Switching Circuit for a Permanent Magnet DC Motor

by

Alex Boatman

Senior Project

Electrical Engineering Department

California Polytechnic State University

San Luis Obispo

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Acknowledgements

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Abstract

The project is a circuit that will basically supply current from the battery to the different stator coils at opportune moments. With a hall-effect sensor on the shaft as a feedback to a microcontroller, I was able to toggle switches based on the position of the shaft at the moments where we would be using as little power as possible. The operation of the control circuit works similar to a stepper motor; it takes a signal from the microcontroller that is sent to some FET drivers, which in turn sends signals to the FETs to open or close as the shaft is rotating. Since the stator coils are set at a certain angle apart from each other, it was an advantage to know where the starting point was, and extrapolate where every other magnet was with respect to the coils by putting the hall-effect sensor in line with one set of permanent magnets. This way, current was only sent to the stator coils when it was necessary to turn the motor. The idea was that we could conserve power by drawing from the battery less often, but made little progress in the final testing stages in conjunction with the motor. We ran into many problems with the inductor coils on the stator due to a communication error, so the core for the inductors needed to be completely redesigned.

Introduction

The goal of this project was to develop and test an idea that Robert had for an in-wheel dual rotor permanent magnet DC motor, and to spend the summer developing said idea when we actually had time to work on it. Initially, the project was to develop and test some new theories about DC motors, and to build a prototype to test these theories. The goal was to create a switching circuit that would be controlled by a microcontroller, and switch on and off stator coils only when necessary. In order to do this, a Hall-Effect Sensor setup was created to capture the angle and speed on the shaft of the motor by attaching a magnet on the inside of the shaft. The switches on the hall-effect sensors would be closed by the rotating magnet and the feedback from this hall-effect array would be able to give us a pretty good idea of exactly where the shaft was at any given time. In order to operate, the microcontroller will send a signal to some FET drivers in order to switch current to flow in the coils, with the notion that only the minimum amount of power would be flowing through the circuit and coils at any given time. This effort was to reduce power losses due to current flow without letting the current flow continuously. One of the advantages we had by switching the current was that we could induce a changing magnetic field in the coils as the magnets on the rotor pass by each coil. By doing this, the goal was to run the motor more efficiently by controlling the current flow. Thus, we would be able to send current into the coils to repel and attract the magnets on the rotor itself at the exact moments in order to turn the shaft of the motor at an increasing rate, giving us maximum torque for a small amount of current. Also, by using samarium-cobalt magnets on the rotor [magnetic field of 1 Tesla], the force on the shaft from the attraction/repulsion of these magnets is very high, which will allow the shaft to achieve very high speeds very quickly. The goal of the switching circuit is to take a DC signal from the battery and distribute it to the coils as directed by a microcontroller that has feedback from the shaft as described above. With the two signals, it will open and close FETs based on the signals it receives from the FET drivers that are connected to every FET. Additionally, a couple of voltage regulators on the board were necessary to lower the voltage from the input voltage down to the FET driver V_{CC}, and also to operate the microcontroller when the unit was mobile.

Background

DC motors have been around for quite a long time, converting electrical energy into mechanical energy for many, many types of applications. Additionally, mechanical energy can be converted into electrical energy for use, and in this case we refer to it as a generator. DC motors are typically constructed with a field circuit in order to produce magnetic flux in a magnetic material such as ferrite. However, one variation of a DC motor is the permanent magnet DC motor, which has no brushes and has permanent magnets on the stator or rotor. This fact allows the motors to be constructed without brushes or a field circuit – this aspect reduces the power used by the motor and allows for smaller design. Typical applications for DC motors are motors that run CD drives because they require little input power and are highly efficient. Figure 1 below shows two examples of permanent magnet DC motors, with two poles and four poles.

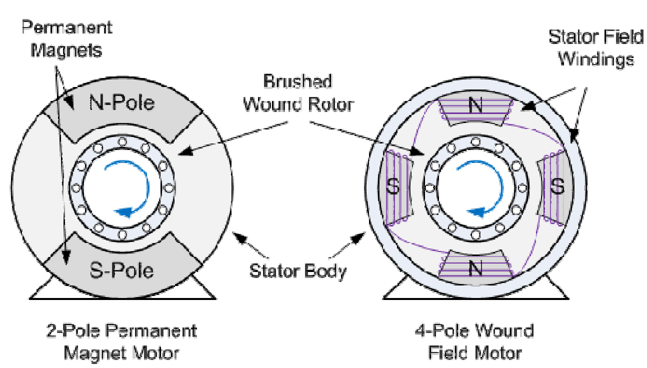

Figure 1: A typical permanent magnet DC motor – left side shows a 2-pole motor and the right is a 4-pole

The focus of this project, however, was brushless permanent magnet DC motors, which typically come in two varieties: inner rotor and outer rotor. The construction depends on the application, but in both cases they are constructed so that the stator coils do not move; only the rotors move. In Figure 2 below, we see a typical example of a PMDC brushless motor, this configuration shown with the outer rotor removed so the contents can be seen. Here, the flux goes into the four teeth that extend beyond the inductors. The direction of the current through the coils determines the direction of the magnetic flux lines, and this will cause the rotor to spin. Each of the permanent magnets will be repelled by the previous tooth, and attracted to the next tooth. This constant repulsion and attraction system causes the rotor travelling outside the stator to run the motor.

Figure 2: Example of a PMDC brushless motor stator – The flux travels in the teeth on the outer edge of the inductors which will repel and attract the permanent magnets on the rotor (not shown)

Finally, we come to the important part of the brushless DC motor; its control. Obviously, if there was no control, the motor would not operate because as soon as the current was turned on, the magnets would just be attracted to its opposite-poled tooth, and would completely lock the shaft and rotor from moving. So, some sort of control must be used to alternate the current that travels in each of the coils. Typically, this is done with an H-Bridge circuit, shown in Figure 3 below:

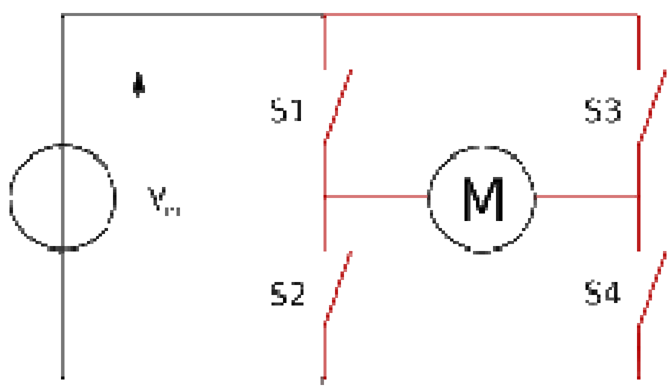

Figure 3: H- Bridge circuit typically used to control a brushless PMDC motor – this shows what will happen to the current in the motor in order to get it to operate.

In order to get the motor to run, the current must travel in opposite directions to cause the poles in the teeth to alternate. First, current travels through the circuit by closing switches S1 and S4 in the diagram above, and then closing S2 and S3 afterwards. Although there are many ways to control a brushless permanent magnet motor, this is one of the many accepted methods. This is the focus of what was explored throughout the completion of the senior project, and we explored various techniques with controlling a brushless PMDC motor with a microcontroller.

Requirements

The switching circuit is required to help drive the DC motor by controlling the current path through the coils in the stator of the motor. There are FET drivers that take a signal from the microcontroller which will open and close switches. Based on the signals the FETs receive from the drivers, they direct current through coils that are being used to run the motor. The current for the model is supplied by a 48V battery that initially charges up a capacitor bank of twenty 390 μF capacitors. These capacitors are charged through a pre-charge circuit in order to reduce the demand on the battery, and, once charged, the switch will open and send current directly from the capacitors to the coils of the stators. However, the capacitors will only discharge when the FETs receive the signal from the drivers to close and allow current to flow through; else, the capacitors will remain charged. The circuit will basically act like a giant switch which lets current go only to the stators that have magnets near them, thus increasing the efficiency of the motor by reducing excess current flow. As the perma-magnets on the rotor spin around and pass by the coils, the hall-effect array will detect the position of the shaft at a given time. The coils are positioned such that if we know the position of the shaft, we know exactly which FETs to close and where the current needs to flow. The feedback from the hall-effect goes to the microcontroller, and the controller sends a signal to each one of the FETs when it is supposed to operate. With successful operation, the shaft should rotate with great pull due to the magnetic force that the magnets are feeling, and produce a large torque for a little bit of power input. Additionally, some other circuits were designed on the board, such as two buck converters that are necessary to convert 48VDC to 12V and 5VDC for the other components that need lower voltages. The board will take the DC signal from the battery and buck it down to 5V where it powers the FET driver IC's, and the 12VDC will power the microcontroller when it is not connected to the wall. These circuits are shown in the following pages along with their design, and any other necessary additional information.

Design

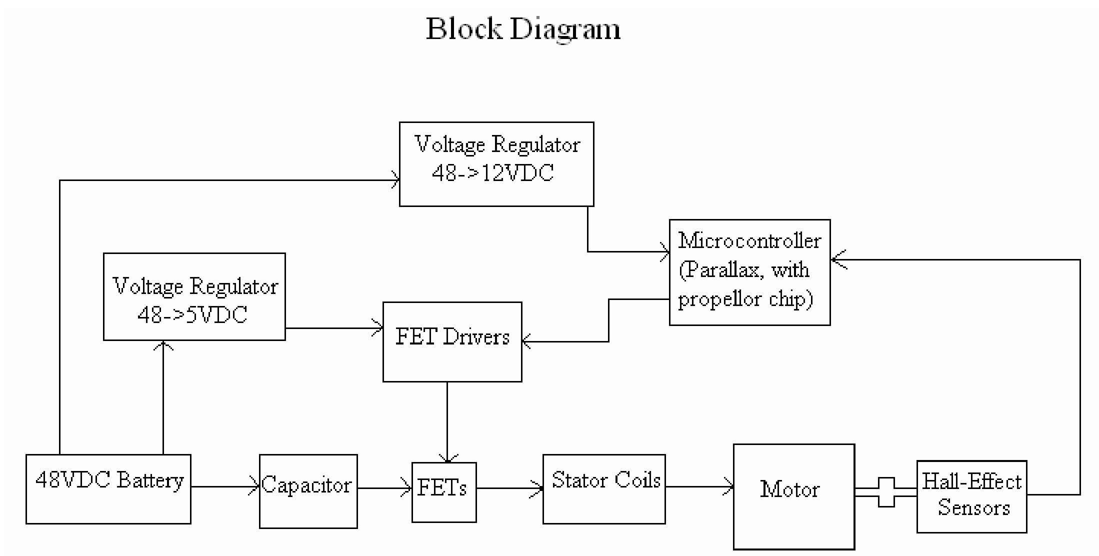

Figure 4: Block Diagram for the Design of the Control Circuit – this is what will control the switching circuit.

The battery stores a charge on the capacitors to be used in short bursts that will be required to send the current where and when it is needed. It also provides voltage to the FET drivers and the microcontroller itself with the 48->12VDC and the 48-5VDC regulators on the board. Once the FET driver receives a signal from the microcontroller, it will open the FETs based on where the permanent magnets are with respect to the stators that are set a certain distance apart, angularly. When the FET is closed, the capacitor discharges over a small resistance and sends a high current to the coils in the stators. This high current causes a magnetic field to develop and will provide torque for the shaft by repelling and attracting the permanent magnets in the rotor. Finally, once the cycle is complete, the hall-effect sensors return a signal to the microcontroller to update the position of the rotor as it moves – allowing the current to flow where it is needed as the shaft spins.

The datasheets provided the external circuitry required to build the voltage regulators that would reduce the voltage from 48V down to 5V and 12V. As long as the voltage is constant, then the following circuit diagram shown in Figure 5 below can be used in the design.

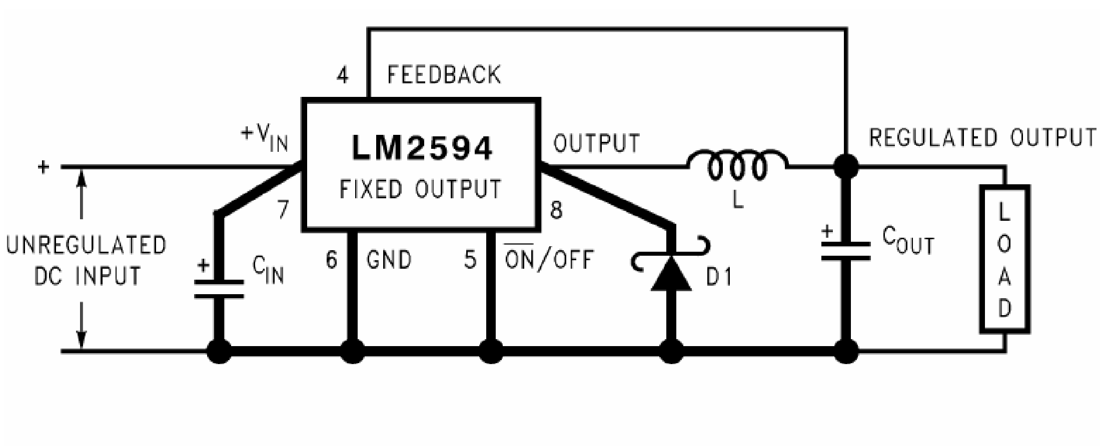

Figure 5: Voltage Regulator circuitry – shown above, the circuitry required to regulate the voltage from 48V down to 5VDC. The circuit for the 12V regulator is the same, only required different values for the capacitance values on C_{IN} and C_{OUT}.

The final design for the control circuit was created using the program ExpressPCB and the associated program ExpressSCH. The software is almost exactly the same as the OrCAD versions of the same thing (capture and schematic), but they are a little limited with their uses. The benefit of using this software, however, is that the boards do not have to be etched – the software is designed by a company that does the etching for you. The final design for the PCB is shown in Appendices F and G, the PCB layout and schematic, respectively.

Test Plans

Initially, a test program was being written for the microcontroller that would open and close the FETs as necessary to see if it actually worked, but the project ran into many flaws before we ever had a chance to reach that point. With the test program unwritten, I still had to prove that my circuitry is functional. First, I went through and tested all of the solder joints to make sure all the connections that were supposed to be functioning properly were indeed intact. Also, I went through and tested the FET drivers for their functionality. By obtaining a 5V supply, I was able to power the IC's and apply a signal to the pin where it would receive the microcontroller signal. Once applied, I verified the correct operation of the circuit by measuring the output voltage on the FET to see if it was indeed open or closed. Also, the DC voltage regulators were tested to verify their output voltages as 12 and 5VDC, but the charging circuit remains untested due to the technical difficulties that the project ran into around the fourth week of the summer.

Development and Construction

The construction phase consisted of soldering many joints on the printed circuit board, and then checking each individual solder connection to ensure that there was a connection between every trace. Using a voltmeter to continuity test, I tested every single point on the board to verify continuity at all the points. Once all the points on the board were verified, I began to test the operation of the FET drivers by applying a high or a low to the input of the driver. Since the driver acts like a NAND gate, by grounding one terminal and applying a high and low, the FET that is attached to the output of that particular driver would open and close. Additionally, after constructing the voltage regulators, I applied a 48VDC signal to each of the areas where it was supposed to regulate the voltage down to 12VDC and 5VDC. The only thing on the board that remains untested is the capacitor charging circuit that would send current pulses to the coils of the stators on the motor. These were untested due to the fact that the microcontroller program was never written and we never made a header connector that would connect to the header pins on the board that would accept the signals from the controller.

Integration and Test Results

Although the circuit was never extensively tested and interfaced with all of the parts of the motor, the individual components of the board are still functional. The final integration of the board was never completed because we never constructed the stator coils, the microcontroller header or the program that would switch the FETs, and the batteries were never sized nor ordered due to a lack of research for the project that we ran into around week four of the project. Even though these things were lacking, I was still able to verify proper operation of the individual components on the board and speculate that the board might work if some more parts were purchased, and some more research was done to size the batteries correctly to drive the motor. As far as switching the current, the board should pulse a current through the traces and switch them when it receives a signal from the microcontroller. When attached to the coils, the capacitors should discharge when the switch opens and that was the intent of the board. So, even though the rest of the project was not finished, I can say that the board was somewhat of a success.

Conclusion

One of the biggest lessons I learned on this project is the importance of engineering management. A manager is necessary to receive reports, collaborate, and activate discussions among group members so that engineers can work effectively and efficiently together; engineers working apart from each other on separate projects that eventually combine to one product is completely counter-productive, and is a waste of everyone's time and resources. Often times, separate development is required on a project; but with no collaboration, the products of many different small projects that will eventually integrate together are completed and are useless because the engineers were not thinking ahead.

However, after completing a lot of research on DC motors and developing my circuit, I successfully built a circuit that would work with the motor that we were designing. It uses a feedback loop to determine the position of the shaft, and then opens and closes switches based on the shaft position. As the rotors rotate, the permanent magnets pass by the coils, and the goal of the circuit is to supply current to the coil that is nearest a magnet. The coils were spaced such that there was always a magnet next to a coil, so it was necessary to operate the correct FET as the magnet passed by. The only unfortunate part of the circuit was that we were unable to test it with the motor because it never was completed. Perhaps, in future iterations of the motor the circuit will be able to provide the switching that it needs. The only testing that we were able to do was with the microcontroller test program and the board, verifying that the FETs opened and closed when they were prompted by the drivers. It would have been nice to see all of the work in action at the end of the project, but unfortunately it doesn’t always work out for the best.

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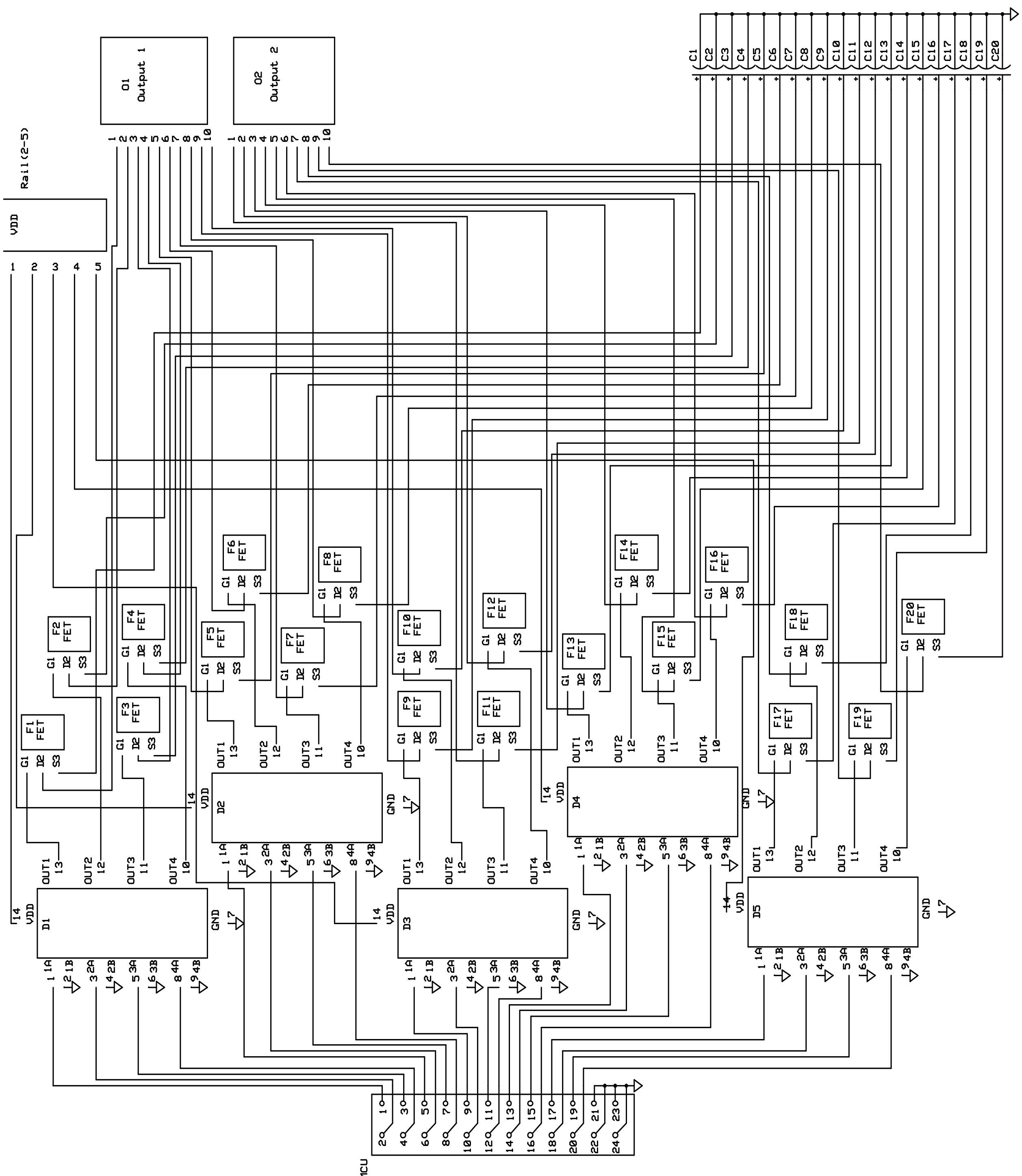
Parts List and Cost

Part	Quantity	Cost ($)	Total ($)
Printed Circuit Board	1	175	175
Magnetic Sensor Bushing	1	42.12	42.12
Terminal Blocks	2	3.7	7.4
PCB Terminal Block	2	1.81	3.62
MOSFET Quad NAND I/P	5	3.09	15.45
MOSFET PWR Transistor	20	2.27	45.4
Terminal Blocks	2	6.98	13.96
Capacitor, 390uF 100V	20	1.56	31.2
Capacitor, 68uF 50V	4	0.48	1.92
RF Choke, 330uH	2	2.72	5.44
Capacitor, 82uF 25V	2	0.38	0.76
Capacitor, 120uF 16V	2	0.28	0.56
Schottky Diode 1N5819	3	0.54	1.62
Buck Switch, 48-5V	1	4.63	4.63
Buck Switch, 48-12V	1	4.63	4.63
1kohm 10 watt	1	0.49	0.49
MOSFET Drivers	5	2.56	12.8
24 Pin Header	1	1.14	1.14
Total:	368.14		

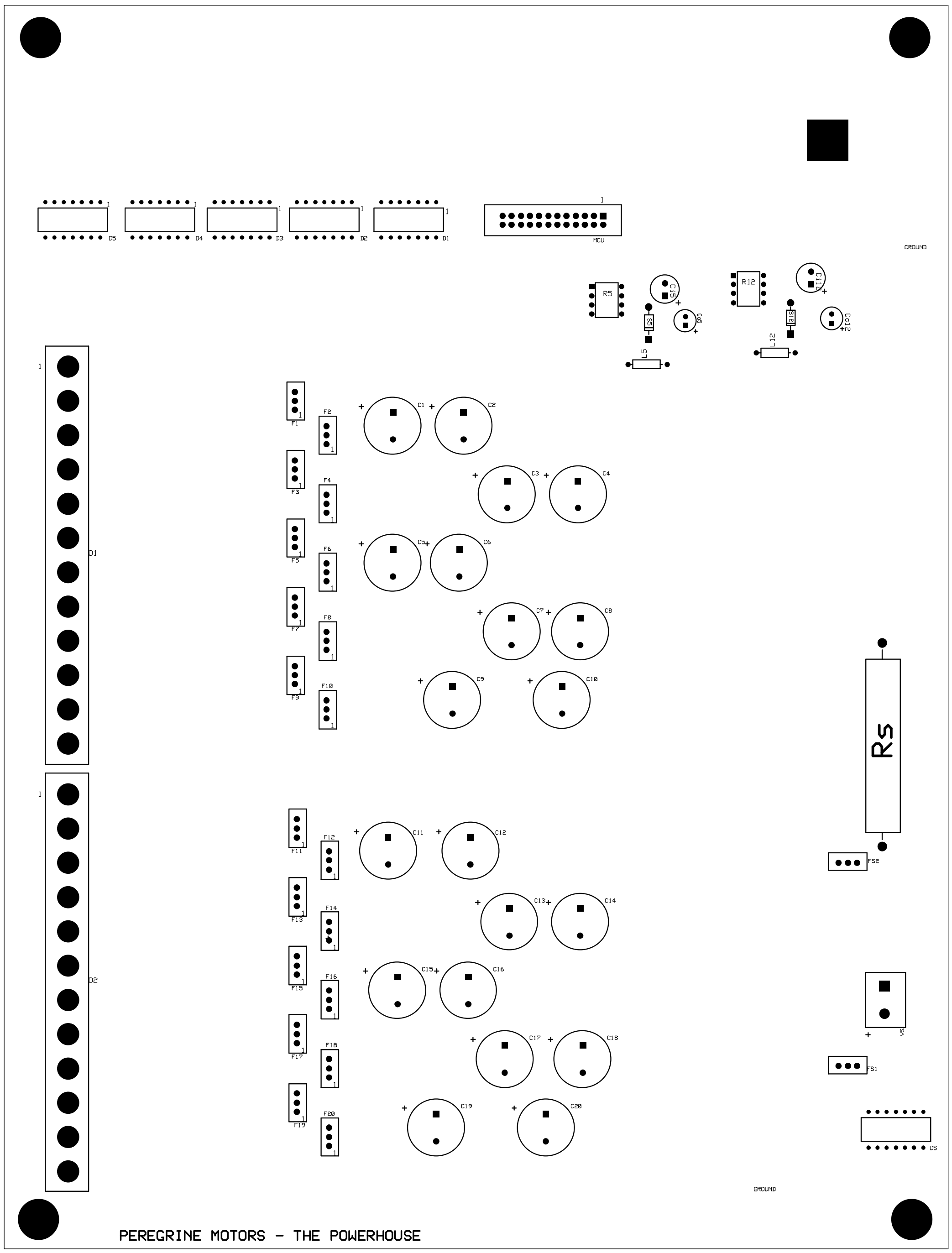
Schedule – Time Estimates

Schedule: 2 Weeks				
Monday	Tuesday	Wednesday	Thursday	Friday
8:00a-1:00p	8:00a-1:00p	8:00a-1:00p	8:00a-1:00p	8:00a-1:00p
2:00p-7:00p	2:00p-7:00p	2:00p-7:00p	2:00p-7:00p	2:00p-7:00p
Total Hours: 100				

Schematic for the PCB Layout



PC Board Layout



Analysis of Senior Project Design

Summary of Functional Requirements:

The circuit is designed to control the current flow in a permanent magnet DC motor. A hall-effect sensor array determines the position of the shaft as the motor is turning, and sends it back to a microcontroller. The microcontroller will then send a signal to a series of FET drivers on a printed circuit board that will each send a signal to the FET that goes with them, and the FETs will open close. As the shaft turns, the FETs will turn on and off current to the coils that are attached to the FETs, and send current only where it needs to be. This process is repeated infinitely while the motor is spinning, and is always awaiting the signal from the controller. However, the majority of this project is concerning the printed circuit board, and less on the microcontroller design.

Primary Constraints:

The biggest challenge that the board faced was integrating with the rest of the project. There were lots of things that needed to work correctly in order for all of the pieces to interface with each other, and if one thing was out of place or incorrect it wouldn't work. The biggest limiting factor was the knowledge that I possessed before I started, so a lot of research was necessary in order to do anything useful as far as the project progressed.

Economic:

The original cost of the motor was estimated at around 200 dollars for the prototype, but due to some mistakes that occurred along the way, the final cost of the motor ended up being around 365 dollars; as documented in the project. The original estimated time to complete the project was about 1 week of work, or about 50 hours if everything went according to the plan. However, there was a learning curve with the software and none of the parts were in the library, so they had to be all designed based on the component specs. The actual time for completion was about 100 hours, or 2 weeks of work.

Environmental:

There were no environmental impacting factors associated with the project, all of the parts used were RoHS compliant and recyclable. The only factor would be the materials that were used to ship all of the components used in the project, but they were all recycled.

Manufacturability:

Since this project was mainly concerned with a printed circuit board, it is very easy to duplicate once the final design is completed. All that needs to be done is etch more boards and have the parts soldered on and you have an exact copy.

Sustainability:

All of the parts used are electronic devices, so naturally they all have a limited number of times they are able to switch before they need to be replaced. However, as with all electronic devices, if they are used properly and not abused they should last quite a long while. As stated on the previous page, all the materials used were RoHS compliant so there is no environmental impact. More research on the matter and further testing could lead to upgrades that would improve the design, as well as any new technology that comes about would help to upgrade it as well. As far as challenges with performing upgrades to the design, there is plenty of space leftover on the board to add or subtract new parts. The only issue would be replacing the board with different components, so there really would be no huge ordeal with upgrading the final design.

Ethical, Health/Safety, Social/Political:

There were really no ethical, health or safety, social or political concerns with the construction and development of this project.

Development:

For the duration of this project, I needed to learn how to use the two programs ExpressPCB and ExpressSCH, which are basically recreations of the OrCAD programs used in printed circuit board development. The programs are nearly identical, but as with any new software, there is a learning curve that one must learn before any work can be done.