Active magnetic bearing driver circuit design featuring current measurement integration

Lukas Girlevicius
Abstract

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Researchers at Uppsala University are developing a flywheel energy storage device intended to be used in electrical vehicles. Kinetic energy storage technology has potential to make purely electric powertrain both more effective and efficient. While deployment of the third prototype is approaching there has been a request for a more precise and noise-immune circuitry to power active magnetic bearings that hold and stabilise the rotor. A similar circuit designed for powering electromagnets was recently developed at the Uppsala University’s Electricity department and is used as a template in development of the new active magnetic bearing driver circuit. Current measurement integration technique is tested and implemented as a way to increase circuit’s control feedback loop performance. To further boost precision and noise-immunity 0-20 mA current loop signals are adapted as the standard for output signals. Results of this project include a thorough analysis of the electromagnet driver circuit development, implementation of a new current sensing technique including an experimental self-inductance measurement, printed circuit board layout design and a full list of components necessary to power and control two sets of active magnetic bearings consisting of 8 individual electromagnets.
Foreword

This bachelor thesis work was done at the Uppsala University’s Department of Electricity. Special thanks to PhD Johan Abrahamsson for introducing me to the flywheel research group and making this thesis work possible. Warm thank you goes to this thesis supervisor, PhD candidate Magnus Hedlund, for all the inspiration and support I have received during period of this project. As a token of gratitude I hereby declare PhD candidate Tobias Kamf and MSc Fredrik Evestedt my personal heroes because of their help and contributions.
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Nomenclature

FES - Flywheel energy storage
AMB - Active magnetic bearings
EMI - Electromagnetic interference
H-Bridge - Power electronics circuit able of delivering current to the load bi-directionally
Op-amp - Operational amplifier
EMD - Electromagnet driver circuit developed by Tobias Kampf
PWM - Pulse Width Modulation

$V$ - Voltage [V]
$I$ - Current [A] or Moment of inertia [kg*m^2]
$R$ - Resistance [Ω]
$P$ - Power [W]
$\omega$ - Angular velocity [rad/s]
1. Introduction

1.1 Background

Today flywheels are most commonly associated with the internal combustion engine, where it balances the engine’s operation by providing continuous rotational energy between piston’s strokes. The rotating mass of the flywheel offers a medium to efficiently store large amounts of energy for a shorter period of time. Using a high performance flywheel as a buffer between the electrochemical battery and the electric motor would extend the battery’s capacity and longevity. High rotation speeds that are necessary to achieve this performance can be sustained by placing the rotor in a vacuum chamber and supporting it with active magnetic bearings. These consist of several electromagnets surrounding the center axis at two locations. By constantly pulling with an equal force these magnets keep the rotating body suspended in the center while allowing it to revolve around it’s axis freely. To balance this system precise position of the body and force exerted by every electromagnet have to be known. Therefore a control feedback loop consisting of position and the current measurements are aiding a controller device to actively balance the body supported by the electromagnets. Accuracy of these measurements is very important to the overall performance of the magnetic bearings and the flywheel energy storage system as a whole. There is need of analog, digital and power electronics to operate active magnetic bearings and it makes for an interesting and challenging circuit to design.

Flywheel energy storage devices are already being used in transportation, uninterrupted power supplies and aerospace applications. The flywheel research group at Uppsala University’s Electricity Department is working on improving the current flywheel technology in order to make it available for the broader market. This technology has several advantages such as high energy density, fast discharge rate and long lifetime while the complexity of a complete system is one of its disadvantages. A properly designed FES would be a great addition to large electrical vehicles such as trucks or busses, where frequent high power discharges that have a detrimental effect to the battery’s health could be handled by the flywheel.
1.2 Objective

Researchers at the division of electricity at the Uppsala University are soon deploying a new flywheel energy storage prototype and a new set of improved driver circuits to power the active magnetic bearings were requested. The new circuit has to consist of 8 full H-bridges capable of operating at maximum supply voltage of 100 V, maximum current of 10 A and switching speeds of up to 50 kHz. The current delivered to every individual electromagnet in the bearings has to be precisely measured and sent back to the controller by using a current loop signal. The circuitry needs to be robust and immune to electromagnetic interference as it will be working alongside high power components. Development of the new active magnetic bearing driver circuit should be based on a comparable and recently developed electromagnet driver circuit. The design of this circuit will be studied, analysed and summarised so that the new so that it is clear how the new driver is following and improving upon existing circuit design.

1.3 Restrictions

This project focuses on development and design of a new driver circuit. Performance of this circuit together with the rest of the flywheel circuitry is prioritized but not guaranteed as it may need additional hardware such as an interface card for optimal compatibility with the controller device.
2. Theory

2.1 Flywheel energy storage

The energy storage capacity of a typical flywheel used in combustion engines is usually very limited, as it rotates on mechanical bearings at relatively low speed of a few thousands revolutions per minute. However there are ways to make a flywheel perform on a level where it would be competing with batteries in terms of energy storage density and capacity. Energy stored in a rotating body is equal to the product of moment of inertia $I$ and square of the angular velocity $\omega$, divided by two:

$$E_k = \frac{1}{2}I\omega^2.$$  

Geometry and mass of the rotating body determine moment of inertia but it is clear that because of the square proportionality a high rotation speed is the key factor in increasing flywheel energy storage capacity. Limiting factors such as aerodynamic drag and friction-caused wear of bearings also depend on the rotation speed, reducing efficiency of the whole system. Therefore many modern FES devices are avoiding these negative effects by placing the rotating body in a vacuum chamber and keep it levitating by using magnetic bearings. An electrical reluctance motor is integrated into the device in order to allow efficient conversion between kinetic and electric forms of energy, broadening the list of FES’s potential applications (Abrahamsson 2011).

Figure 1. Flywheel energy storage device developed at Uppsala University (Abrahamsson 2011).
2.2 NI CompactRIO

National Instruments CompactRIO embedded real-time controller is at the core of the whole FES system developed by the Flywheel research team. Through a stack of various analog and digital swappable I/O modules CompactRIO is overseeing everything from power management to position sensors, including the active magnetic bearings control. Its processor and FPGA unit are programmable in Labview graphical environment. It’s adaptability has proven an asset during the years as it is easy to add additional circuitry and generate new control signals. Hence the CompactRIO is intended to deliver and receive all signals from the driver circuit developed in this project.

2.3 Active magnetic bearings

Most commonly implemented magnetic bearings use actively controlled electromagnets. A bias current is activating one or several pairs of opposing electromagnets placed around an axis. While the magnets are pulling the axis, a position sensor is keeping track of the axis and making adjustments in order to keep it balanced and centered. Therefore it is necessary to measure the current delivered to the electromagnets so that it can be accurately adjusted. This type of magnetic bearings offers several advantages such as variable dynamics and complete monitoring of the system performance (Abrahamsson 2011).

![Diagram of electromagnets](image)

Figure 2. Pair of electromagnets in AMB operation (Abrahamsson 2011).

The third iteration of the flywheel energy storage prototype, just like the previous one, will feature two sets of radial active magnetic bearings consisting of two pairs of electromagnets each. This means that the current will have to be delivered, measured and controlled in 8 separate devices.
2.4 Electromagnetic interference

Electromagnetic interference is a high frequency energy that interferes with the operation of electronic devices. It can be produced externally or by the device itself. Coupling is an electrical relationship between two or more signals in which they are affecting each other. In case of EMI these relationships are highly undesirable as they adversely affect signal quality. There are four basic EMI coupling mechanisms:

- **Conductive coupling** occurs when there is a direct conductive connection, such as wire or metal enclosure, connecting the two systems. It is easily avoidable by proper isolation and separation of the conductors.
- **Inductive coupling** is the unwanted magnetic induction of electrical current between two closely located conductors. It is particularly difficult to avoid at high currents and frequencies. The best solution is to place the susceptible conductors as far away as possible from highly inductive ones.
- **Capacitive coupling**, also known as parasitic capacitance, is the electrical induction of voltage caused by an electric field between two conductors. It can be avoided by placing the conductors further apart and having a ground line in between them.
- **Radiative coupling** occurs when a circuit acts as an antenna and picks up unwanted high frequency signals. It can be anything from radio or cellphone signals to sun storm or background radiation. This can be prevented by shielding certain components or the whole circuit with grounded conductive material.

figure: 'Different types of EMI (Wikimedia)'

(PCS Design guidelines for reduced EMI by Texas Instruments 1999).
2.5 Power electronics

Power electronics are electrical circuits intended to control the flow of electrical energy. These circuits are capable of handling power flows at much higher levels than regular small signal electronics. In the FES prototype and AMB in particular, power electronics are the link between the power supply, control devices and the load. Figure 4 illustrates this relationship in terms of a block diagram. In case of the AMB driver circuit the energy source would come from an external power supply, CompactRIO acts as a control circuit while electromagnets are the loads.

![Block diagram of power electronics as part of a larger system (Rashid 2011).](image1)

The H-Bridge is one of the most commonly used power electronics circuits. It is the only piece of power electronics used in the AMB driver circuit, hence it will be referred to as H-bridge in this paper. Consisting of an arrangement of 4 power transistors in an H shaped formation, the load being connected between the lower and the upper bridge as shown in figure 5, H-bridge is capable of controlled and bi-directional power delivery. Pulse Width Modulated (PWM) control signal switches between diagonally placed transistors S1-S4 and S2-S3 in order to change direction of the current. Opening upper S1-S3 or the lower S2-S4 bridges cuts the power delivery but this feature will not be used in this the third prototype of FES (Rashid, 2011).

![H-Bridge circuit (Wikimedia).](image2)
2.6 Analog electronics

Analog electronics work with low power signals that are continuous over time. Most of the natural phenomena such as electrical current are also continuous so they can only be measured by analog circuits. Since analog electronics operate in real-time it comes with a cost of some inherent noise and increased sensitivity to EMI (Analog Devices, 2015). While the transistor is one of the most basic analog component it is more practical to use operational amplifiers also know as op-amps. These are made of tens to hundreds of transistors offering flexibility, high bandwidths and robust performance. Common mode rejection ratio (CMRR) is a measure of how well an op-amp is rejecting the part of a signal that is common on both positive and negative inputs. Since that part is most often caused by EMI and is referred to as noise, CMRR is sometimes called noise rejection ratio. Because t rnoise rejection There are many various op-amp circuits but the unity gain buffer, inverting amplifier, differential amplifier and op-amp integrator are the ones that are being used in the design of the new AMB driver circuit.

![Diagram of Operational Amplifier Circuits](image)

Figure 6. Operational amplifier circuits (Wikimedia).

1. Unity gain buffer is a high input - low output impedance circuit that replicates the input voltage at its output: It is used to assist circuits with low power signals or high output impedances.

\[
V_{in} = V_{out}.
\]

2. Inverting amplifier features a current loop feedback which makes it suitable for inverting, amplifying and generating a current signal.

\[
V_{in} = -V_{out} \cdot \frac{R_f}{R_{in}}.
\]
3. Differential amplifier performs the mathematical operation of subtraction, amplifying only the difference between two inputs, which is useful for measurement of voltage drop.

\[ V_{out} = (V_{in1} - V_{in2}) \]

4. Op-amp integrator performs the mathematical operation of integration of the input current. The integrated current stores charges on the input side of the capacitor causing an inverse voltage at the output.

\[ V_{out} = \frac{1}{RC} \int_{t_0}^{t} V_{in}(t) \, dt . \]

(Molin, 2009).

2.7 Digital electronics

Digital electronics represent a signal in discrete levels, called logic levels, as opposed to the continuous spectrum of their analog counterparts. These devices are useful since it is easier to control equipment by switching between distinct states (most often on/off). For that reason digital signals are more immune to EMI. However the rapid switching nature of digital components create interference that can be harmful to analog signals. The FES is controlled by a digital automation controller CompactRIO that uses digital signals to interact with the AMB driver circuit. A digital gate driver receives the control signal and operates the H-bridge accordingly. Analog current measurements received by the CompactRIO are first converted to digital data and then processed by the controller. Several logic gates such as inverters, AND-gates and D flip-flops are used in the AMB circuit to provide timing sequences and lower the amount of input signals.

Figure 7. CompactRIO real-time controller (National Instruments).
2.8 Current loop measurement signal

It was requested that the current measurement would be reported back to CompactRIO using a current loop signal. This means that measurement values will be represented by a small current that is proportionate to the current in the electromagnets. Current as a signal bearer is inherently more immune to noise because EMI induced current are tiny compared to the signal. Robustness of this signal is further increased by the closed loop feedback that adjusts voltage so that the current stays stable. 4-20 mA is a common signal range for industrial process control instruments. Zero current would indicate that the sensor/device is broken and has to be replaced, which is a useful feature in large factories containing thousands of sensors (Acromag Inc, 2015).

![4-20 mA Current Loop](image)

Figure 7. An example of a current loop signal transmission (National Instruments).

2.9 Software

An array of simulation and design software was used in order to examine, simulate and design the AMB circuit. A short summary of the programs used is provided in this sub-chapter.

2.9.1 LTSpice IV

LTSpice IV is a high-performance electrical circuit simulator capable of dealing with complex electrical circuits and visualising various signals. While not being able to simulate entire EMD or AMB circuits due to the lack of several IC models, this freeware was successfully used for smaller simulations and verifications. Generally it was the first step between a theoretical electrical circuit and its implementation.
2.9.2 Mathworks Matlab and Simulink

Matlab is a powerful computational software that can perform even the most complex simulations. Simulink is an additional module that offers ready-made tools and algorithms to simulate electrical systems. Since everyone working or studying at Uppsala University can acquire a MATLAB license it is frequently used for any type of mathematical computations.

2.9.3 NI Labview

Labview is a graphical programming language that is used to program and control CompactRIO as well as its’ expansion modules in real time. Labview was used to generate signals similar to the ones that will be controlling the H-bridges and current measurement components.

2.9.4 CadSoft Eagle

Eagle is a simple to use printed circuit board (PCB) design software that is commonly used in various electronics projects at Uppsala University. Freeware version allows users to make 2-layer PCBs of a limited size but since the Electricity Department holds a professional license there are no size restrictions and 16 signal layers are available. Division between the electric circuit schematic and the actual circuit board views enables design of a circuit theoretically first before the transition to PCB view where every component and wire has to be placed on the board manually.
3. Method

3.1 Electromagnet driver circuit development analysis

The project started with a study, analysis and documentation of the electromagnet driver circuit developed by PhD candidate Tobias Kamf at the Uppsala University’s Electricity Department. Since this circuit was designed to deliver current to a high impedance inductive load. Ratings for the system were as follows: voltage of 24V, maximum current of 5A and switching frequency of <100 kHz. These specifications are lower than the ones for the magnetic bearing driver circuit but there are many valuable lessons to be learned from this circuit.

The first step was the creation of a detailed list comprising all ICs used in latest version of the EMD circuit. In order to break down the complexity of this system every component was analysed individually by studying the datasheets. The second step was analysing the circuit schematics in order to understand how these components interact and form a complete system. The final step was a study of the PCB layout: supply and ground plane design, IC package choice, component placement and other practical matters. Through all the steps designer of the EMD circuit was interviewed, explaining and motivating various design choices. The final circuit blueprints are shown in figure 8 and figure 9 below.

![Schematic of the final version of the EMD circuit (Kamf).](image-url)
The following paragraphs briefly describe development of the EMD circuit from the first to the final generations, such as the circuit shown in figure 10. This chronological analysis is useful when trying to understand the circuit “bottom up”. That approach is especially valuable when learning of the development process is just as important as the final solution.

1. A basic H-bridge circuit was built on a prototype board using n-channel power mosfet transistors that met the requirements. The transistors had to be arranged in a straight line since the standard H-formation made it hard to avoid control signals crossing the high current wires. In order to control the current it needs to be monitored. Real time current measurements are necessary to actively control the delivered to the load. This is done by placing a very low ohmic resistance anywhere in the H-bridge and then measuring the voltage drop. Two shunt resistors of 0,05 Ohm each were placed on the ground end of the circuit. Generic instrumentation amplifiers used for current measurements and a HIP4080 H-bridge driver powering the gate signals were set up on a separate breadboard. Control was also done externally using a simple logic circuit. For testing purposes a
ferromagnetic core coil similar to an electromagnet was used as the load. The complete
driver circuit showed satisfactory results and the printed circuit board design was started.

2. The new prototype circuit was based on a single two-layer printed circuit board, using
through hole mounted control and power electronics. In addition to previously described
components, a charge pump was introduced to provide a negative rail voltage to the
operational amplifiers. The circuit was still controlled by an external logic circuit,
operating one side of the H-bridge at a time. During testing an unacceptable amount of
noise was present in nearly all signals and the power transistors were producing too much
excess heat. Since all the components were sharing a homogenous ground plane on the
bottom layer of the circuit board, it was suspected that the rapid switching operation of
power transistors interfered with the rest of components. A new pcb design had to be
made to protect the more sensitive driver and current measurement electronics. Similar
circuits were studied to find the most viable design solution.

3. This iteration introduced a lot of new design and component changes. Analysis of similar
circuits showed that it is common practice to separate power component’s ground and
voltage planes from rest of the circuit while still maintaining a common reference. It is
done by creating an insulating divider between the conducting plane segments but not
separating them entirely, similarly to a breakwater protecting a harbor. Fast switching and
high power components usually are isolated by removing any conducting material on the
back layer of the pcb to prevent induction of noise in other planes. This was especially
applicable to the new surface mounted Texas Instruments mosfets CSD88537ND, chosen
to replace the bulky and inefficient hole mounted transistors. These are completely
encapsulated and lack a proper heatsink. Drain and source nodes were given a larger
conducting surface layer than electrically necessary to improve heat dissipation and
ensure optimal operational temperatures. Bulky shunt resistors from the lower bridge
were replaced by a single low profile 0,025 Ohm shunt resistor directly on the load line.
This design choice lowered the amount of components but the generic instrumental
amplifier had to be replaced by a high CMRR dedicated shunt monitor to deal with the
switching polarity of the measured current. This component requires a negative rail
voltage so a charge pump was to be used. A fuse was introduced to protect the circuit
components in case of power transistor failure. Testing showed mediocre performance
with noise in both control and measurement signals. While the power electronics were
isolated from rest of the circuit, the charge pump was unshielded and emitting too much
high frequency noise. Isolating this component was impractical and therefore an external
-15 V supply was adopted in the final versions.
Figure 10. One of the latest EMD circuit prototypes (Kamf).
3.2 Adoption of electromagnet driver circuit sub-circuits

It is important to note that while the whole circuit will be redesigned, certain sub-circuits of the EMD circuit have all the desired functions and have been adopted straight into the AMB circuit. A schematic of the inherited circuitry is shown in figure 11. After that follows a list and description of these.

![Schematic of components inherited from the EMD circuit (Kamf).]

- H-Bridge circuit layout was designed for two dual N-channel power MOSFETs. There are several SO-8 packaged power transistors that are able to deliver power at ratings requested and well above. All N-channel MOSFET H-Bridge is the most efficient alternative as it has the lowest on-resistance. The only consideration is that the high side transistors require a gate signal that is at higher voltage than the drain voltage, which is the supply. However there are driver ICs developed particularly for this application that use a bootstrap capacitor to generate gate signal pulses required to switch the high side transistors on.
• Power MOSFET full bridge driver Intersil HIP4081a is kept since it is tested to operate properly together with the previous transistors and its maximum ratings are deemed sufficient to meet the specification. IC’s logic threshold levels are compatible with both 5 and 15 V signals, allowing control straight from the NI9401 digital input/output module. HIP4081a will be sending out bootstrapped high power and high frequency pulses that are necessary to control the power MOSFETs. As a result of this, it will create a lot of EMI and special consideration will have to be taken in order to minimise its impact on the performance of other circuits.

• Current measurement is done inside the H-bridge circuit by measuring voltage drop over a small value shunt resistor connected in series with the load. This technique allows bipolar measurement but requires a differential amplifier with a high CMRR in order to measure the voltage drop. Analog Devices AD8210 is a suitable component for this task with 120 dB CMRR and therefore this current measurement solution will be adopted in the AMB driver circuit. AD8210 has gain of 20 times and its output voltage has a range of 0 to 5 V. Since the maximum current specification of the EMD circuit is 5 A it will be necessary to replace adjust the shunt resistor value in order to accommodate measurements up to 10 A. Figure 12 illustrates the current measurement circuit used in the EMD and AMB circuits.

![Figure 12. H-bridge current measurement (Analog Devices).](image-url)
3.2 Current integration measurement technique

3.2.1 Background

All of the EMD circuits featured instantaneous current measuring at discrete intervals. In this operation an A/D is converting the measurement signal into digital data that is fed back to the control device. The problem with this measurement technique, apart from the errors that come with discretisation, is that it offers low immunity to noise. A voltage spike caused by EMI will be recorded as a high value while the average signal value might be much lower. This can cause problems in the feedback loop as the current measurement together with axis position measurements determine the current that will be delivered to the electromagnet during the next control period. Noise introduced in this complex system lowers the maximum rotation speed of the flywheel as the active magnetic bearings are not able to deliver their best axis-balancing performance.

3.2.2 Simulation

Project supervisor Phd candidate Magnus Hedlund provided a MATLAB Simulink simulation of the impact a current integrator circuit would have on a noise-afflicted current measurement. In the simulation, a power supply of 100 V is delivering a current to an inductive load having approximate properties of an electromagnet used in the AMB. Actual current is measured before a randomly generated noise signal is superimposed on the measurement signal. An integrator circuit processes this purposely EMI-afflicted signal by integrating it over a period of time that is much longer than a typical EMI period. Dividing this sample by the integration period produces an average of the current measurement signal’s value. The result is more representative of the actual current than an instantaneous value acquired from the noisy measurement as the integration process cancels out oscillations caused by high frequency EMI. Figure 13 shows two current measurement signals:

- Yellow - an actual current measurement with added random oscillations of 0.5 A in amplitude at a frequency of 10 MHz.
- Pink - same signal after being processed by an integrator at a sample frequency of 25kHz.
This simulation provided evidence that a current integration feature would be a beneficial addition to the magnetic bearing driver circuit as it greatly reduces the impact EMI has on the quality of the current measurements.

3.2.3 Circuitry

Since current integrator is a very basic Op-amp circuit it first seemed like a simple task to develop a complete integration sub-circuit. Sample & Hold functionality is critical since the integrator should stop integrating and hold its value while the CompactRIO module is reading the signal. After measurement acquisition is done the integrator should reset and start another integration period. A considerable amount of time was spent on this but it proved that a circuit with all the desired features such as reset and sample & hold would need quite a large arrangement of timers, logic gates and transistors working perfectly in sync.

After some online research an integrated circuit capable of integration and all the other features was found. Texas Instruments ACF 2101 Dual Switched Integrator (Figure 11.) features two sets of Op-amps integrating over 100pf precision capacitors and TTL-logic controlled hold, reset and select switches. Having a select feature enables two integrators to work in a complementary fashion, one integrates while the other holds a measurement value. If reset is done during the
hold-period it possible to integrate over 100% of the measured signal. Since this IC presented a convenient and feature-rich solution several were ordered for prototyping and testing.

Figure 14. ACF2101 function diagram and its 3 modes of operation (Texas Instruments).

3.2.4 Implementation

While the all-in-one current integration solution provided by the dual integrator IC fit perfectly in theory, it had to be adopted and tested together with rest of the driver circuit. Since the integrator circuit is dependant on several logic input signals triggering between Integrate, Hold and Reset modes of operation, it was most convenient and efficient to use the rising edge of the main PWM-signal for triggering.

Integrate and Hold periods have to be controlled by a 5 V logic 50% duty cycle signal so that both periods are equal in length. Maximum frequency of the PWM-signal is 50 kHz which is halved in order to dedicate half of this period for integration and the other half for holding the measurement value. Integrator HOLD signal frequency of 25 kHz translates to 20 us of integration and another 20 us for holding which provides enough time for the CompactRio to read the measurement (7 us), reset (6 us) and settle at 0 V (2 us) before another integration period starts. A rising-edge triggered D flip flop modulates the PWM-signal into a 25 kHz square
wave that works as the logical HOLD signal for the integrator A while the inverse of this signal controls integrator B.

The RESET signal has to come approximately halfway through the HOLD period and since the operating frequencies of this whole system can vary, the easiest way is to send a RESET signal directly from one of the CompactRIO digital output modules. The SELECT signal is used to switch between the two integrators and since only the integrator in Hold mode is of interest, this signal can be dependant on HOLD. More precisely SELECT A is the inverted HOLD A signal. Figure 15 illustrates the logic circuit used to derive control signals for a single integrator pair.

![Integrator control signal logic model](image)

**Figure 15. Integrator control signal logic model.**

Besides consideration of the necessary logic control signals it is also important to note that ACF2101 maximum input current is of 100 uA which integrates negatively from 0 to -10 V on the output pin. By using the formula in figure 13 it is possible to calculate the input current that is suitable for any combination of integration capacitor and operating frequency.

\[
V_{OUT} = \frac{I_{IN} \times \Delta t}{C_{INT}}
\]

\[V_{OUT} = \text{the maximum output voltage (in volts)}\]
\[C_{INT} = \text{the integration capacitance (in farads)}\]
\[I_{IN} = \text{the input current (in amperes)}\]
\[\Delta t = \text{the integration time (in seconds)}\]

**Figure 13. Integrator output voltage formula (Texas Instruments).**

The PWM-signal at 50 kHz results in an integration period of 20 us. The built-in capacitor of 100 pF is used and 10 V is the maximum output voltage. Calculation of input current that yields maximum output under an integration period:

\[
I = (10 \, V \times 100 \, pF) / (20 \, \mu s) = 50 \, uA.
\]
Shunt monitor AD8210 output range is 0-5 V with 5 V for a current of 10 A and 0 V for -10 A. Maximum output of 5 V should result in a 50 uA input current to ACF2101. This is achieved by connecting a 100 kΩ resistor in series with input. Resulting resolution of the current integrator is:

\[
\frac{\text{Measurement range}}{\text{Actual current range}} = \frac{5 \text{ V}}{20 \text{ A}} = 0.25 \text{ V/A}.
\]

Figure 16. Testing integrator circuit with control signals from CompactRIO.

3.2.5 Axis position measurements using current integrators

Additional current integrators are considered to be added to the circuit in order to fully monitor the currents in the electromagnets. Even though implementing a dual integrator in complementary operation (described in the previous chapter) will read current values continuously, it will provide a sum of these values as a result. Dividing this value by the integration period time will yield an average value that is optimal for the feedback loop. Another important piece of information can be acquired through multiple simultaneous measurements, namely the current rate of change with respect to time.
Since self-inductance in an AC-powered coil (such as an electromagnet) is directly proportional to this change,

\[ v(t) = -L \frac{di}{dt}, \]

it would be possible to use integrator measurements to determine \( \frac{di}{dt} \) and thus the self-inductance of the electromagnet in an active magnetic bearing. In turn, this relationship is directly proportional to the distance between the rotor axis and the electromagnet due to the fact that magnetic flux changes because of the changing reluctance caused by variations in the air gap. Measuring this distance for every electromagnet in an AMB would allow calculation of the rotor position, thus removing the need of additional position sensors connected to the feedback loop. This would make a single AMB driver circuit capable of both powering the bearings and conducting all the necessary control feedback measurements.

The integrator IC is yet untested and its main objective remains to measure the average current. However in order to test the position measurement capabilities of this circuit an additional ACF2101 is connected to every H-bridge current sensor. Results of these measurements are delivered through a different output so that it does not occupy output pins and interfere with the main current measurements. Having this experimental feature turned off will have no effect for the rest of the AMB driver circuit performance.
3.3 Current loop measurement signal

There are several IC solutions such as Texas Instruments XTR-series that convert a voltage signal into an either 0-20 mA or 4-20 mA current loop signal. Due to their low cost several XTR117 ICs were purchased and tested with on a prototype board together with a signal generator and oscilloscope. However a problem with these ICs were that it has a built-in +5 V linear regulator that should power all of the input (measurement) circuitry and then all the current drawn has to return back to the IC through a local ground point. The integrator circuit is powered by both +5 V and -10 V supply which makes it impossible to mate it with this particular series of voltage-to-current loop converters. Designing a current loop circuit using Op-amplifiers was the option chosen. This provided more flexibility as the circuit could be designed to match the specific measurement components rather than adapting the measurement system to fit with the XTR-series. LTSpice was a great asset while testing various Op-ampifier circuits that could properly condition the voltage signal.

![Graph showing a switched output with an op-amp based voltage-to-current converter.]

Figure 17. Switched output with an op-amp based voltage-to-current converter.

Having 4 mA represent the minimum value of a measurement while 0 mA is an indication that the sensor malfunctioned is part of the industrial process standard but it is not necessarily the best option for the FES. Industrial instrumentation, especially sensors, are usually powered by the current loop signal itself these 4 mA are enough to keep the circuit running. However in case of the AMB driver no instruments are powered this way and there was no request for a current sensor failure detection feature. Hence it was deemed that the range of 0-4 mA can be added to the measurement signal range instead, resulting in a higher resolution 0-20 mA current loop signal. This is illustrated in the schematic and graph in figure 17 above.
3.4 AMB driver circuit PCB Layout

Digital and power electronics draw current in short, rapid surges that can disturb the power supply and ground potentials. Analog components on the other hand rely on these potentials to be stable in order to provide accurate performance. Hence it is critical to plan the layout of a mixed signal circuit in a way that is minimizing the possibility for interference. It is commonly recommended to use a completely separate circuit for analog components so that they don’t have to share ground or supply with switching digital and power electronics. As previously learned from the electromagnet driver circuit analysis however it is quite possible to use mixed signal components on the same circuit board. There are several features that should be incorporated in design of such circuit but the most important of these features is one of the most basic: to keep noisy components away and if possible shielded from the sensitive ones.

Layout of this PCB follows design of the latest EMD circuit while making necessary adjustments to accommodate the increased number of components and signals. Since the complete AMB driver circuit has to power 8 bearings it needs 8 H-bridges along with all the current measurement components. Placing everything on a large single PCB would save components and enable use of the same HOLD, SELECT and RESET signals for every current integrator circuit. However due to the size of the resulting circuit board, it would take weeks to manually configure the layout. Hence 4 identical PCBs consisting of 2 H-bridges each will be produced and interconnected for more efficient use of the current integrator control signals.

Several of the components will require special attention due to the fact that the AMB driver circuit is a mixed signal circuit. There are PCB placement guidelines provided in the datasheet of almost every IC used and these will be followed to ensure proper operational environment. Just like in the EMD circuit, large ground and voltage supply planes will cover every empty piece of the circuit board, increasing stability of their potential and improving thermal conductance (cooling). Decoupling capacitors will be placed next to the supply pin of every component in order to filter high frequency electromagnetic noise. Current measurement signal traces will be kept as short as possible in order to minimise risk of signal distortion by interference. After the current measurement signal has been integrated it will be converted to a current loop signal that can withstand nearby presence of noisy digital signals which will ease the component and trace placement.
4. Results

4.1 Integrator Circuit performance

A complete current measurement integrator circuit was assembled on a prototyping breadboard and tested together with control signals generated by the CompactRIO NI9401 module. A 10 kHz PWM-signal was chosen because while the ACF2101 should not have problems operating at the maximum frequency of 50 kHz, parasitic capacitances in the breadboard and measuring equipment used would distort the test results. An integration period of 100 us with a constant input current of 10 uA yielded a linear decline of the output voltage from 0 to -10 V. The capacitor discharge (reset) time was measured to 5 us and the capacitor voltage settling time was approximately 2 us, holding the values specified by the circuit’s producer Texas Instruments. Figure 18 shows the Hold A signal in yellow next to integrator A output in purple and inverted integrator B output in green color.

![Figure 18. Complementary operation](image1)

![Figure 19. Multiplexed output signal](image2)

The actual output signal of the integrator is multiplexed by the Select switching signal and is shown above in figure 19. The output node had to be grounded through a 50 kOhm resistor in order for the switch to operate. This will have negligible effect since output is connected to a unity gain buffer that stabilises the output signal.

Because it is yet unclear how well the integrator circuit is going to perform in the AMB feedback control loop an additional current measurement method was introduced as a backup. It features a more conventional approach of using AD8210 output signal directly and only conditioning it by the V-I converter in order to produce a current loop signal. Combination of a jumper and a cable socket change is necessary to switch between the two current measurement techniques.
4.3 Current loop signal implementation

Op-amp inverting amplifier circuit can be used as a V-I converter. The resulting current signal passes through the negative feedback resistor. Having this resistor at the receiver (one of the CompactRIO input modules) creates a closed current loop signal since the input is not sinking the signal current. Instead it measures the voltage drop over the feedback resistor with a differential amplifier. Texas Instruments OPA2132 high speed FET input op-amp was chosen because it offers good performance in terms of high slew rate of 20V/us, wide bandwidth of 8 MHz, low noise of 8 nV / kHz and operates in the required +15 V region. High slew rate is important as the input signal will drop to zero when coming to the end of a hold period due to the capacitor being discharged (reset period) and then immediately rise when the integrator output is switched at the beginning of a new hold period. It is critical that the op-amps adjust their voltage levels fast enough before CompactRIO starts reading the measurement signal. 20 V/us rating implies that a change from 0 to 10 V will be adjusted to in 0.5 us which is sufficiently fast compared to the 8 us total measurement signal reading period.

Final resolution of the current measurement signal is 1mA per 1 A in the electromagnet.

![Figure 20. Integrator and voltage-to-current converter circuit schematic.](image-url)
4.4 Printed circuit board design

The PCB circuit was designed using Cadsoft Eagle Professional software. Components for every sub-circuit as well as miscellaneous parts such as wire-to-board connectors were chosen and are ready to be ordered. The circuits physical dimensions were kept minimal with consideration to the cost and space that it will occupy since 4 such PCBs will be used. 150 x 160 mm was the minimum size feasible by using only two signal layers. Signal traces of 0.4 mm width and isolation of 0.2 mm were used with all signals and planes except for the H-bridge part of the PCB. There the isolation between planes was increased to 1 mm and large planes were used as conductors for reduced resistive losses and better cooling. Both H-bridges are located on the left side of the circuit and are designed to be powered by a separate high power supply. This supply signal is given a large plane on the top layer with two 100 uF electrolytic capacitors placed next to every MOSFET pair to stabilise the voltage. As in the EMD circuit, H-bridges are connected to a ground plane that is separated from the rest of the components except for a little path next to the power supply connector. This little connection ensures that both ground planes have the same electric potential but prevents the EMI created by H-bridge to spread across the whole circuit.

Since the shunt resistor is inside the H-bridge circuit differential amplifier AD8210 has to be placed next to it. The rest of the analog components such as integrators and other op-amps were clustered right behind AD8210. Surrounded by the mosfet gate driver signal traces, this analog “island” is where all the sensitive signals are handled. Every component has its own supply voltage plain decoupled by at least one capacitor, most commonly a 100 nF ceramic. Negative 15 V power supply received a plane on the bottom side in order to reach the necessary op-amp components. Digital components were placed right next to the left side D-Sub inputs because the PWM-signal together with main RESET will to go through a series of gates before being used to control the integrator circuits.

Illustrated in the figure 21 is the complete CAD blueprint of the circuit, with top layer components, traces and conducting planes displayed in red and the bottom ones in blue. No components were placed on the bottom layer to keep the surface tidy and low profile.
Figure 21. Complete PCB layout.
5. Analysis and Discussion

5.1 Operational Specifications and requirements

This AMB driver circuit has the following electrical specifications:

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>Maximum</th>
<th>Requested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small signal electronics power supply voltage</td>
<td>+/- 15 V</td>
<td>+/- 20 V</td>
<td>Unspecified</td>
</tr>
<tr>
<td>Power electronics power supply voltage</td>
<td>60 V</td>
<td>60 V</td>
<td>100 V</td>
</tr>
<tr>
<td>Power electronics current output</td>
<td>10 A</td>
<td>15 A</td>
<td>10 A</td>
</tr>
<tr>
<td>PWM-control signal frequency</td>
<td>50 kHz</td>
<td>50 kHz</td>
<td>50 kHz</td>
</tr>
</tbody>
</table>

Since the dual power mosfet CSD88537ND and its driver were adopted from the EMD circuit the requested specification of 100 V supply for the H-bridge was not met. However the 50% higher maximum current rating of 15 A is able to deliver approximately the same amount of active power to the magnetic bearings with a supply voltage of 60 V. This however would lead to higher resistive losses since they are proportional to the square of the current. It is yet to be seen how this will affect the AMB performance as a power supply rated at 48 V was used in the previous FES prototypes (Abrahamsson 2011).

\[ S(\text{requested}) = VI = 100V \times 10A = 1kVA \quad S(\text{actual}) = 60V \times 15A = 0.9kVA \]

Operating temperature range of -40 to +125 Celsius makes the circuit suited for outdoor or vehicular use if an appropriate watertight case is provided.

The requirement of robust performance and noise immunity for the AMB driver circuit is somewhat relative to the previous circuits and should be tested once the circuit is assembled. Although it would be fair to assume that following design of previous iterations and adding additional noise-reduction features should provide measurable improvements.
5.2 PCB Design

As a result of the design choices mentioned in chapter part 4.3 the complete PCB is distinctly divided in areas of digital, analog and power electronics. This makes it easy to overview and troubleshoot the circuit while also the risk of EMI between these components is minimised.

Due to the large number of different signals at certain parts of the PCB, sometimes there was hardly enough space for signal traces either on the top or bottom layers. Increasing board size would have solved this problem but the circuit’s compact dimensions will be beneficial in terms of space occupied and material needed if a shielding case is added. Making a 4-layer card instead could have been another solution but there was simply not enough time to redraw and rethink the circuit.

5.3 Inputs and Outputs

<table>
<thead>
<tr>
<th>Total inputs (TTL or CMOS)</th>
<th>Total outputs (0-20 mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 PWM-control signal</td>
<td>8 Integrated current measurements</td>
</tr>
<tr>
<td>1 Enable</td>
<td>8 Current rate of change measurements</td>
</tr>
<tr>
<td>1 Reset</td>
<td></td>
</tr>
<tr>
<td>24 Current rate of change measurement</td>
<td></td>
</tr>
</tbody>
</table>

The circuit is compatible with both 5 V TTL and 15 V CMOS control signals. Enable and Reset signals are shared between the 4 circuit boards. Current rate of change measurements demand a large amount of input signals but those are not necessary for the intended AMB driver circuit operation.

5.4 Costs

Eurocircuits are chosen to manufacture the PCBs because of their user-friendly online order placement, fast delivery and competitive pricing.

Order of 6 PCBs including a soldering stencil with a delivery of 5 working days was priced at approximately 270 Euro. Soldering stencil will ease soldering with a reflow oven that is available at one of the Electricity Department’s laboratories.
Components for the whole AMB driver circuit are purchased at Farnell due to the high availability of components and fast delivery. Approximated prices of all components is 400 Euro.

5.5 Future work and improvements

Since design of the AMB driver circuit built heavily upon the EMD circuit, certain limitations were inherited. Power MOSFETs in the H-bridge can be changed to higher rated ones, such as Vishay Siliconix rated at 100 V/ 35 A and having the same casing, but then it would also be necessary to swap the HIP4081a driver IC as well. Replacing the AD8210 with a shunt monitor IC of higher output range would provide better first current measurement stage resolution than 0.25 V / A. Increasing the amount of layers to 4 or 6 would probably lead to better EMI immunity and more optimal trace placement. This would leave almost none of the EMD design left but in order to achieve best performance it is often necessary to create new designs from scratch.

A lot of future work can be done experimenting with position measurement through measurement of the current rate of change. If successful this solution could be beneficial in applications where position sensor placement is not practical.

6. Conclusion

Design of a low profile, low noise and EMI immune AMB driver circuit capable of delivering high power at high frequencies is a challenging task due to the radically different EMI nature of components that have to be used. If precise current measurement are of key importance, separate circuit boards should be used for H-bridges and analog electronics. In some environments however it is impossible to avoid high frequency EMI and it is then better to use a circuit that is designed to operate in such conditions.
References


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Appendix

List of electronic components

<table>
<thead>
<tr>
<th>Component description</th>
<th>Product name</th>
<th>Units per PCB</th>
<th>Farnell order #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full bridge driver</td>
<td>Intersil HIP4081</td>
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<tr>
<td>Dual power MOSFET</td>
<td>TI CSD88537</td>
<td>4</td>
<td>2430179</td>
</tr>
<tr>
<td>Dual FET-Input Op-Amp</td>
<td>TI OPA2132</td>
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<td>1206934</td>
</tr>
<tr>
<td>Quad FET-Input Op-Amp</td>
<td>TI OPA4132</td>
<td>2</td>
<td>1212302</td>
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<tr>
<td>5V Linear Regulator</td>
<td>TI LM78L05ACM</td>
<td>3</td>
<td>9489436</td>
</tr>
<tr>
<td>Switched Dual Integrator</td>
<td>TI ACF2101BU</td>
<td>4</td>
<td>1754679</td>
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<tr>
<td>Current sense amplifier</td>
<td>AD8210YRZ</td>
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<td>Current sense resistor</td>
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<td>Voltage Reference</td>
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<td>Potentiometer 500k</td>
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<td>Potentiometer 1k</td>
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<td>Film capacitor 0.47u</td>
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<tr>
<td>SMD Resistors and capacitors</td>
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List of other parts

<table>
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<tr>
<th>Part description</th>
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<td>H-bridge output terminal</td>
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<td>H-bridge output wire housing</td>
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<td>H-bridge output crimp contact</td>
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<td>PCB coupling wire header</td>
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<td>PCB coupling wire housing</td>
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<td>PCB coupling wire crimp contact</td>
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<td>High voltage supply crimp contact</td>
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<tr>
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</tr>
<tr>
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<td>D-sub headers 9/25 pins</td>
<td>3/1</td>
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</tr>
<tr>
<td>D-sub housings and cables</td>
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</tr>
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</table>
PCB Map

This map is meant to provide guidance to the person assembling the circuit.
PCB coupling contact is used to share the global Reset and Enable signals between the paired circuit boards so that fewer D-Sub 25 connectors and cables are needed. Rest of the signals on the 25-pin connector are purely for the experimental rotor position measurement. XOUT 1,2 are the output signals that these optional measurements provide. PWM 1,2 are the signals that control the H-bridge circuits and from which the integrator hold signals are derived. Current measurement output can be chosen to be either the regular direct voltage or the current integration measurement. However both of these are delivered through 2-wire current signal.

Schematic and PCB layout files can be accessed by the following link:

https://www.dropbox.com/sh/fupui8hwc52lmu/AADKMekFonnreYWGPmDBI44a?dl=0