High Current Switch

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science degree in Physics from the College of William and Mary

by

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Abstract

The design, construction, and basic testing of an externally and digitally controlled electronic switch, designed to reverse current flow through magnetic coils is described. It is designed specifically to handle large currents up to 150 A. Furthermore, this switch is used in combination with magnetic coils for accessing Feschbach resonances in ultracold atom experiments.

1 Introduction

1.1 Objective

To build a device for switching the direction of current though a coil. This switch must be able to handle high currents (150 A maximum) and switch the current quickly and reliably, without adding a significant load. The specialized switch will be used with an ultracold atom apparatus, in order to switch current in one coil of a pair of magnetic coils, converting between Helmholtz and anti-Helmholtz configurations. This reverses the magnetic field generated by one of the coils, changing the configuration of the overall field generated by both coils.

1.2 Motivation

The Ultracold Atoms, Molecule, and Optics (AMO) Laboratory at William and Mary uses high, opposing magnetic fields produced by an anti-Helmholtz coil pair in order to transport very cold rubidium and potassium atoms to different parts of the experimental apparatus [1]. These atoms are cooled to microkelvin temperatures and lower ($0.28\mu K$ for ^{87}Rb), at which point they become Bose-Einstein Condensates, which are useful for experiments in many-body physics [2], atom interferometry [3], and quantum pumping [4].

Remarkably, ultracold atoms have scattering resonances, referred to as Feshbach resonances, at certain magnetic field values [3]. These resonances allow the scattering cross-section (and scattering length) between two colliding atoms to be increased or decreased by tuning the local magnetic field. This allows experimentalists to control the extent to which ultracold atoms interact. The resonances typically occur at field values between 1 G and 1000 G. We believe that our apparatus will be able to achieve field values up to 500G using the current direction switch we have designed. Table 1 displays some of the relevant Feschbach resonances for fields up to 500G.

The Ultracold AMO Laboratory uses magnetic gradients generated by anti-Helmholtz coils to hold and transport ultracold atoms. These coils may be used to achieve Feschbach resonances, if the magnetic field generated by one is reversed, which may be done by reversing the direction of current flow, as shown in Fig.1.

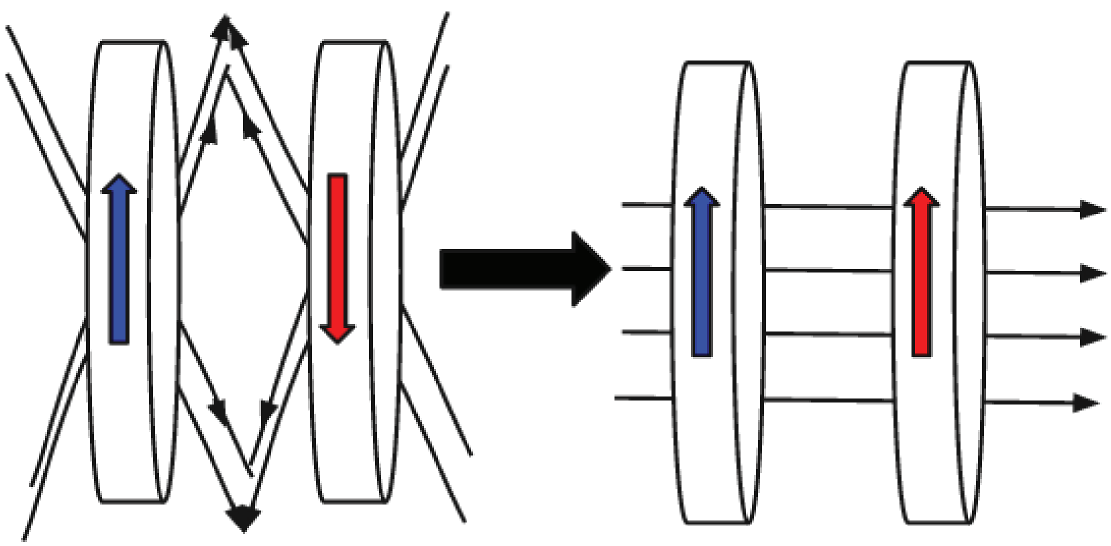

Figure 1: Anti-Helmholtz and Helmholtz configurations of the coils. On the left is the anti-Helmholtz configuration, where there is a magnetic gradient, used for atom transport. On the right is what we aspire to create, in order to achieve Feschbach resonances.

Table 1: Significant Feschbach resonances for Rb and K below 500G. B and Δ refer respectively to the magnetic field strength at which the Feschbach resonances occur, and the width of the resonance. The atomic states are labeled by each state's hyperfine quantum numbers $|F, m_F\rangle$. This is by no means a complete list, but includes resonances with a width greater than 0.1G.

Atomic System	B(G)	Δ (G)	States	Ref
^{85}Rb	155	11.65	$\|2,-2> +\|2,-2>$	[5]
$^{39}K -^{87} Rb$	117.6	-1.3	$\|1,-1> +\|1,-1>$	[5]
$^{39}K -^{87} Rb$	247.9	0.28	$\|1,1> +\|1,1>$	[5]
$^{39}K -^{87} Rb$	317.9	7.6	$\|1,1> +\|1,1>$	[5]
$^{41}K -^{87} Rb$	35.2	5.1	$\|1,1> +\|1,1>$	[6]
$^{41}K -^{87} Rb$	78.6	0.35	$\|1,1> +\|1,1>$	[6]
$^{39}K -^{39} K$	25.9	0.47	$\|1,1> +\|1,1>$	[8]
$^{39}K -^{39} K$	403.4	52	$\|1,1> +\|1,1>$	[8]
$^{39}K -^{39} K$	(zero at 350 G)		$\|1,1> +\|1,1>$	[8]
$^{39}K -^{39} K$	59.3	9.6	$\|1,0> +\|1,0>$	[8]
$^{39}K -^{39} K$	66.0	7.9	$\|1,0> +\|1,0>$	[8]
$^{39}K -^{39} K$	471	72	$\|1,0> +\|1,0>$	[8]
$^{39}K -^{39} K$	490	5	$\|1,0> +\|1,0>$	[8]
$^{39}K -^{39} K$	32.6	-55	$\|1,-1> +\|1,-1>$	[8]
$^{39}K -^{39} K$	162.8	37	$\|1,-1> +\|1,-1>$	[8]
$^{41}K -^{41} K$	51.35	-0.3	$\|1,-1> +\|1,-1>$	[7]
$^{40}K -^{40} K$	202.1	7.8	$\|9/2,-9/2> +\|9/2,-7/2>$	[9]
$^{40}K -^{40} K$	224.2	9.7	$\|9/2,-9.2> +\|9/2,-5/2>$	[9]

2 Design

The main requirements for the switch, its basic design, and the design of its individual components will be discussed.

2.1 Requirements

Switching the current direction is the primary requirement of our system. However, the switch must meet the following, experiment-driven specifications.

1) **Maximum Current:** The switch must handle up to 150 A of current, the maximum which existing power supplies are able to deliver.

2) **Load:** The switch should increase the load associated with the coils minimally, so that excessive voltage is not wasted on the switch itself.

3) **Speed:** It must be able to make the switch in current direction in less than 10ms.

4) **Controls:** The switch must interface with the existing ultracold atom apparatus computer systems via a TTL input. It will also be operated by a manual switch, which will control the state of the switch.

5) **Safe Operation:** Control electronics must only allow the direction of the current to change while there is no current flowing through the coils. This prevents dangerously high inductive voltage spikes which may damage the power supplies, experimental apparatus, or even the switch itself.

6) **Footprint:** The switch must take up minimal physical space, and must be easily installed in the already crowded experimental space.

2.2 Basic Design

The switch requires two input wires for the coil power supply: one positive (in) and negative (out). The corresponding outputs supply the coil with current. As shown below in Fig.2, the switch has two configurations. In configuration B, the current enters and exits the switch box on the same side: current flows through the closed gates (II and IV). In configuration A, each gate's state has changed, causing current to flow through the now closed gates (I and III) to the opposite side of its input. This effectively reverses the direction of current flow through the coil. It is easy to conceptualize these gates as pairs of transistors, as in Fig.4. They work in pairs in order to handle the current load. They also accept a digital control signal.

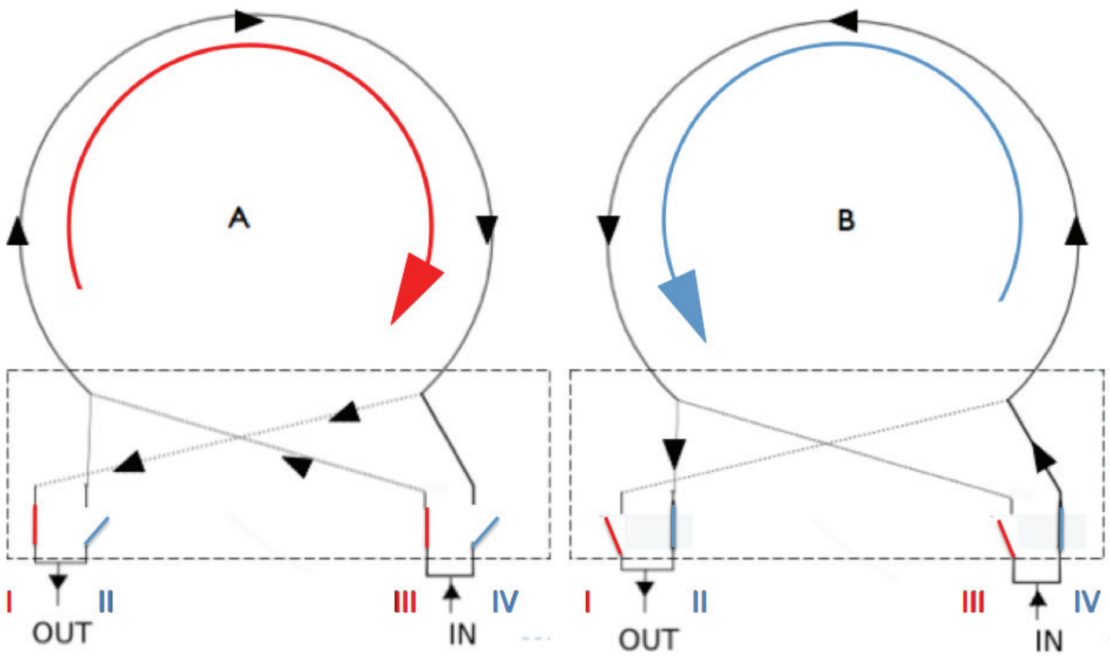

Figure 2: Basic switching design using four sub-switches (gates): In configuration A, gates I and III are closed, causing current to flow clockwise. In configuration B, gates II and IV are closed, causing counter-clockwise current flow. Each sub-switch (or gate) represents two MOSFETs.

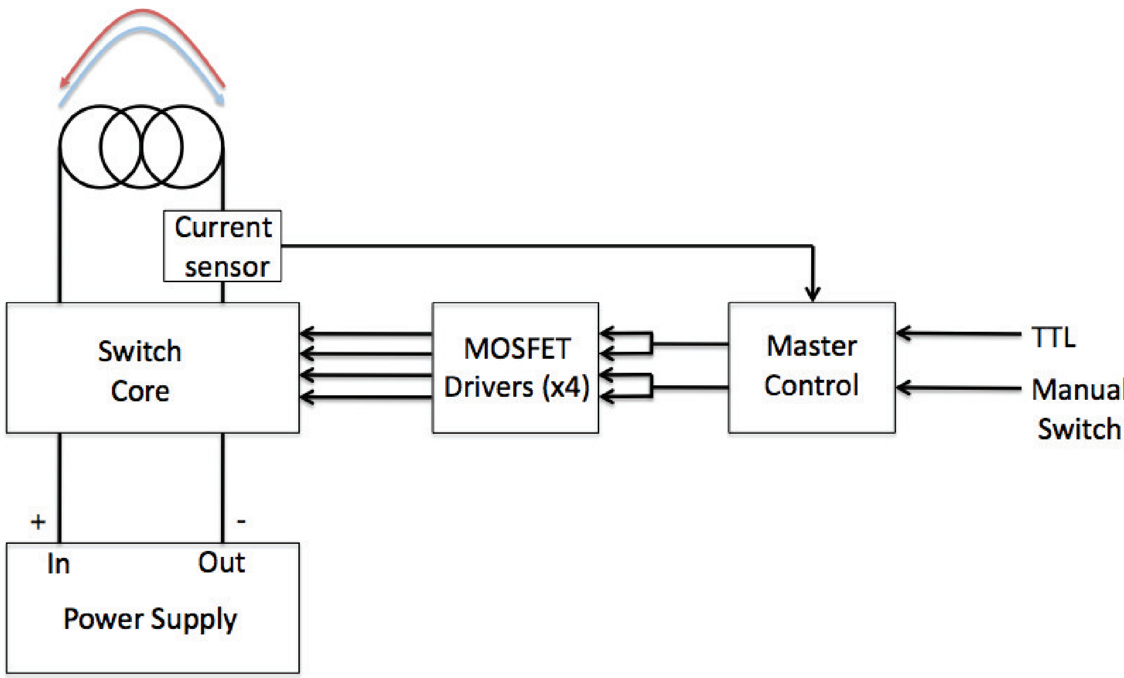

Figure 3: Box diagram of the overall design of the anti-Helmholtz-to-Helmholtz switch: The switch consists of four subsystems. These include the MOSFET based *switch core*, which contains the transistor based sub-switches, which control the actual current direction. The floating *MOSFET Drivers*, which supply power and control input (0 or 10V) to the gates contained in the *switch core*. The *current sensor*, which senses current inductively and provides an input to the *master control* block. The *master control* block, which accepts inputs from the manual control, TTL signal, and the current sensor. It decides whether a switching event may occur, based upon the input from the current sensor.

2.3 System Design of Switch

The four major sub-systems in the overall switch design, as shown in Fig.3:

1) **Switch Core:** The switch core consists of four MOSFET transistor-based gates, which work in tandem in order to direct the current flow through the coil. Each gate is driven by its own floating MOSFET driver.

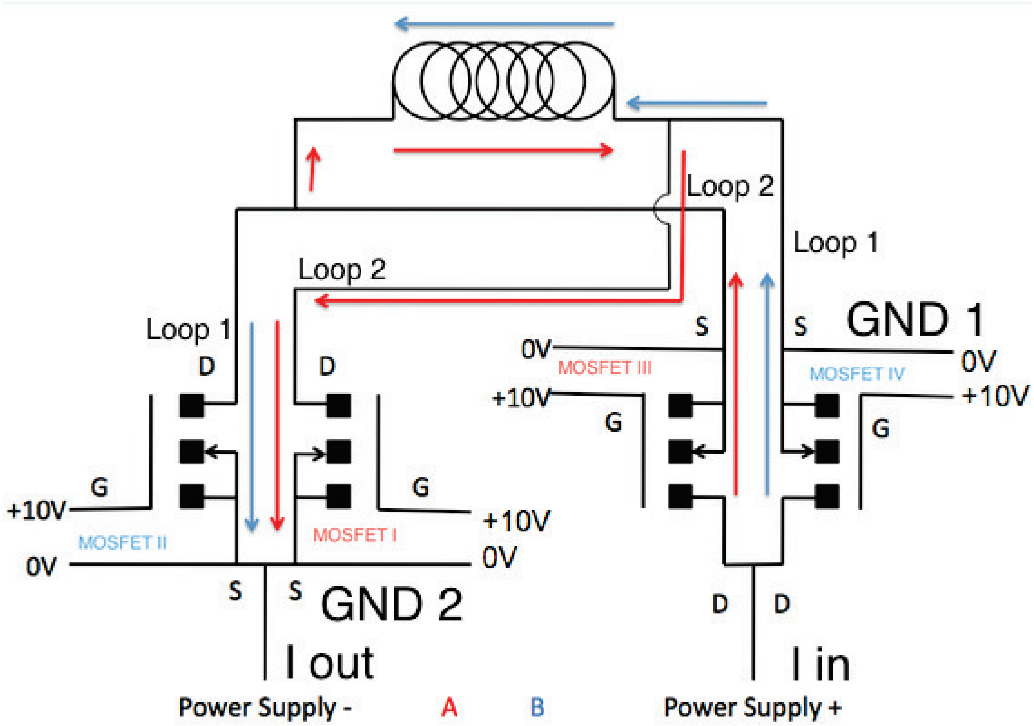

Figure 4: Switch Core: Each transistor symbol stands for a pair of STV270N4F3 transistors working in parallel. The path that flows through the rightmost gate first demonstrates switch configuration ‘A’, where the two central transistors (I and III) are open, and the outermost ones (II and IV) are open. The other path indicates switch configuration ’B’. G,S, and D refer respectively to the gate, source, and drain terminals of the MOSFET.

2) **Floating MOSFET Drivers:** The MOSFET drivers control the gates in the switch core. These driver circuits are designed specifically not to share a ground voltage with the coil and main power supply, as this could potentially result in catastrophic misdirection of current.

3) **Current Sensor:** The current sensor measures the current flowing through the coil. It supplies an input for the Master Control circuit, which is used to decide whether or not a switching went may occur. If there is nonzero current in the coil, no switch-

ing may occur. This helps safeguard against dangerous inductive voltage spikes when currents are rapidly turned off, which are potentially hazardous to the experimental apparatus.

4) **Master Control:** The master control circuit is designed to primarily accept inputs from the user, and secondarily makes decisions as to whether or not a switching event may occur. The user input included are: an external TTL signal from the ultracold atom apparatus computer system, as well as a manual control switch, which determines the state of the switch (as in whether a high or low signal in the TTL translates to normal current direction or reverse current direction). It also accepts an input from the current sensor, and does not allow switching when there is current flowing through the coil.

2.4 MOSFET Based Switch Core

The formal switch core design is as shown in Fig.4. In each configuration, each gate refers to a pair of Metal Oxide Field Effect Transistors, or MOSFETs. We opted for STV270N4F3 MOSFETs, from ST Microelectronics [10]. The operation is straightforward enough: when the odd switches (I and III) are closed, the even switches (II and IV) are open, and vice versa. In actuality, this means that the control voltage supplied to the gate terminal of the odd numbered MOSFET pairs is 10V, while 0V are supplied to the even numbered MOSFETs. In the second configuration, each pair of MOSFETs is in the opposite configuration. This means that we are able to switch between current directions, and therefore the polarity of the magnetic field generated by the coil.

High current MOSFET transistors were chosen over mechanical switches as they are more reliable, and do not 'bounce' as mechanical switches are bound to do. When a physical switch is thrown, it may physically bounce off of its contact, creating short timescale oscillations in on/off state, which typically are insignificant, but in this case may cause inductive problems in the apparatus.

2.5 Floating MOSFET Drivers

The driver circuits are what supply the 0-10V signal to the gate terminal of the high current MOSFETs. The driver circuit is shown in Fig.5. These are designed in such a way that they do not share a common ground voltage with each other, or the master control circuit. These must not share a ground with each other because, if they did, the current intended for the coils would flow through the driver electronics, which are not able to handle such high currents as 150 A, as is intended to be run through the coils. Hence, in order to prevent overloading the driver circuits, they must be floated with respect to each other. In order to accomplish this, the main power source for the switch electronics is fed to a DC-DC converter (RS24-15D) [12]. This isolates the ground of the power source from the ground of the driver circuit. The remaining input, a TTL signal from the Master Control circuit, is isolated via an optocoupler (VO4661) which uses an LED/photodiode pair in order to communicate a digital control signal without an actual electrical contact.

The 15 V output of the DC-DC converter supplies two voltage regulators. The two voltage regulators output 5V (LM7805) and 10V (LM7810) in order to reliably power the optocoupler and control transistor (2N7000), respectively [14, 15, 16].

The 0-5 V TTL output from the optocoupler is insufficient to power the high-current MOSFETs (STV270N4F3) which require 0-10 V [10]. This signal is fed to a second transistor (2N7000), a small signal MOSFET, where it is boosted to a 0-10 V output, sufficient to control the high-current MOSFETs [10, 16].

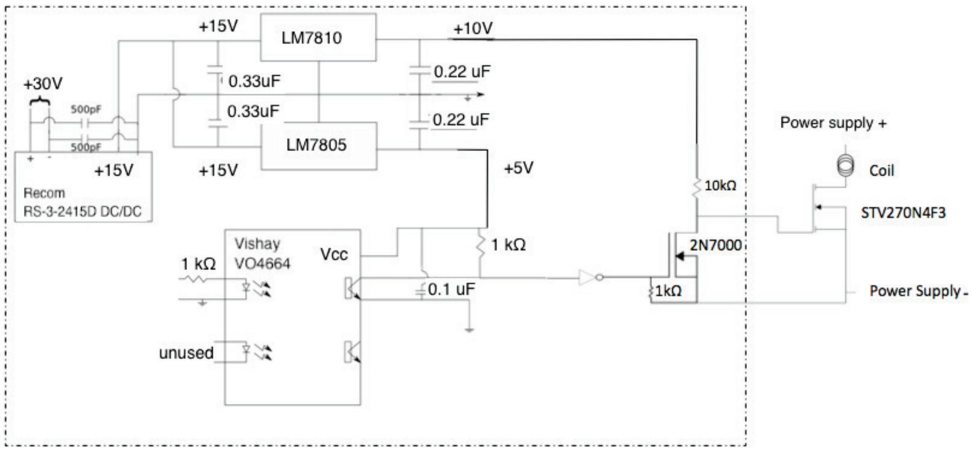

Figure 5: Floating MOSFET Driver Circuit: The portion in the dotted box is the driver circuit; external to it is the high-current MOSFET and coil that it controls, or ”drives.”

2.6 Master Control Circuit

The master control circuit (see figure 6) tells the MOSFET gates in the *switch core* and their drivers what to do. In other words, which are open and which are closed, given a particular set of inputs. The states of the *switch core* MOSFETs are what determine whether current flows normally, or is reversed with respect to the current direction in the opposing coil. Explicitly, it forces either the even numbered gates (II and IV) open while closing the odd numbered ones, or vice versa, as shown in Fig.2 and Fig.4.

This circuit also take an input from the current sensor, and does not allow any switching to occur while there is current flowing in the coil. This feature protects against dangerous inductive voltage spikes, which may damage equipment.

The external switch controls, i.e. the external TTL signal and the manual control switch, are fed into the circuit through an XOR gate, which allows the user to define the meaning of the high/low TTL signals. In other words, with the manual control in

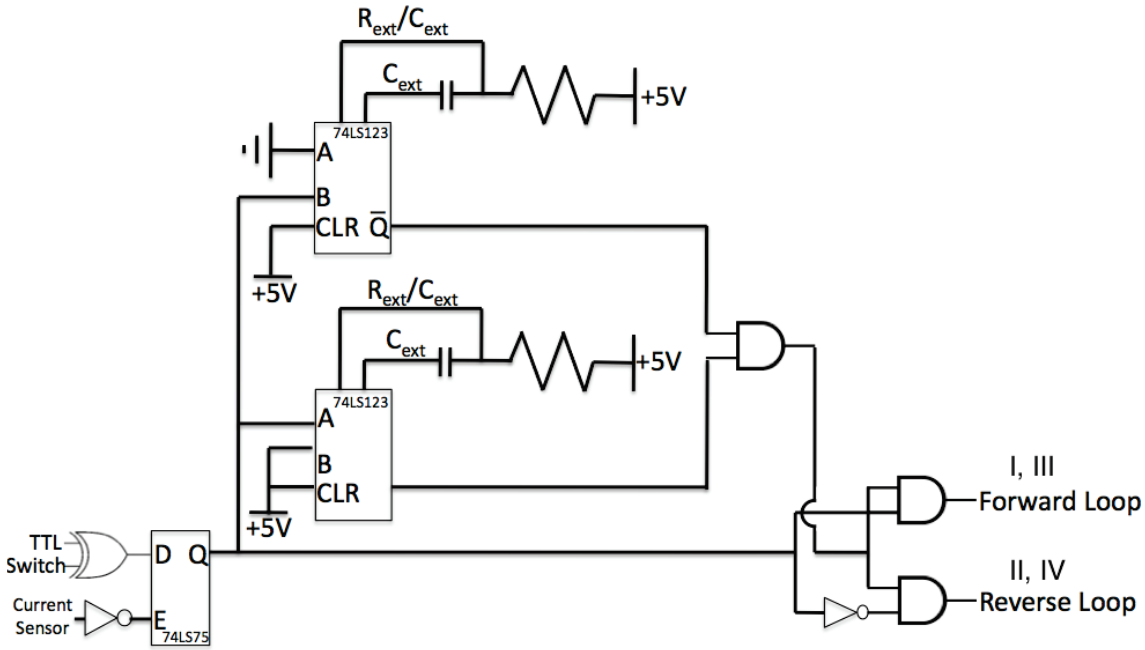

Figure 6: Master Control Circuit: The circuit only allows switching when no current is flowing. When a switch is made, this circuit also forces all high-current MOSFETs open, further ensuring that no current is flowing through the coil. It outputs two signals: one for each set of gates.

one position, high TTL means normal current, and low means reversed current, and when the manual control is in the opposite state, the external TTL signal does the opposite.

The XOR gate output is sent into a transparent D-type latch (74LS75) which also accepts the current sensor's signal as its enabling input. That is to say, if the current sensor is indicating no current flowing in the coil, the D-Latch remains 'transparent' (conducting) [17]. It is by this mechanism that we guarantee that switching only occurs while there is no current flowing through the coil. If the current sensor indicates that current is flowing, then the D-Latch will maintain its present output regardless of the signal on its main input.

The resultant signal is delivered to the driver circuits for the switch core's high-current MOSFET sub-switches via two AND gates. These gates are also controlled by a timing circuit based around a one-shot (74LS123) which forces all of the AND gates' signals to be low, and therefore the sub-switches open, for one millisecond [18]. This further ensures that there is no current flowing through the coil when a switching event takes place, thus safeguarding against dangerous inductive voltage spikes. This process also means that the switch core never goes from A to B (shown in Fig.2) but from A to nil to B.

2.7 Power Management

Due to the high current required to generate large magnetic fields necessary for Feschbach resonances, the switch must dissipate a considerable amount of power. In this section, I present the power consumption results, as well as several methods that are used to manage the heat produced by the switch.

2.7.1 Power Considerations

While each STV270N4F3 MOSFET is nominally able to handle up to 270 A, we needed to consider the power that each would need to dissipate within the switch core, which may be sensitive to excessive temperatures [10]. Using just one MOSFET per gate we have:

$$R_{MOSFET} = 1.5\ m\Omega$$

$$\Delta V = (150\ A)(1.5\ m\Omega) = 0.23\ V$$

$$P = (0.225\ V)(150\ A) = 34\ W$$

34 Watts is not negligible. By using two MOSFETs acting in parallel, we reduce

the pair resistance to $R_{MOSFET} = 0.75m\Omega$. As such, we have:

$$R_{MOSFET} = 0.75\ m\Omega$$

$$\Delta V = (150\ A)(0.75\ m\Omega) = 0.11\ V$$

$$P = (0.11\ V)(150\ A) = 17\ W$$

This results in 17 Watts delivered across two separate MOSFETs, i.e. 8.5 W per MOSFET at 75 A each, which is a far more reasonable amount of power to dissipate via passive heat management.

2.7.2 Baseplate and Epoxy

In order dissipate the heat generated by the high-current MOSFETs, we made use of a thermally conductive epoxy (Epoxies Etc. 50-3170) between all surfaces intended to be in thermal contact [11]. In this case, there were three main areas of concern; the MOSFETs, the copper baseplate upon which they reside, and the aluminum structural baseplate upon which the copper sits. First, the copper plate was affixed to the aluminum via a combination of epoxy and screws, and then the MOSFETs were gently clamped and epoxied to the copper.

2.8 Current

Handling the high current needed for generating high magnetic fields poses a problem for many types of electronics. The switch is designed to handle a maximum of 150 A. Each of the high-current MOSFETs carries a practical maximum of 100 A, though we use them in pairs so that none of them ever come near this limit. We use eight total, with each pair acting as a sub-switch.

In addition to the MOSFET's, we use bus bars to carry most of the high current. The leads of the individual MOSFETs are attached to the bus bars. We use 0.75 cm x 0.75 cm square cross-section bus bars, which are the largest size that the terminal blocks allow.

2.9 Mechanical Design

In order to fit and mount the box to the current apparatus, it must have a reasonable size and weight. As such, the design is as compact as possible. This is why we mount the smaller copper plate on an aluminum one; to preserve heat sinking, while keeping the overall weight of the box to a minimum. As opposed to using a completely copper baseplate, this design is roughly half as heavy. Fig.6 shows the mechanical layout for the switch core.

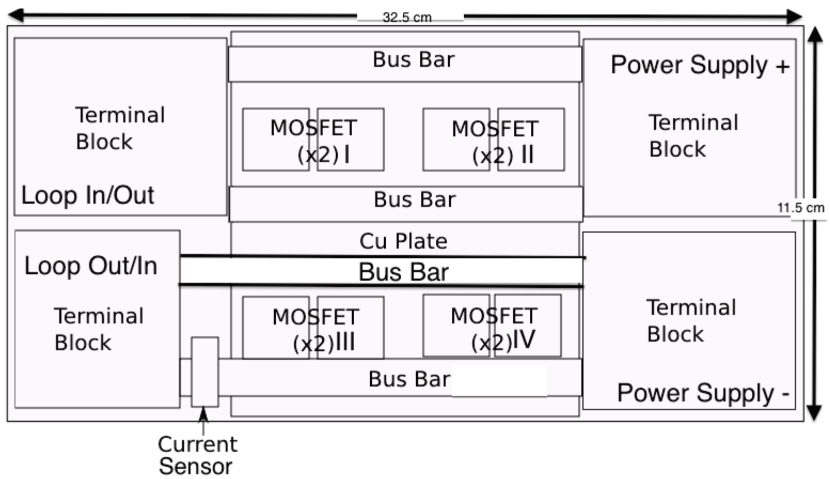

Figure 7: Mechanical layout of the switch core, as seen from above. Including the copper baseplate, high-current MOSFET pairs, bus bars to handle most of the high current, terminal blocks used to connect to input and outputs, as well as support the bus bars.

3 Construction

Construction began with the Switch Core, which involved machining of parts, and a lot of mechanical work. Once this was made functional, the MOSFET driver circuits were constructed. This was where the electronic work began. The Master Control circuit remains to be constructed, and the current sensor also remains to be installed.

3.1 Switch Core Construction

The switch core was designed mainly with concerns of heat sinking, current handling, serviceability, and size and weight in mind. An aluminum baseplate was cut for a secondary copper baseplate to sit upon. The Al plate is intended as a structural foundation, and the Cu base was implemented primarily as a heat-sink. The two were connected via bolts, and thermally conductive epoxy (Epoxies Etc. 50-3170). The MOSFET pairs were connected to the Cu baseplate via the same thermally conductive epoxy, as shown in Fig.8 and 9. The MOSFETs are electrically insulated from the baseplates with a layer of electrically insulating Kapton tape.

Figure 8: The switch core as seen from above. This is the physical implementation of the layout sketched in Fig. 6.

In order to interface the gates with each other, the coil, and their power supply, bus bars were implemented. These are long bars of copper, roughly 0.75 cm x 0.75 cm in cross section. Two cross pieces were brazed on to each bus bar, to allow for easier connection of the gates' inputs and outputs. These bars are held above the baseplates by four terminal blocks, each situated in a corner of the aluminum baseplate. These terminal blocks also serve to interface with the power supply and coil.

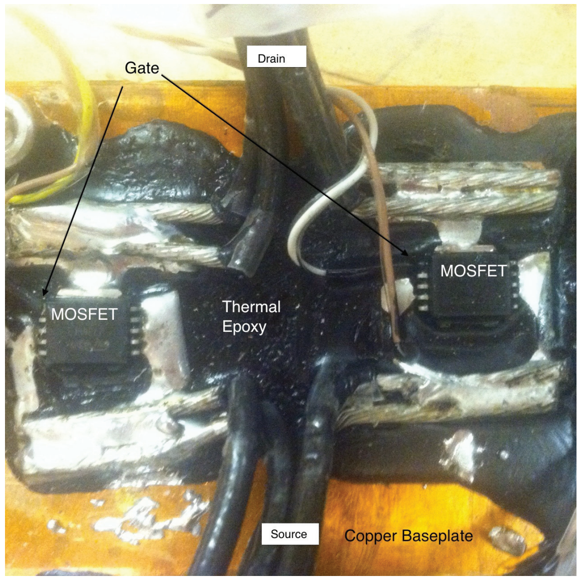

Figure 9: MOSFET Gate: A pair of MOSFETs glued to the copper baseplate, and configured as a functioning sub-switch. Larger black wires represent the drain and source terminals of the MOSFETs, and are connected to the bus bars. The thin wires provide the 0-10V digital control signal to gate terminals of the MOSFETs

3.2 MOSFET Driver Circuit Construction

Driver circuits were tested first on a breadboard, and then soldered onto printed circuit boards (PCB). They were produced as sub-circuits, starting with the DC-DC converter and voltage regulators. Once these were constructed, they were tested to ensure that the voltage regulators, LM7810 and LM7805, each output 10 V and 5 V respectively.

The optocoupler circuit (VO4661 chip) was then put into a breadboard and tested, and then added on the same PCBs as the voltage regulator circuit. The optocoupler is powered by the 5V output of the voltage regulator sub-circuit.

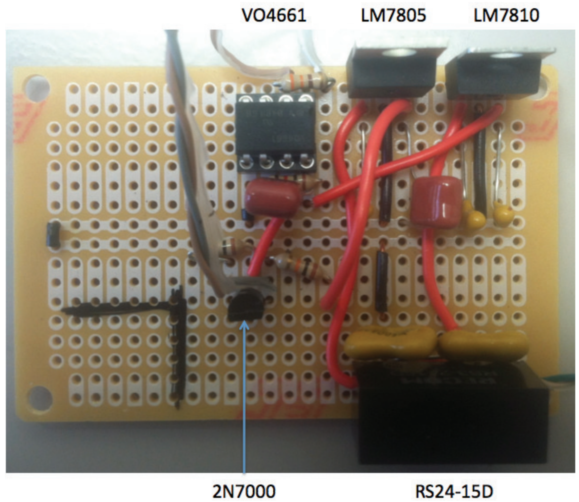

Figure 10: The floating MOSFET driver diagrammed in fig.4

Finally, the MOSFET controller was breadboarded and installed. This consisted of the 2N7000 MOSFET, which accepted the output of the optocoupler as control, and the 10V output of the voltage regulator sub-circuit as its power source. The output of this sub-circuit was then connected to the STV270N4F3 MOSFETs.

Four floating MOSFET driver circuits were constructed. Fig. 9 shows one such circuit. They were all tested once they were completed.

3.3 Master Control Circuit

The master control circuit has yet to be constructed. It has been designed, however, and its components selected. Table 2 gives a list of chips required to build the circuit. The master control circuit's design is shown in Fig.6.

Table 2: Gates, chip, and quantities needed for building the master control circuit

Gate Type	Gate Quantity	Chip	Chip Quantity	Pin-Count
D-Type Latch	1	74LS75	1	16
One-Shot	2	74LS123	1	16
AND	3	74LS08	1	14
XOR	1	74LS86	1	14
NOT	2	74LS04	1	14

3.4 Current Sensor

The current sensor will be implemented outside of the switch core, on a direct input to the coil (See Figure 3). Its output will then be connected to the master control circuit. However it has yet to be constructed. The sensor itself, pictured in Figure 11, is an LEM HTB 200-P [19].

Figure 11: Current Sensor: The sensor will be implemented to provide an 'enable' signal to the D-Latch gate, thereby impeding any switching while current is flowing in the coil.

3.5 Pre-Construction Testing

Before any construction took place, we tested the individual parts. In this case, the main two things that needed testing were the MOSFETs and the epoxy. All of the MOSFETs performed as they were intended to, although testing was conducted at reduced currents for safety purposes. The epoxies sometimes did not set correctly, though we resolved this problem with more liberal use of the hardening compound, as well as thinner layers compared to the test batches.

3.6 Testing

At each step of construction, individual circuit blocks were tested in order to ensure that they were performing as they were intended to. All of them function as intended, with the exception of the master control circuit, which has yet to be constructed.

All of the control circuits were tested, and function as they are expected to. We have also tested that they will operate the main, load-bearing MOSFETs, which was also successful at a current of 2 A (roughly two orders of magnitude below the true expected current load).

A test of the switch core and MOSFET drivers was conducted as a proof of concept. Operating at 2.4 A, the switch core and the drivers functionally switched the direction of current flowing through a test coil, from 2.4 A, to 0 A, to -2.4 A. This test was controlled manually, as the master control circuit is incomplete.

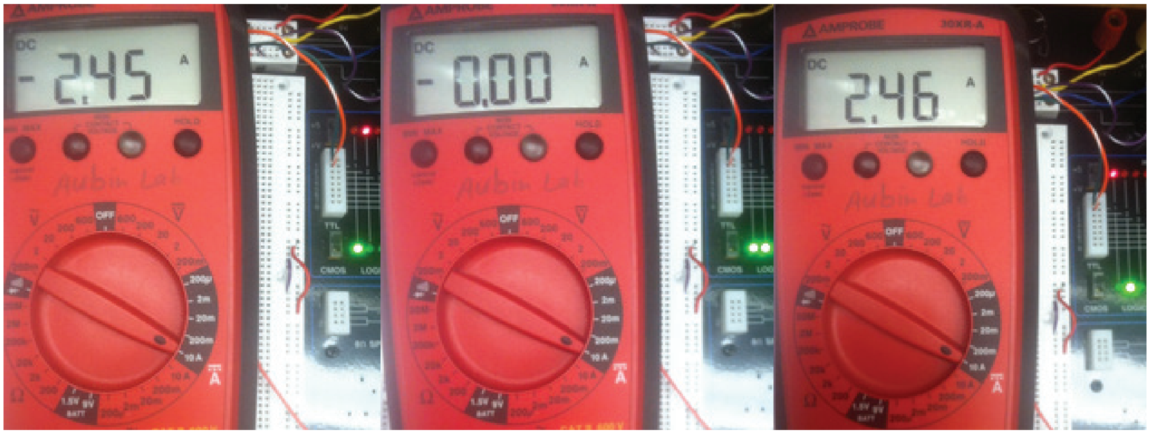

Figure 12: Demonstration of the functionality of the switch core and MOSFET drivers. On the far left, the switch is in configuration A. As in the photo, it is conducting 2.4 A. In the center, all of the MOSFETs are closed, and so there is no current flowing in the coil. On the far right, the switch is in configuration B. Each driver has switched its output with respect to what it was in configuration A. As shown in the picture, there is now -2.4 A flowing in the coil. In other words, current direction has been switched successfully.

4 Outlook

The vast majority of the apparatus has been constructed. The switch core and the MOSFET driver circuits have been built. The master control circuit has not yet been constructed, and the current sensor has not yet been implemented. The switch core and MOSFET drivers have been tested, and both function as they are intended to.

What remains to be done is construction of the master control, installation of the current sensor, testing the whole apparatus, and then integration into the rest of the AMO apparatus.

5 Conclusions

The construction and testing processes thus far allow us to conclude that the core design principles of the switch core are sound, and effectively switch the direction of current through a load attached at its outputs. Additionally, we may conclude that the MOSFET driver circuitry performs effectively at low current.

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