volts. Compared to 45V main bus level, 0,20 V is negligible, and thus V_{OUT} is assumed to be 0 volts while constructing equation 1.

After the chopper starts to operate, the main bus voltage is being decreased. When the main bus voltage decreases down to a certain level V_{OFF}, the comparator output again becomes LOW, and just before reaching this point the equation for node V_{OUT} can be written as (using the superposition principle):

$$V_{CC} \times \frac{R_1 \parallel R_2}{(R_3 + R_4) + (R_1 \parallel R_2)} + V_{OFF} \times \frac{R_2 \parallel (R_3 + R_4)}{R_1 + R_2 \parallel (R_3 + R_4)} = V_{REF} \qquad ②$$

It should be kept in mind that the input resistance of the driver circuit is high enough to be assumed as infinity, while constructing equation 2.

Now there are totally 2 equations which include 4 unknown values of resistances. One more equation is needed in order to obtain exact ratios for resistance values so that when one of them is selected (arbitrarily) the values of the other three resistors will be determined. The third equation is obtained by use of the constraint which is an approximation for the output voltage value of the Comparator when it is ON. The input high level threshold voltage for the MOSFET driver (TPS2829, Appendix 7.1.e) is about 7.5 volts, so it is a good choice to select the output voltage of the comparator as 10 volts when it is on. In fact, this constraint is not necessary but useful in selecting proper ratios. At this point, the main bus line voltage is approximated as the average of V_{ON} and V_{OFF}. The equation governing this situation is (again by the use of the superposition principle):

$$V_{CC} \times \frac{(R_1 \parallel R_2) + R_3}{(R_3 + R_4) + (R_1 \parallel R_2)} + \left(\frac{V_{ON} + V_{OFF}}{2}\right) \times \frac{R_2 \parallel (R_3 + R_4)}{R_1 + R_2 \parallel (R_3 + R_4)} \times \left(\frac{R_4}{R_3 + R_4}\right) = V_{OUT} \qquad ③$$

Starting with selecting $R_1 = 1$ units, and taking the voltage values as $V_{CC} = 12V$, $V_{REF} = 5V$, $V_{OUT} = 10V$, $V_{ON} = 45V$ and $V_{OFF} = 35V$ (as specified earlier), simplifying equation 1 results in:

$$R_2 \parallel R_3 = 0,125$$

Here, instead of performing analytical solution for the values of R_2, R_3 and R_4, which is hard to obtain, by trial and error (using equation 2), some proper values are achieved as:

R1 =1units, R2 = 0,15units, R3 = 0,75units, R4 = 0,9units

The crosscheck is made by putting these values into equation 3, which results in:

$$12 \times \frac{(1 \parallel 0,15) + 0,75}{(0,75 + 0,9) + (1 \parallel 0,15)} + 40 \times \frac{0,15 \parallel (0,75 + 0,9)}{1 + 0,15 \parallel (0,75 + 0,9)} \times \left(\frac{0,9}{0,75 + 0,9}\right) = 8,56\text{volts}$$

Although the resulting V_{OUT} value is lower than the desired value (which was 10 volts), it is appropriate for the proper operation of the MOSFET driver. Also instead of $(V_{ON} + V_{OFF})/2$, putting V_{ON} and V_{OFF} into equation 3 will result in the values of V_{OUT} just at the edge point of comparator’s turning ON and OFF times, which are:

$V_{OUT(ON)}$ = 8,88volts, $V_{OUT(OFF)}$ = 8,23volts

Finally, by determining the value of a „unit“, all the resistance values will have been determined. Another criteria that must be considered is that the voltage comparator is a low power device, and thus, it would be beneficial to use resistance values in the order of tens of kiloohms so that the current would be in the range of milliamperes. As a conclusion, the following values are selected as the resistance values:

R1 =22K, R2 = 3.3K, R3 = 16.5K, R4 = 20K

3.5 Current Sensor

Current Sensors are used to sense the current on the phases. By this way, the DSP sets the pulse width modulated outputs accordingly to achieve the desired current, and thus the desired speed and torque.

In this application, the current sensors all selected to be HX 10-P (Appendix 7.1.d) modeled Hall Effect type current sensors produced by LEM. The nominal current for the current sensor is 20A, which is scaled to produce 4V output.

The current sensor is bidirectional, i.e., it would create a negative voltage when the current flows in negative direction. However, due to the nature of the switched reluctance motor, a current in the negative direction will be never achieved during the operation of the motor. Also, the output of the current sensor will be fed back to the analog to digital convertors of the DSP, and the input voltage to DSP is allowed to swing between 0 and 3.3 V, so a negative voltage level must be avoided. To achieve all the requirements explained above, by the help of a voltage divider, the voltage level of the input to the DSP is scaled to 0V - 3.3V. To avoid any lack out and in order to protect DSP to be exposed to voltages higher than 3.3V, a buffer is used as an interface between the current sensors and the DSP. By this way, the phase conductor carrying a current of 0 to 20A is reflected as an input voltage to DSP as 0 to 3 volts. The schematic diagram of the current sensor with the interface buffer is shown below:

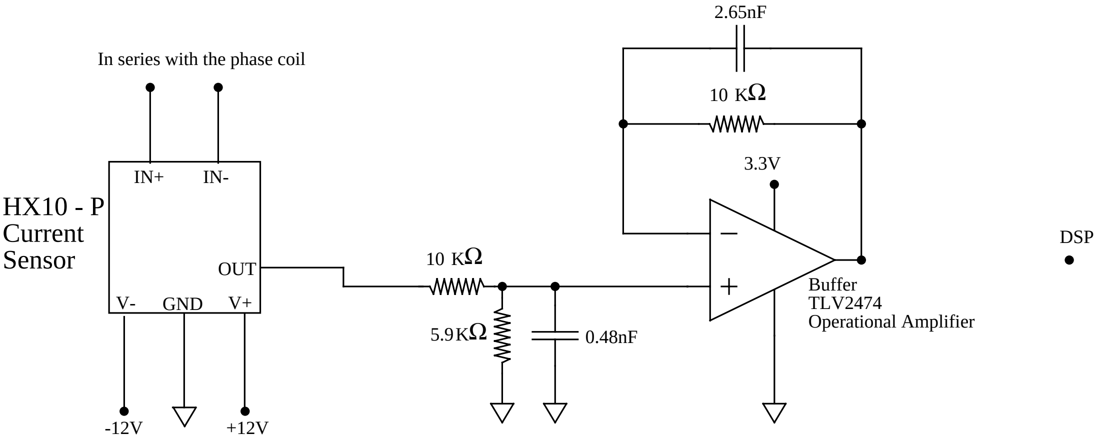


Fig. 3.5-1 Current Sensor with the input interface to DSP

3.6 Speed Control Input Interface

As a speed control input, +-10 volts Analog input is desired to be used. As explained before, the DSP input voltage must be in the range of 0 to 3 volts, so, the +- 10 volts of analog input must be scaled and amplified to fit this certain range. In order to simplify the design the amplifier (AD822, Appendix 7.1.k) used as an interface between the speed control input and the DSP is selected to be a non inverting one, thus creating 0 volt at the output when the input is -10 volts, and 3 volts when the input is +10 volts. 0V input corresponds to a 1.5V output, and to achieve this, a voltage offset of 1.5V is used at the inverting amplifier. This offset voltage is created from a high precision 5V voltage source. With the use of an adder, this voltage is added to the speed input, as shown in the following schematic (Figure 3.6-1):

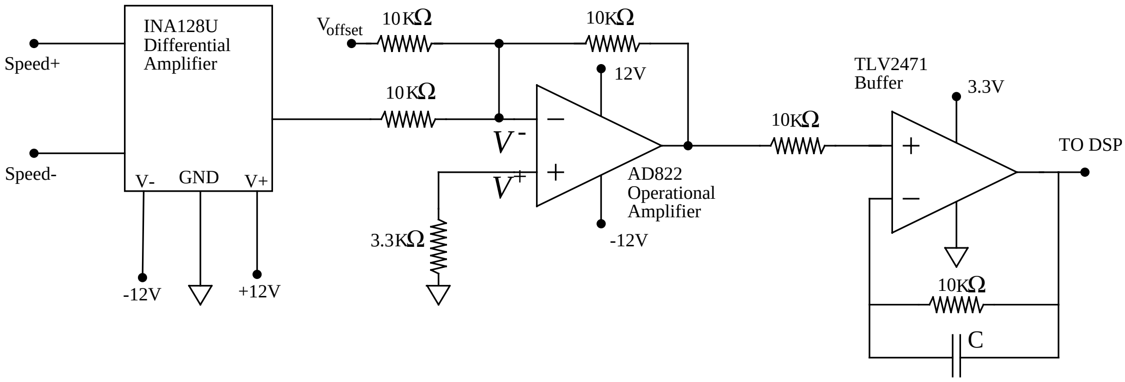


Fig. 3.6-1 Speed Control Input Interface

Here, to create an input bus which is immune to common mode noise, a differential amplifier (INA128U, Appendix 7.1.m) is used as an input stage. Also, to avoid any misusage, the output voltage is guaranteed not to exceed 3.3V by use of a buffer (TLV2471, Appendix 7.1.l), so that the Analog-to-Digital converter inputs of the DSP are not damaged.

3.7 Level Shifter (Logic Level Converters)

The input and output pins of the DSP do only accept a voltage level of maximum 3.3V, so all the 5V level logic inputs and outputs must be made to fit this level. For this purpose, buffer/driver IC’s are used, which would perform the voltage level convertion from 5V to 3.3V and vice versa. The texas instruments 74AHC244 and 74AHCT244 (Appendix 7.1.f - 7.1.g) octal buffers fit well to this need.

For the conversion of 5V signals to 3V signals, 74AHC244 IC’s are used. The advantage of this IC is that it can be used with a supply ranging from 2V to 5.5V. To protect the DSP inputs against voltage levels higher than 3.3V, the 74AHC244 IC’s are biased with 3.3V.

For the conversion of 3.3V signals to 5V signals, 74AHCT244 IC’s are used. The advantage of this IC is that it has an input high level voltage about 2V, that when it is supplied with 3.3V TTL, in can operate properly supplying a high noise margin of 3.3 - 2 = 1.3V. The following figure (Fig. 3.7-1) shows the logic level conversion.

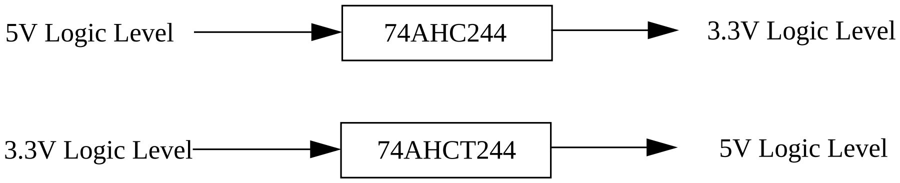


Fig. 3.7-1 Logic Level Conversion

3.8 Rotor Sensor

The SR motor purchased for is the product of Maccon GmbH and which the data sheet is given. The SR motor has an rotor sensor and a temperature sensor built in. Since not necessary, the connections to the temperature sensor of the motor are not made, and the temperature sensor will not be used in this application.

The rotor sensor has totally 3 output pins. Two of them are the channels (specified as channel A and channel B) which produce continuous pulses during the time the rotor is rotating. The third output pin is the index pin on which a single pulse (with very short duration compared to the whole cycle) is being produced on each rotation, for position alignment purposes. All these connections are fed to the DSP and by this way, the position and speed information of the rotor can be obtained and the PWM signals can be set accordingly.

3.9 CAN/RS232 Transceivers

CAN (Control Are Network) and RS232 protocols are used in order to control the DSP. As an interface to CAN protocol, an IC modeled PCA82C251 (Appendix 7.1.i) is used. Also, as an interface to RS232 protocol, MAX3232CSE integrated circuit is used.

3.10 Digital Signal Processor

In this project, Texas Instruments’ TMS320C2812 Digital Signal Processor is being used, being operated with an evaluation board commercially named EzDSP.

3.10.1 Benefits of Using DSP In Motor Control

(Reference Text 2)

A powerful processor such as a DSP controller does the following:

- It enables system cost reduction by efficient control in all speed ranges, allowing correct dimensioning of power device circuits.

- It performs high level algorithms due to reduce torque ripple, resulting in lower vibration and longer lifetime.
- It enables a reduction of harmonics using enhanced algorithms, to meet easier requirements and to reduce filter cost.
- It removes speed or position sensors by the implementation of sensorless algorithms.
- It reduces the number of look-up tables which, in turn, reduces the amount of memory needed.
- In real-time it generates smooth, near-optimal reference profiles and move trajectories, resulting in better performing.
- It controls output switching inverters and generates high-resolution PWM outputs.
- It provides a single chip control system.

For advanced controls, the DSP controllers may also do the following:

- Enable control of multi-variable and complex systems using modern intelligent methods such as neural networks and fuzzy logic.
- Perform adaptive control. DSPs have the speed capabilities to concurrently monitor the system and control it. A dynamic control algoritm adapts itself in real to to variations in system behaviour.
- Provide diagnostic monitoring. Diagnostic monitoring is achieved with FFT of spectrum analysis. By observing the frequency spectrum of mechanical vibrations, fairlure modes can be predicted in early stages.
- Produce sharp-cut-off notch filters that eliminate narrow band mechanical resonance. Notch filters remove energy that would otherwise excite resonant modes and possibly make the system unstable.

3.10.2 Applications of DSP Controllers

The target applications for a DSP having the necessary features may be anywhere where the above mentioned advantages meet the needs. Typical applications are:

- Automotive control (electronic power streering, anti-lock breakes)
- HVAC (heating, ventilation and air conditioning)
- Blowers and compressors
- Factory automation

- Major appliances (direct drive horizontal axis clothes washers)
- Office products (printers, copiers, tape drivers)

4. TEST RESULTS

After having finished the design and manufacturing of the switched reluctance motor driver circuitry, some tests have been made on the circuitry and on the motor in order to confirm the operation of the circuitry. The following sections include detailed information about the tests that have been made.

4.1 Switched Reluctance Motor Inductance Measurement Tests

The inductance of each of the phases of the switched reluctance motor must be known in order to determine the parameters that would be used in exciting phases. The simulation models that are going to be created to perform detailed analysis depend on the value of phase inductance.

The phase inductance depends on the rotor position, i.e., the highest inductance is achieved when the rotor and stator phases are exactly aligned and the lowest inductance is achieved when they are totally misaligned. In order to determine the phase inductance varying with the rotor position, an inductance measurement device is used while the rotor is manually set in a position. Changing the position of the motor and recording the corresponding inductance values at each position results in a phase inductance versus rotor position curve, as shown below in figure 4.1-1:

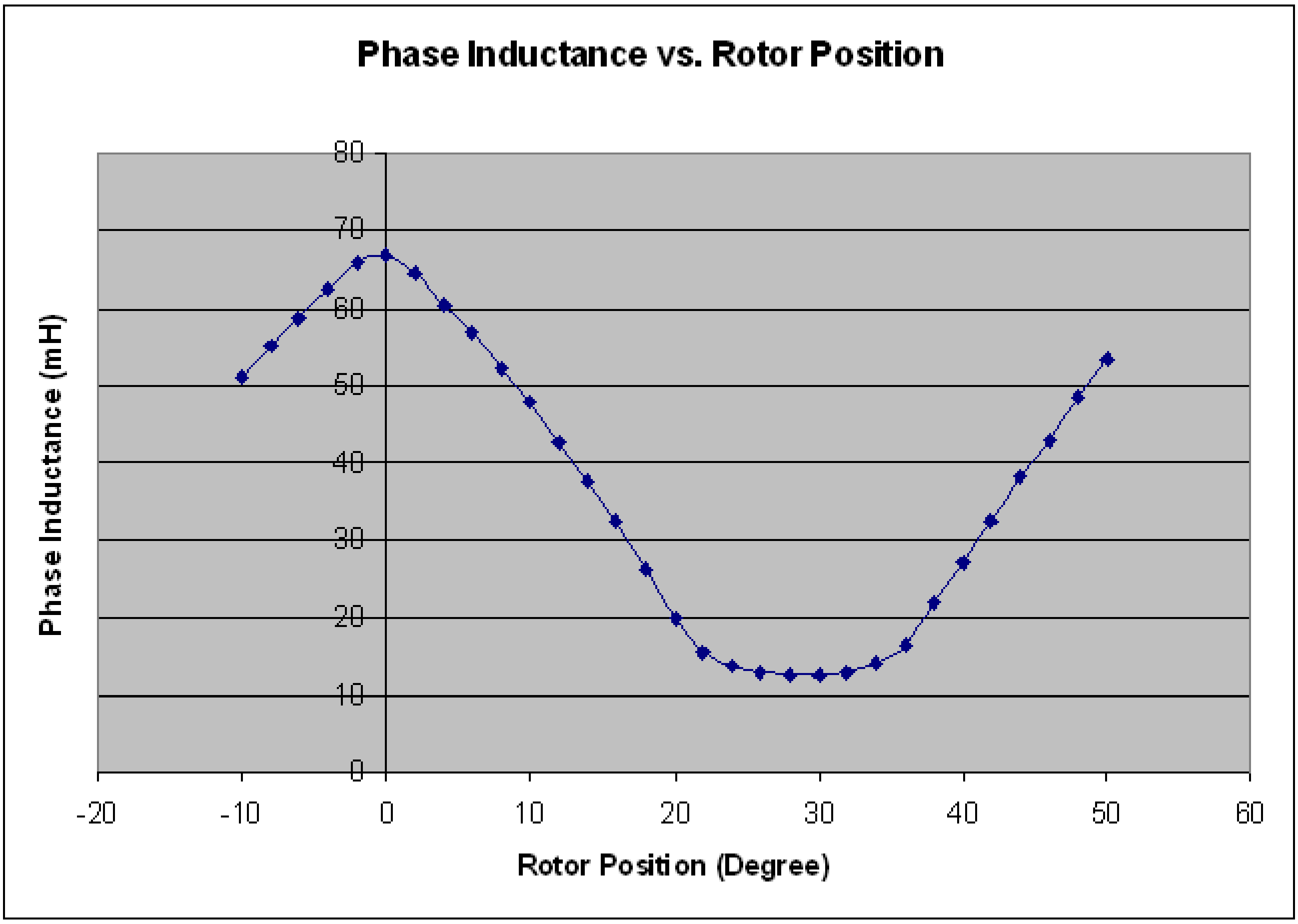


Fig. 4.1-1 Phase Inductance (mH) vs. Rotor Position (Degrees)

As it can be interpreted from figure 4.1-1, the maximum value of the phase inductance (at the aligned position) is about 68mH and the minimum value of the phase inductance (at the misaligned position) is about 12 mH.

The result of the measurement made above is accurate when the phase current is assumed to be low. The measurement device that is used to make the above measurement applies only a few milliamperes of phase current. However, during the normal operation of the motor, the phase coils are fed with currents up to 2,5 amperes, which could result in saturation in the magnetic material, and thus a change in the inductance of the coil.

To obtain the inductance value at a high phase current, another test is made. when the rotor is at its aligned position, a high voltage pulse is being applied, that would result in a steady state current of 1 ampere. According to the transient behavior of the phase current, the inductance of the phase can be calculated, while the DC resistance of the phase coil is known.

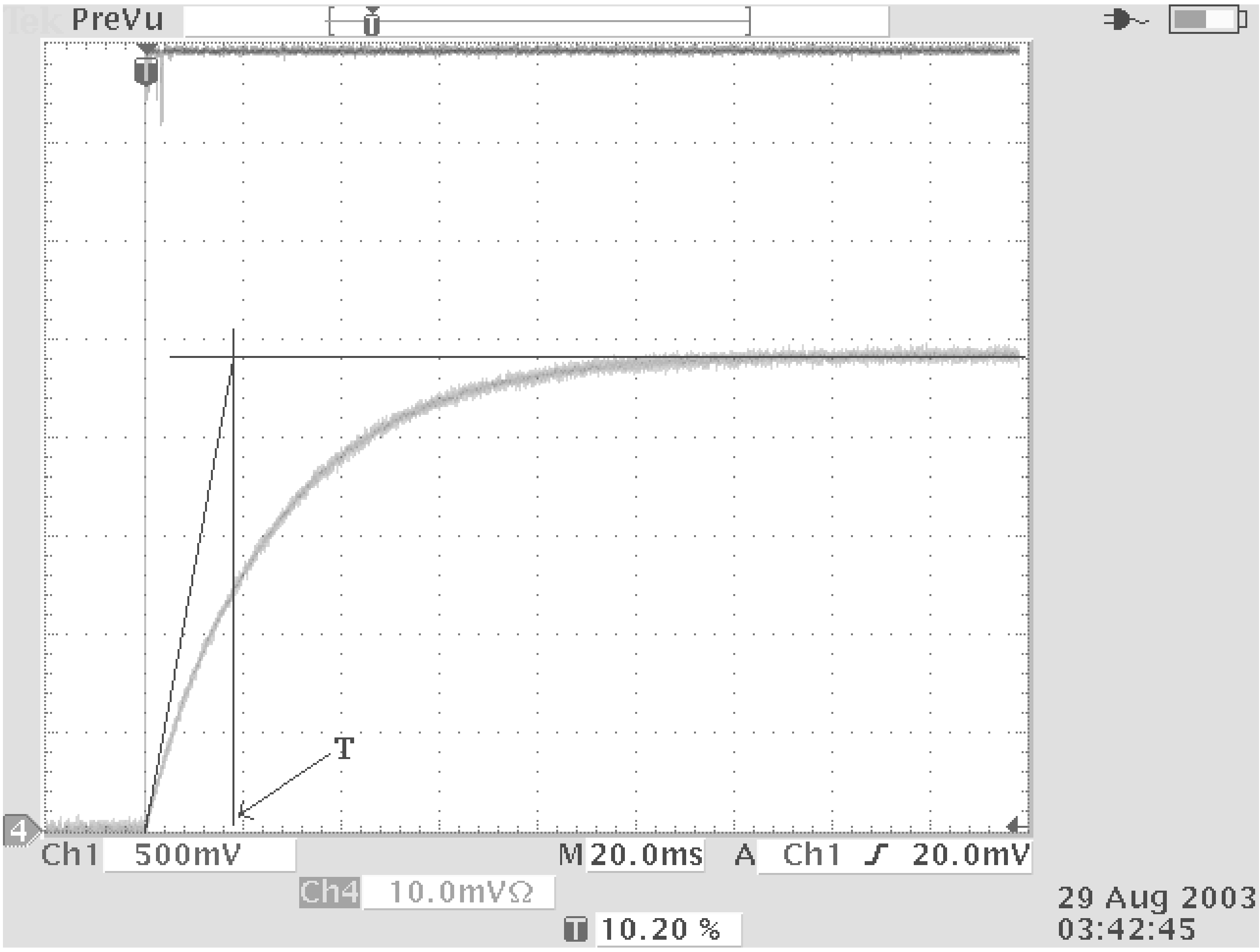


Fig. 4.1-2 Phase current transient behavior

In the Figure 4.1-2, the square pulse shows the voltage waveform that is being applied to the phase coil, and the curve shows the transient behavior of the phase coil current. The phase current is being observed by a current probe (Hall Effect type) and a current probe amplifier, by which, when the corresponding channel’s scale is set 10mV/div, each division corresponds to 200 mA. The steady state current of the phase coil is about 960 mA. As shown in the figure, the intersection point of the steady state asymphtode line and the line having the initial slope passing through the origin determines the time constant of the circuit, which is a measure of the inductance of the phase coil.

From the figure above, the time constant is;

$$T = 18\,\mathrm{msec}$$

$$R = \frac{4}{0,96} = 4,17\,\mathrm{ohms}$$

$$T = \frac{L}{R} \longrightarrow L = T \times R = 75\,\mathrm{mH}$$

The calculated inductance value is close to the result of the previous measurement. The following measurement is made with an increased value voltage applied to the phase coil as shown in the figure 4.1-3 below.

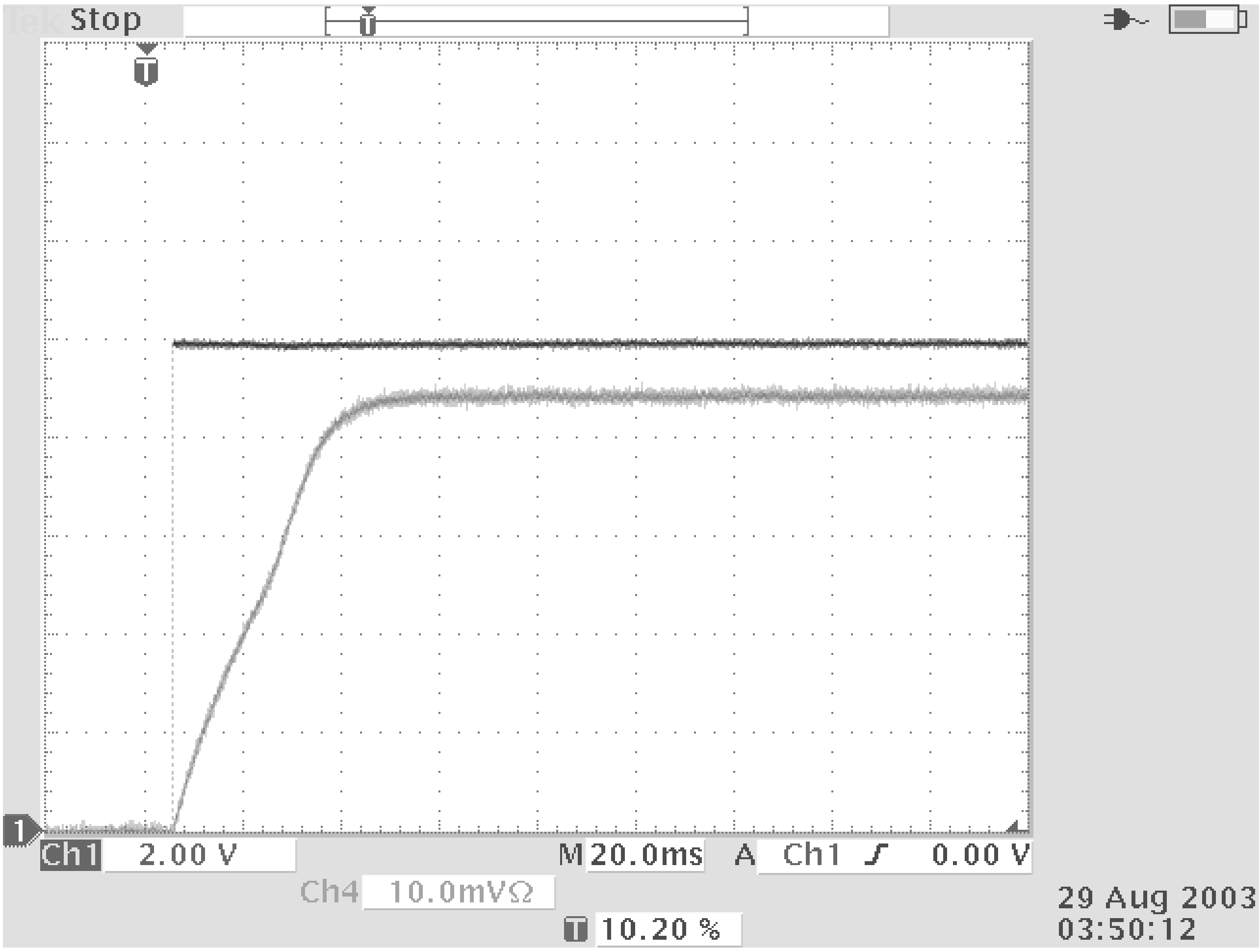


Fig. 4.1-3 Phase current transient behavior; increased input voltage

Now, a pulse of 10V is applied to the phase coil, resulting in a much higher phase current. It can be easily seen from the figure that the current curve is now not like a natural exponential because of the change in the inductance as the current is increased. The steady state current of the phase coil is about 2 Amperes. from the figure, it can be concluded that the change in the inductance of the phase coil is not so big that it can be assumed to have the values obtained from the measurement made with the inductance measurer device.

4.2 Phase Coil Excitation Test

As to confirm the operation of the high and low side drivers one of them is excited without the DSP. To simulate a PWM signal, a square wave with a duty cycle of 20% is being applied to the high side power MOSFET and a constant excitation is applied to the low side power MOSFET.

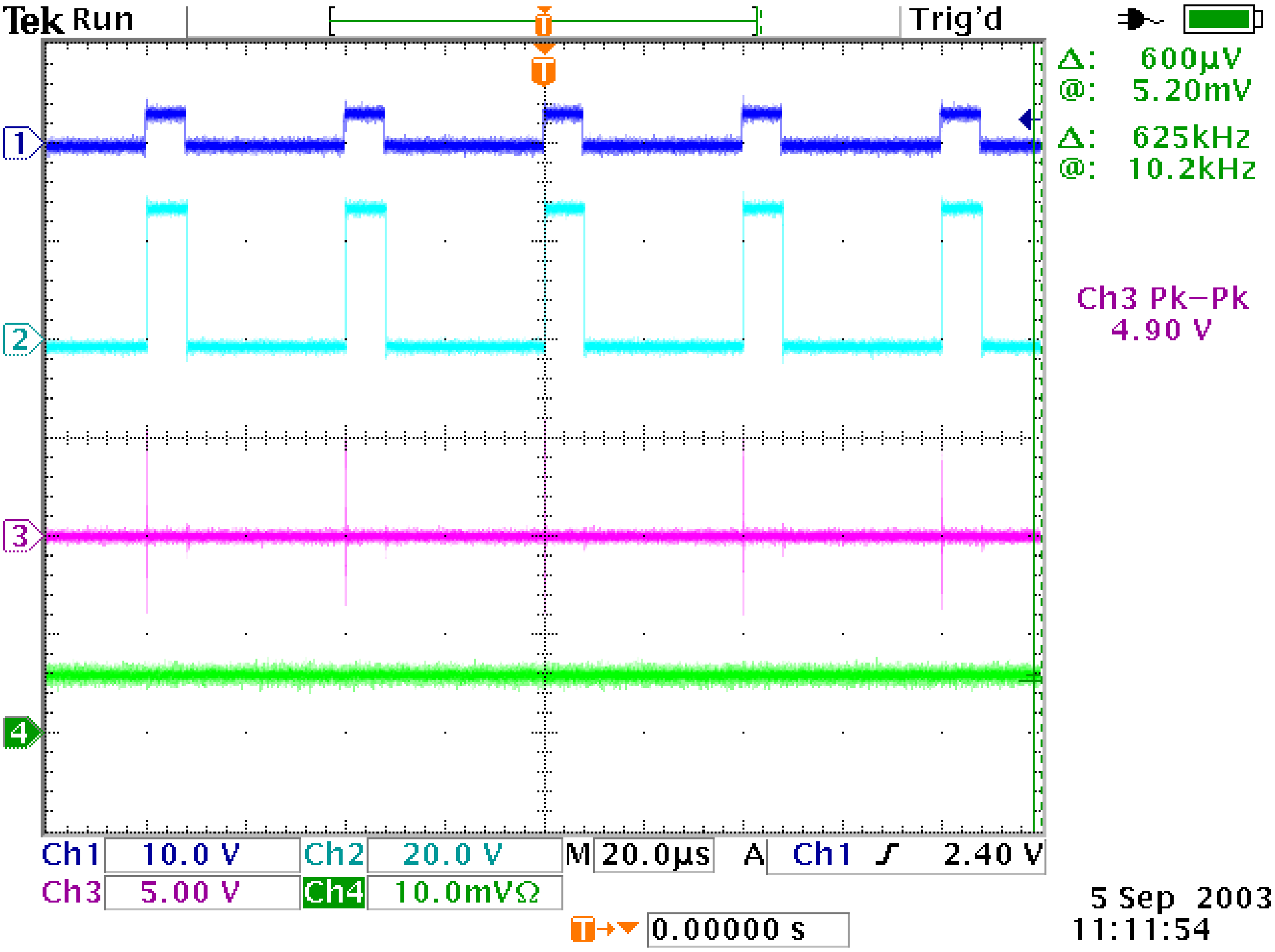


Fig. 4.2-1 Phase coil excitation test

The signals shown in the figure 4.2-1 are the following;

(1) The excitation given directly to the pin where the DSP is supposed to be connected (PWM - A High Side).

(2) The voltage of the source of the high side power MOSFET (one end of the phase coil).

(3) The voltage of the drain of the low side power MOSFET (other end of the phase coil)

(4) The current through the phase (scaled to 5A/div)

The signals are observed to be as expected. With the low side driver permanently turned on, the signal 3 is a ground signal, except for the impulses that occur at the moments that the current commutates from the transistors to the diodes, as the high side power MOSFET is being switched on and off. The current passing through the phase coil is almost constant since the phase inductance is big and the frequency of the excitation signal is high (25kHz).

Not being included in this report, the propagation delays for switching on and off times of the high side driver + power MOSFET system are also observed. They are:

$t_{p,on}$ = 200 ns

$t_{p,off}$ = 300 ns

4.3 Hardware Operation Tests

After the design has been manufactured, all the individual parts of the driver circuitry have been tested by signal tracing methods.

5. CONCLUSION

Before it had started, my general view about the summer practice was positive. My aim was to gain skills and techniques that are applicable to electrical engineering and to become more competent by practicing on the subjects that I have learned during the semester in the courses. Truthfully, not all but most of my expectations were covered. I had a chance to contribute work just like an engineer in some cases, but I also had tasks that I was still too inexperience to deal with. It was helpful to learn how important the practical experience is, yet along with a strong theoretical background.

One thing that hereby must be told is that for me it has been a great experience to be in a foreign country and in a big company that has an engineering experience gained over decades. Speaking a different language to discuss technical issues and to communicate during the work is itself a valuable experience for an engineering career.

After all, it has been very useful to me that I have learned a lot about the structure of an industrial company. This work I performed helped me in gaining practical experience that served as complementary knowledge to my theoretical background. It was challenging and fun.

6. REFERENCES

1) „Implementation of a Current Controlled Switched Reluctance Motor Using TMS320F240“, Application report, SPRA282, Texas Instruments, September 1998.

2) „Digital Signal Processing Solutions for the Switched Reluctance Motor“, BPRA058, Texas Instruments, July 1997.

3) „Bootstrap Component Selection For Control IC’s“, J. Adams, Design Tip DT 98-2a, International Rectifier, 1998.

4) „HV Floating MOS-Gate Driver IC’s“, Application Note AN978-b, International Rectifier, 1997.

7. APPENDICES

7.1 Data Sheets

- (a) IR2110/IR2113(S), High And Low Side Driver, Data Sheet No. PD60147-S
- (b) IRF2805, Automotive MOSFET, Data Sheet No. PD94428
- (c) 60APU02, Ultrafast Soft Recovery Diode, Data Sheet No. PD20749 rev:C
- (d) LEM HX10-P, Current Transducer, 021202/5
- (e) TPS2829, Single Channel High Speed MOSFET Driver, SLVS160C
- (f) SN74AHC244Q, Octal Buffers/Drivers with 3 State Outputs, SGDS017
- (g) SN74AHCT244Q, Octal Buffers/Drivers with 3 State Outputs, SGDS024
- (h) LM393, Low Power Dual Voltage Comparator, Document Order Number: 939775010182
- (i) PCA82C251 CAN Transceiver for 24V Systems, Document Order Number: 939775006611
- (j) 1N4148, Small Signal Diode
- (k) AD822, Low Power FET Input OPAMP, C00874-0-1/03(E)
- (l) TLV2471, High Drive OPAMP with Shut Down, SL0S232B
- (m) INA128U, Low Power Instrumentation Amplifier, PDS-1296C

7.2 Switched Reluctance Motor Specifications

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