

IN-WHEEL HUB SRM SIMULATION AND ANALYSIS

by

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ABSTRACT

Is it feasible to replace the conventional gasoline engine and subsequent drive system in a motorcycle with an electric switched reluctance motor (SRM) by placing the SRM inside the rear wheel, thereby removing the need for things such as a clutch, chain, transmission, gears and sprockets?

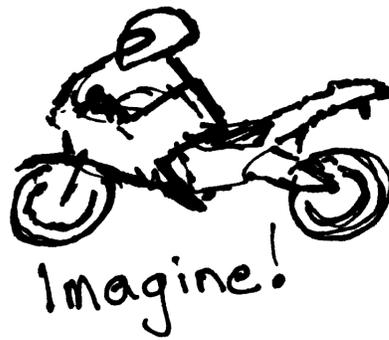
The goal of this thesis is to study the theoretical aspect of prototyping and analyzing an in-wheel electric hub motor to replace the standard gasoline engine traditionally found on motorcycles.

With the recent push for clean energy, electric vehicles are becoming more common. All currently produced electric motorcycles use conventional, prefabricated electric motors connected to the traditional sprocket and chain design. This greatly restricts the efficiency and range of these motorcycles. My design stands apart by turning the rear wheel into a SRM which uses electromagnets around a non-magnetic core to convert electrical energy into mechanical force driving the rear wheel. To my knowledge, there is currently no motorcycle designed with an in-wheel hub SRM.

A three-phase SRM and a five-phase SRM will be simulated and analyzed using MATLAB with Simulink. Factors such as friction, weight, power, etc. will be taken into account in order to create a realistic simulation as if it were inside the rear wheel of a motorcycle. Since time and finances will not allow for a full scale build, a scaled model three-phase SRM will be attempted for demonstration purposes.

DEDICATION

This thesis is dedicated to my son Isaac, without whom it would not exist.



ACKNOWLEDGMENTS

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I would also like to thank Paul Schoen (P S Technology, Inc., www.pstech-inc.com) for his advice in the building of the three-phase SRM.

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Contents

LIST OF TABLES	viii
LIST OF FIGURES	ix
CHAPTER 1: INTRODUCTION	1
1.1 A Brief History	1
1.2 Some Equations	2
CHAPTER 2: GENERIC DESIGN OF THE SRM	4
2.1 Some Advantages and Hurdles	4
2.2 Introduction to Design with Basic Operating Concept	6
2.3 Original Design	11
2.4 Equations Used Throughout	13
CHAPTER 3: DESIGN IN SIMULINK AND ANALYSIS	21
3.1 Design of Three-Phase SRM	21
3.2 Analysis of Three-Phase	41
3.3 Design of Five-Phase SRM	49
3.4 Analysis of Five-Phase	53
CHAPTER 4: BUILDING THE THREE-PHASE	60
4.1 Materials and Cost	60
4.2 Construction	61
CHAPTER 5: WHERE TO GO FROM HERE	72
5.1 Starting the SRM	72
5.2 Balance and Riding of Motorcycle	74

5.3 Building the Motorcycle	75
5.4 Regenerative Braking	75
CHAPTER 6: FINAL THOUGHTS	77
6.1 Personal Hurdles	77
BIBLIOGRAPHY	80

List of Tables

1	Electricity 101	14
2	Three-Phase SRM Components	23
3	SRM Output Components	23
4	3 Phase SRM Components	49
5	Hardware Expenses	61
6	Software Expenses	77

List of Figures

1	<i>Sturgeon's Electromagnet</i>	2
2	<i>Magnetic Field Generated</i>	6
3	<i>Rotor Shape</i>	7
4	<i>Three-Phase SRM Movement</i>	8
5	<i>Rotor Position</i>	9
6	<i>Ideal Flux</i>	10
7	<i>Common SRM Ratios</i>	11
8	<i>Original Design</i>	13
9	<i>Electrical Components</i>	14
10	<i>Phase Steps</i>	15
11	<i>Energy</i>	17
12	<i>Flux Density</i>	19
13	<i>Simple Simulink Example</i>	22
14	<i>Scope of Simple Example</i>	22
15	<i>Three-Phase SRM Block</i>	24
16	<i>Simple Torque</i>	25
17	<i>Resistance</i>	26
18	<i>Switch, Power Converter and Power Source</i>	28
19	<i>Converter</i>	29
20	<i>Element Wise Gain Block Parameters</i>	30
21	<i>Discrete Integrator Block Parameters</i>	31
22	<i>Degrees and Integration</i>	32
23	<i>Mod 90 Output</i>	33

24	<i>Converter Output</i>	34
25	<i>Main Scope 30° 90°</i>	35
26	<i>Main Scope 45° 75°</i>	36
27	<i>Flux 45° 80°</i>	37
28	<i>Flux 40° 75°</i>	37
29	<i>Switch</i>	38
30	<i>Switch Zoomed-In</i>	39
31	<i>Three-Phase SRM Diagram</i>	40
32	<i>Rapid Acceleration</i>	41
33	<i>Three-Phase One Second Main Scope</i>	42
34	<i>Three-Phase One Second After Integration</i>	43
35	<i>Three-Phase One Second Converter</i>	44
36	<i>Three-Phase One Second Rad/s vs RPMs</i>	44
37	<i>Three-Phase One Second Switch</i>	45
38	<i>Three-Phase Five Seconds Main Scope</i>	46
39	<i>Three-Phase Ten Seconds RPMs</i>	47
40	<i>Three-Phase Ten Seconds Torque</i>	48
41	<i>Five-Phase SRM Block</i>	50
42	<i>Battery Block Parameters</i>	51
43	<i>Five-Phase Diagram</i>	52
44	<i>Five-Phase One Second Main Scope</i>	53
45	<i>Five-Phase One Second Integration</i>	54
46	<i>Five-Phase One Second Converter</i>	54
47	<i>Five-Phase One Second Switch</i>	55
48	<i>Five-Phase Ten Seconds Main Scope</i>	56

49	<i>Five-Phase Ten Seconds Torque</i>	57
50	<i>Five-Phase Ten Seconds Battery Scope</i>	58
51	<i>Five-Phase Ten Seconds Battery Discharge Characteristics</i>	58
52	<i>Five-Phase Ten Seconds Magnetization Curves</i>	59
53	<i>Three-Phase Design Front</i>	62
54	<i>Three-Phase Design Measurements</i>	62
55	<i>Three-Phase Electrical Design</i>	63
56	<i>LED Assembly</i>	64
57	<i>Three-Phase Built</i>	65
58	<i>PIC24HJ64GP502 Schedmatic</i>	67
59	<i>Control Computer</i>	68
60	<i>Complete Build</i>	68
61	<i>Start of Five-Phase Angles Chart</i>	73
62	<i>Example of Start Angles</i>	74

CHAPTER 1

INTRODUCTION

1.1 A Brief History

Since the invention of the motor vehicle in 1807, the need for more powerful and efficient motors has been a never ending endeavor. The biggest concern of the future is breaking our dependency on fossil fuels to power our vehicles; from this we see electric motors and hybrids growing in popularity. However, since electric motors have always been second best to internal combustion engines, many new electric prototypes are being built and tested in the hope of discovering an electric motor which will topple the gasoline engine. The goal is to find the most efficient, practical and economic design.

An SRM's force comes from its electromagnets. The original electromagnet was invented in 1825 by William Sturgeon. It was a crude design of a horseshoe shaped piece of iron with copper wire loosely wrapped around it; when a current was passed through the coil, a magnetic field was produced which could be applied to any one of numerous engineering endeavors. For example, the original telegraph system used an improved electromagnet designed by Joseph Henry; sending a current through a wire a mile away caused the electromagnet to attract a lever towards it, resulting in the dinging of a bell. The applications were endless.

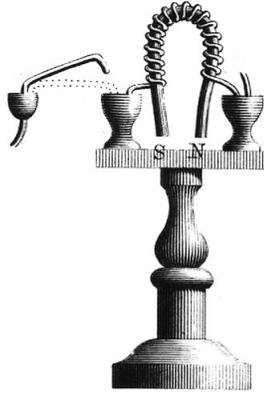


Figure 1: *Sturgeon's Electromagnet*

Fast forward to 1969 when S.A. Nasar designed what may be considered the blueprint of the modern SRM. An SRM uses a ring of electromagnets surrounding a rotor which is connected to an axle – similar to a brushless DC motor. The primary difference of the SRM to almost all other electric motors is that its rotor is not magnetized. This gives it many advantages, such as no required permanent magnets, reduced heat, zero magnetic friction when OFF and more reliable controllability.

1.2 Some Equations

There are many equations that govern magnetic fields, electricity and, of course, physics. The most common are Maxwell's Equations which include:

$$\text{Gauss's Law} : \nabla \cdot \mathbf{D} = \rho_v \quad (1.2.1)$$

$$\text{Gauss's Magnetism Law} : \nabla \cdot \mathbf{B} = 0 \quad (1.2.2)$$

$$\text{Faraday's Law} : \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (1.2.3)$$

$$\text{Ampere - Maxwell Law} : \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (1.2.4)$$

where ∇ is *divergence of*, $\nabla \times$ is *divergence of the curl of (or how a field wraps around an object)*, \mathbf{E} are the electric fields, \mathbf{H} are the magnetic fields, \mathbf{D} and \mathbf{B} are the proportional electric fields and magnetic fields respectfully to \mathbf{E} and \mathbf{H} . \mathbf{D} and \mathbf{B} can be represented by $\mathbf{D} = \epsilon\mathbf{E}$ and $\mathbf{B} = \mu\mathbf{H}$. $\mathbf{J} = \sigma\mathbf{E}$ is the electric current density, ρ_v is how much charge exists and t is, of course, time. Simply put, the first describes the flow either to or from positive and negative charges; a positive charge flows outwards and a negative charge flows inwards. The second states that if there is no charge or charges that cancel out (i.e. positive and negative), the magnetic flux is zero. The third represents the relationship between current and the flux of the magnetic field; this is the most important of these equations for this project as I will use the magnetic flux to help determine the position of the rotor. The fourth represents the rotational field around a current. A direct result of these equations derived from experiments yields the Wave Equation:

$$\frac{\partial^2 \mathbf{E}}{\partial \mathbf{z}^2} = \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} \quad (1.2.5)$$

where c is the speed of light (299,792,458m/s) – at which all electromagnetic plane waves travel– and the right hand side is the acceleration of electrical fields in the z direction on a 3D plane, which is equal to the acceleration in time of the electric field. All of these deal with electrical and magnetic fluxes through different surfaces and fields which map how electromagnets behave given certain parameters. Since SRMs use electromagnets around an iron core, all of these equations play an important role in building and analyzing motors.

CHAPTER 2

GENERIC DESIGN OF THE SRM

2.1 Some Advantages and Hurdles

This section gives a general overview of some of the topics which will be covered in more depth in the analysis section.

The great advantages of an SRM include cost and maintainability. The SRM designed here is simple in construction and doesn't contain many parts. It's relatively cheap to build (other than the battery pack) and, with so few parts, maintenance is kept to a minimum; there is no need to worry about oil, filters, gas, transmission fluid, anti-freeze, radiators, carburetors, spark plugs, exhaust, fuel pumps, etc. This makes for a simple, economic design with much less that can go wrong as compared to a standard gasoline-driven motorcycle.

Another advantage of an SRM over a gasoline engine is torque. The gearing of a gasoline engine determines the levels of torque and acceleration that can be achieved at high speeds; low gearing yields greater torque and greater acceleration, whereas high gearing yields less torque and less acceleration. An SRM, which doesn't use gears, yields nearly constant torque for nearly all speeds; therefore, acceleration should be consistent for nearly all speeds. Note that the torque in an SRM –although constant–may not be as high as that of a gasoline engine at its peak –around 95 – 99% of its speed– which does limit speed and acceleration, but only at the highest speeds. This is what allows for a direct drive system, since the SRM designed here is meant to be placed into the rear wheel; this means that the rotor spinning inside the wheel directly corresponds to the speed of the tire as there are no gear ratios.

One of the most important factors and hurdles to be conquered is the torque ripple effect. Torque ripple is a jolting of the rotor forward as the phases of the SRM are switched ON and OFF; the fewer electromagnets the SRM contains, the more torque ripple effect exists. This is most problematic at lower speeds since the rotor is not rotating fast enough to ensure smooth transitions between phases. As speed increases, the torque ripple effect is minimized.

Another factor we must consider in the simulations is the position of the rotor as it moves because timing is crucial. This is tricky because, as the rotor accelerates, the position does not follow a linear track of turning phases ON and OFF. There are several methods being developed to solve this problem. The goal, since we must keep cost and complexity in mind, is to find a way to keep track of the position of the rotor without the addition of mechanical sensors.

One of the more problematic hurdles is how to start the motor in the same direction every time. It would be very troublesome for the motor to start running in reverse as the throttle was "gassed." Note, however, that an SRM can run either forward or backward equally. This would give a motorcycle the ability to run in reverse, which is not something commonly found on motorcycles today.

Also, in a full-scale prototype SRM for a motorcycle, the magnetic fields produced while riding would attract any magnetic object on the road. The constructed three-phase will not have this problem because it is inside in more than ideal conditions; however, in the real world there will be debris on the road. This debris may be magnetic and be attracted to the wheel. This will not be further addressed in this paper; however, to counter this problem a sealed wheel design would need to be implemented in order to keep debris out of the wheel.

2.2 Introduction to Design with Basic Operating Concept

Any motor has two basic sections, the *stator* and the *rotor*. The stator is the fixed part or parts that do not move. The rotor is the part of the motor that physically moves and drives whichever device it is hooked up to, in this case the tire.

The first part of an SRM to consider is the electromagnet which is part of the SRMs stator. An electromagnet is simply a magnet with an ON/OFF switch containing no permanent magnets. It is comprised of an iron core wrapped many times with insulated conducting wire, such as copper with enamel coating. Magnetic wire is used because the coating is very thin as compared to regular wire whose insulation is often just as thick as the wire itself. When an electrical current is passed through an electromagnet (ON), a magnetic field is generated creating the force of a magnet. Hence the term *electromagnet*. Shown is a simple representation of the magnetic field produced.

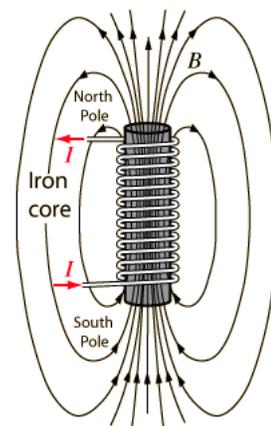


Figure 2: *Magnetic Field Generated*

The next part to look at is the rotor. The rotor is the part that will spin to change electrical energy into mechanical energy when pulled by the electromagnets. *Air gap* is the small space between the rotor and electromagnets. In actual construction it is important to note that the air gap between the electromagnets and rotor must be minimized in order to maximize force and efficiency. To do this we can implement curved poles on the rotor in order to move the rotor closer to the electromagnets. This does not effect the pull of the electromagnets since, with squared poles, there is just as much pole material whose efficiency is lost due to increased distance. In fact, it increases the pull because almost the entire rotor pole end remains just as close to the electromagnet when passing. Shown is a comparison of both designs; on the left is a rotor with squared poles and on the right is a rotor with slightly curved poles. Next it is shown what happens when the differently shaped rotors are rotated with the smaller air gap.

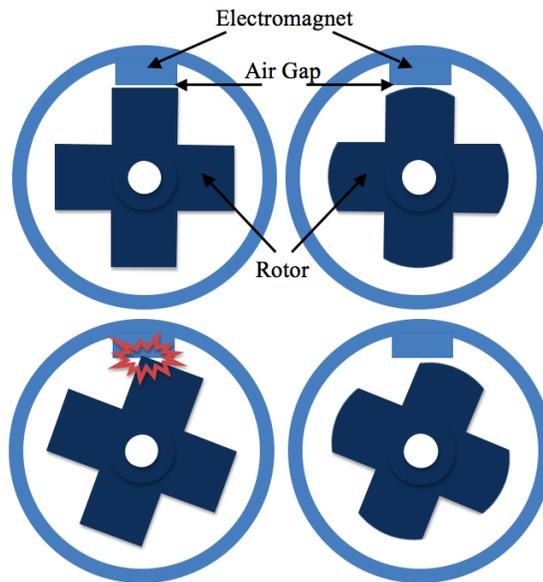


Figure 3: *Rotor Shape*

The next step is to make a ring of electromagnets surrounding the iron rotor which rides on the axle of the wheel. In the three-phase there are six electromagnets and a rotor with four poles. As the electromagnets are switched ON and OFF in phases, magnetic fields are created pulling the rotor poles towards the phase which is ON. A *Phase*, as illustrated, is a set of two adjacent electromagnets which are both turned ON when that phase is ON. Here, Phase A contains electromagnets A and A'. Note the winding orientation of A and A' are opposite. This ensures that the magnetic fields are both pulling instead of one pulling and one pushing, as would happen with the same orientation. Timing the phases ON and OFF in sequence around the ring spins the rotor and thus drives the wheel. In the following figure, if Phase A is ON then R1 and R1' would be pulled towards A and A' respectively. Soon after, Phase B would be switched ON as Phase A is switched OFF, then Phase C would follow and so on in a loop rotating the rotor. The beauty of this design is there are no permanent magnets, only a few parts and no brushes to wear out. This greatly reduces not only cost but precious resources as well.

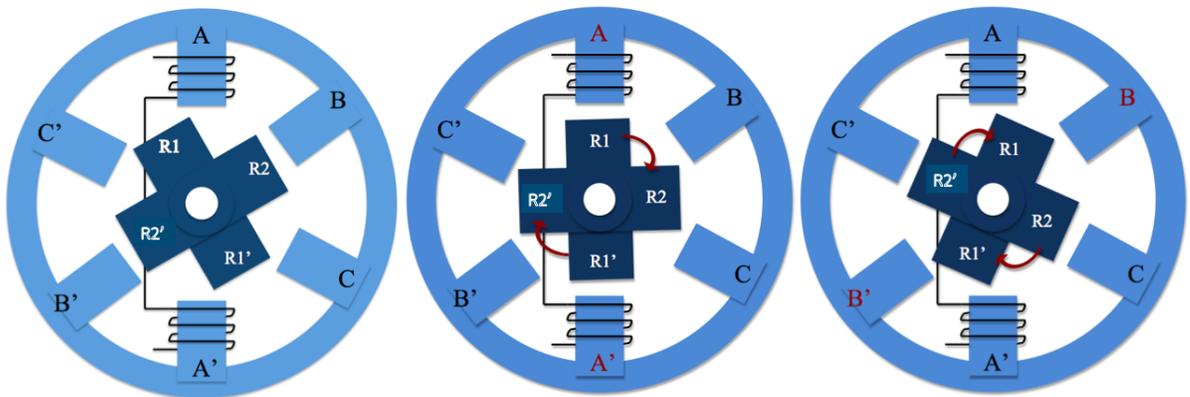


Figure 4: *Three-Phase SRM Movement*

One of the hurdles is to know the position of the rotor. The key is to use what we already have occurring in the SRM; that is, the magnetic flux relationship as the rotor passes the electromagnets. The closer the rotor is to being aligned with an electromagnet, the stronger the flux, being the strongest when the rotor is aligned. The problem in the actual build, however, is that I could not find any such sensors that would not require the addition of magnets, which is something I was trying desperately to avoid.

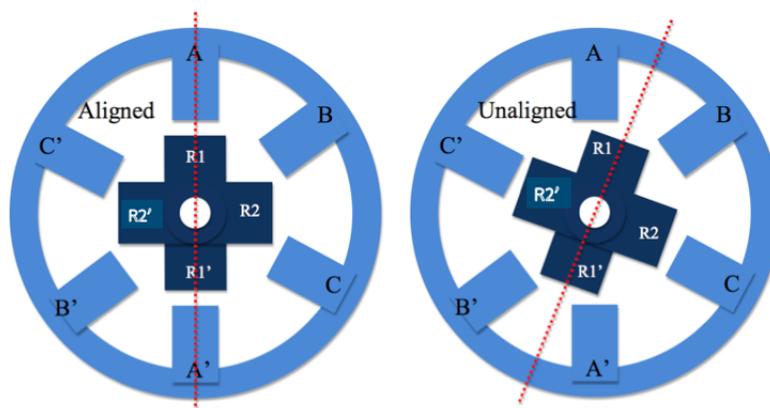


Figure 5: *Rotor Position*

A simple way to understand how flux changes is to think of the Doppler Effect in which moving sound, such as a train, becomes louder as it comes nearer, is loudest when it is directly in front of you, and then seems to become quieter as it passes and moves away. Unlike the Doppler Effect in this illustration, however, pretend the sound remains at the same frequency both before and after it passes you. Now, instead of sound waves, imagine the waves are magnetic forces, the train is the rotor and you are the electromagnet. A computer can determine the position of the rotor by tracking the flux throughout each phase. As each phase's flux peaks, the rotor

becomes aligned with the corresponding electromagnets which in turn gives the position of the rotor. Timing how quickly the rotor is approaching the peak is how the control computer keeps track of the position of the rotor in the simulation. This, in turn, gives the control computer the correct timing of when to switch each phase ON and OFF. The next figure shows the ideal flux through one cycle as the rotor becomes aligned; the following figure is the actual flux output of the three-phase which has been simulated. As with any project like this, you find the ideal situation is different from the simulated situation and the real world situation is different from either. This is the reason research of any project from the ideal to simulated to real world is very time consuming.

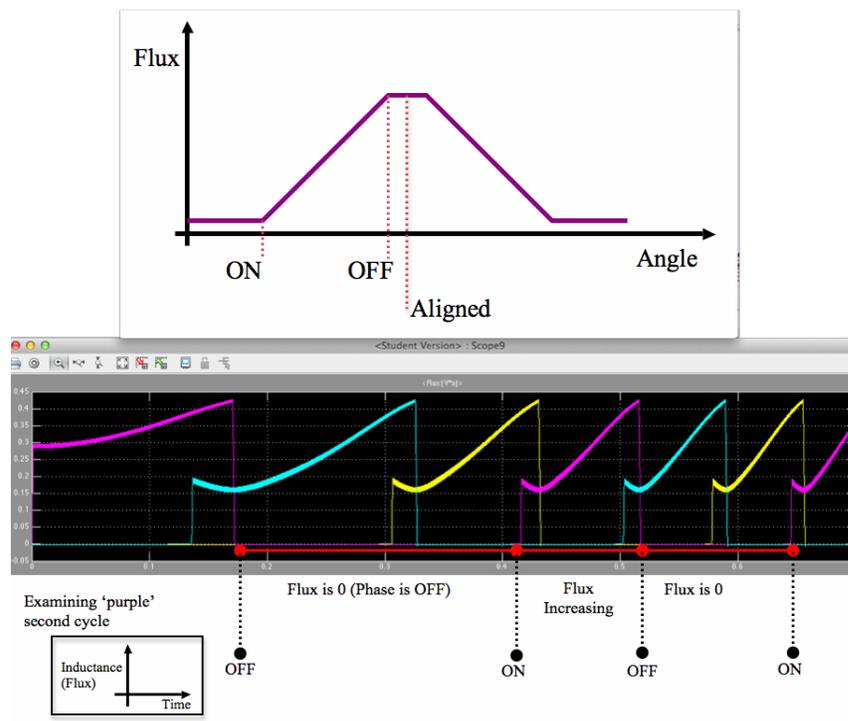


Figure 6: *Ideal Flux*

Something else to note about the construction of SRMs is that they are subject to certain restrictions of the ratio of electromagnets to rotor poles. There are two-phase SRMs whose electromagnet to rotor pole ratio is $4/2$, three-phase SRMs with a ratio of $6/4$, four-phase SRMs with a ratio of $8/6$, and five-phase SRMs with a ratio $10/8$. Any constant multiplier of these can also be used. For example, the original design was to be a 20-phase, which is four times a five phase resulting in a ratio of $40/32$. Below are the most commonly found ratios of SRMs.

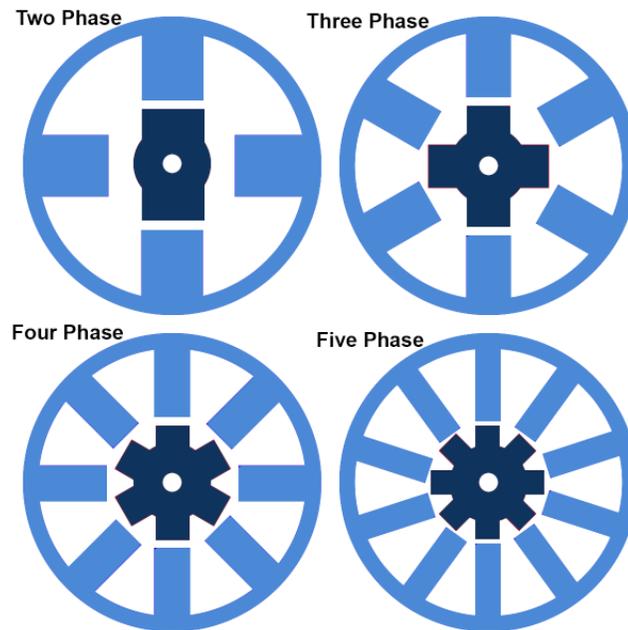


Figure 7: *Common SRM Ratios*

2.3 Original Design

It's worth noting the original design for this project and why the design changed. The original design was basically an inside out SRM, though I knew nothing about SRMs when I first started. The rotor poles surrounded the electromagnets which

faced outwards towards the tire. This design was for the simplicity of the mechanics. The rotor poles would be on the inside of the rim which would be connected to the axle via two sets of ball bearings on either side of the wheel. Mechanically, this is much easier to build than the current design. It's worth noting because, after weeks of investigating this idea, it was decided that this design would not have the power needed for this project due to the concept that SRMs function based on the path of least reluctance. The magnetic flux of a traditional SRM focuses inwards, one phase to the next. The original design would be "pushing" the magnetic flux outwards away from each phase. This is what caused the loss of power. Another factor which played a role in dismissing this design was the RPMs. Although the tire was much closer to the rotor, the speed produced would be much slower. The original design would also not be suitable to gearing if gears had to be added later on. Shown are some of the drafts of the original design; on the gray rim the peg-like, inward protrusions are the rotor poles, the yellow cylinders are electromagnets, and the ball bearings are the red and blue objects on either side. The green would be the inner rim which would be connected to the swing arm of the motorcycle. The dark maroon colored objects were going to be sensors but were eliminated in the new design.



Figure 8: *Original Design*

2.4 Equations Used Throughout

We've already seen Maxwell's equations but there are several more equations to be used throughout this project.

First, we see equations relating to electricity. There are four basic components in every circuit dealing with electricity: voltage, current, resistance and power. Below is a chart of their symbols and the unit of measurement for each.

Name	Sign	Units	Symbol
Voltage	V	Volts	V
Current	I	Amperes (Amps)	A
Resistance	R	Ohms	Ω
Power	P	Watts	W

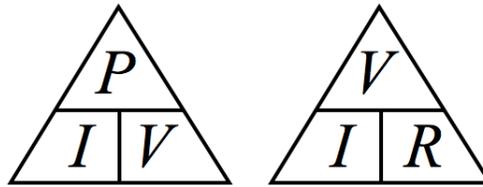
Table 1: Electricity 101

There are two basic equations that describe how they're connected.

$$P = I \times V \quad (2.4.1)$$

$$V = I \times R \quad (2.4.2)$$

Below is a visual representation of how all four are connected.

Figure 9: *Electrical Components*

These are important to understand because, for example, you may be putting 20 volts into a circuit but, without any conductance, there will be no current and hence no power. When first experimenting with electromagnets via a variable DC power source, I found that there was no attraction from the electromagnets to the rotor. Without resistance the volts would drop to zero causing the power to drop to zero resulting in no magnetic attraction between the electromagnets and rotor. A good indicator that there is either no resistance or not enough resistance is the initial connection of the power source to the electromagnet; if there is a spark (sudden

discharge of electricity) there is a problem. Another problem can arise if you do not have a high enough resistor. Imagine a 2Ω resistor in a circuit with 12 volts and a current limited to 6 amps; trying to increase the voltage will literally burn up the resistor and result in a loss of all power. This plays a role in the simulation and building of the SRM because you are dealing with electricity running through your motor. Without the proper resistance, voltage, and current you will either have very little or no power.

A basic equation –though no less important– is the Step Angle. This is the angle that the rotor rotates under in each phase, also known as the rotor electrical angle in degrees.

$$\theta_s = \frac{2\pi}{mN_r} \quad (2.4.3)$$

In the case of a three-phase SRM, $\theta_s = \frac{2(180)}{3*4} = 30^\circ$. This, along with the simple equation

$$\theta'_s = \frac{2\pi}{m} \quad (2.4.4)$$

generates the following step graph for the phases. This is the ideal switching of the phases ON and OFF because the turning ON and OFF of the electromagnets is not instantaneous.

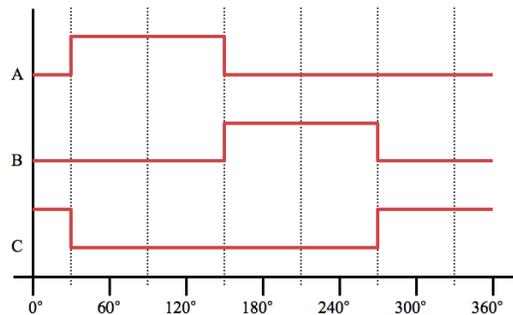


Figure 10: *Phase Steps*

Next, the relationship of flux to current is given by

$$\phi = L(\theta)i \quad (2.4.5)$$

Next is torque. Note that power is the rate of change of energy over time. The Torque Equation of a SRM is

$$T = \frac{i^2}{2} \frac{dL}{d\theta} \quad (2.4.6)$$

Note that torque is limited by available current and voltage. How is the torque equation found? Recall Faraday's Law in the introduction; using this, we can find the voltage across a phase as it is related to the magnetic flux.

$$v = iR_m + \frac{d\phi}{dt} \quad (2.4.7)$$

where v is terminal voltage, i is current, R_m is motor resistance from friction, and ϕ is flux linkage. If we multiply each side by i , we can arrive at the power equation since *voltage* \times *current* = *power*.

$$Power = vi = i^2R_m + i\frac{d\phi}{dt} \quad (2.4.8)$$

Note here that i^2R_m is the ohms lost and $i\frac{d\phi}{dt}$ is the mechanical power output. In order for this to be balanced and maintain any power, $i\frac{d\phi}{dt} = \frac{dW_m}{dt} + \frac{dW_f}{dt}$ where $\frac{dW_m}{dt}$ is the mechanical power and $\frac{dW_f}{dt}$ is the stored magnetic power. Mechanical power can be rewritten as torque times speed. This gives us

$$\frac{dW_f}{dt} = T_w = T\frac{d\theta}{dt} \quad (2.4.9)$$

where T is torque and $\frac{d\theta}{dt}$ is the rotational velocity of the axle. Substituting this back, we then have

$$i\frac{d\phi}{dt} = T\frac{d\theta}{dt} + \frac{dW_f}{dt} \quad (2.4.10)$$

Solving this for T , we find

$$T(\theta, \phi) = i(\theta, \phi) \frac{d\phi}{d\theta} - \frac{dW_f(\theta, \phi)}{d\theta} \quad (2.4.11)$$

The next step is to look at W_f and W_c or the stored co-energy. Graphically we can represent these values by the following.

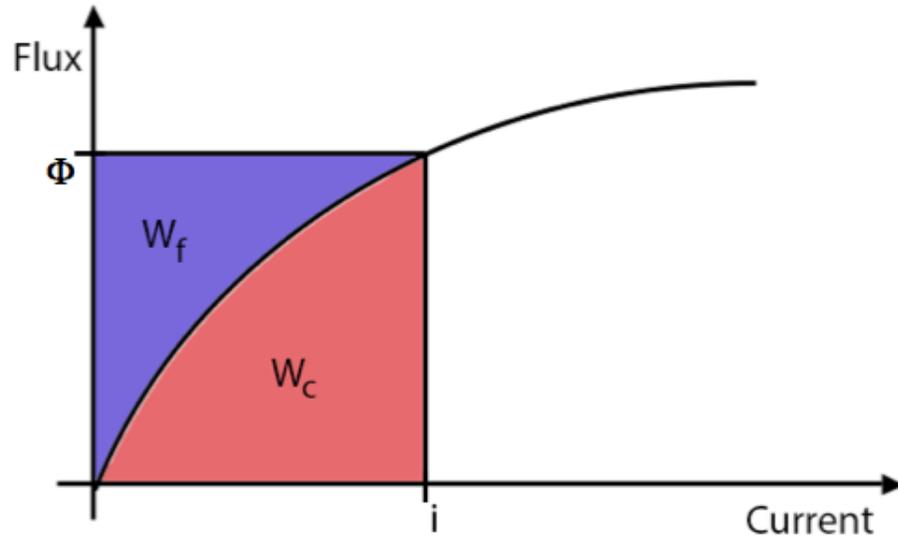


Figure 11: *Energy*

$$W_f = \int_0^\phi i(\theta, \phi) d\phi \quad (2.4.12)$$

$$W_c = \int_0^i \phi(\theta, \phi) di \quad (2.4.13)$$

Also note that

$$W_f + W_c = i\phi \quad (2.4.14)$$

Differentiating both sides, we see

$$dW_f = dW_c = \phi di + i d\phi \quad (2.4.15)$$

If we take this and plug it back into torque above, we see

$$T = \frac{id\phi - (\phi di + id\phi - dW_c(\theta, i))}{d\theta} \quad (2.4.16)$$

Next assume a constant current because the current supplied will not change throughout each phase. This implies that we can rewrite $dW_c(\theta, i)$ as

$$dW_c(\theta, i) = \frac{\partial W_c}{\partial \theta} d\theta + \frac{\partial W_c}{\partial i} di \quad (2.4.17)$$

This allows us to combine the previous two equations and assume a constant current to obtain

$$T = \frac{\partial W_c}{\partial \theta} \quad (2.4.18)$$

Using the relationship between flux and current mentioned earlier, we get

$$W_c = \frac{i^2}{2} L(\theta) \quad (2.4.19)$$

Lastly, using this and substituting back into torque with constant current, we find the simplified torque equation of a SRM to be (2.4.6).

Next is the stator flux density of electromagnets A, B, C, A', B' and C' as seen in the three-phase SRM. We'll assume here all fluxes are the same (except shifting θ_s) from electromagnet to electromagnet and that we are under ideal conditions.

$$\phi_A = \begin{cases} \phi_d \frac{\theta}{\theta_{ON}} & 0 \leq \theta \leq \theta_{ON} \\ \phi_d \left(1 - \frac{\theta - \theta_{ON}}{\theta_{OFF}}\right) & \theta_{ON} \leq \theta \leq \theta_{ON} + \theta_{OFF} \end{cases} \quad (2.4.20)$$

In order to graph this we also need the angle between the flux densities, referred to as the rotor pitch, which is given by

$$\theta_p = \frac{\pi(m-1)}{m} \quad (2.4.21)$$

For example, the ideal flux density of the first three electromagnets of an SRM would be represented as follows.

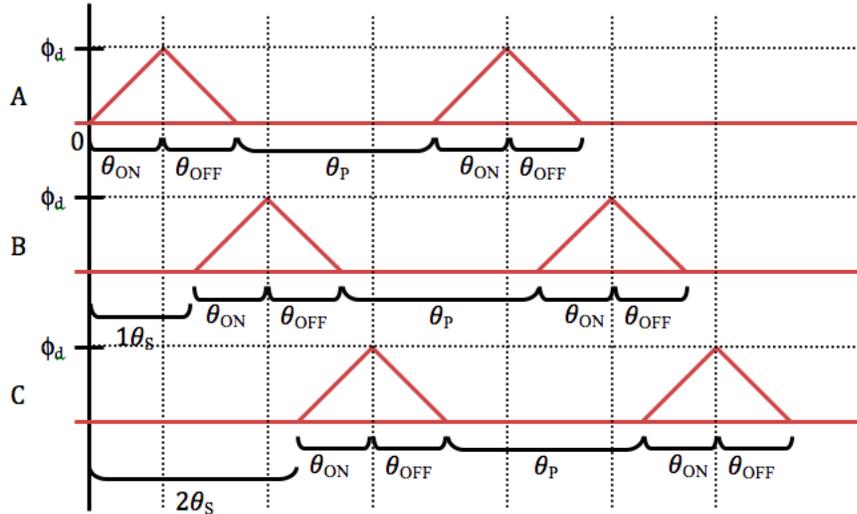


Figure 12: *Flux Density*

A topic that plays an important role in efficiency is so-called eddy currents – the small magnetic fields generated that oppose the larger magnetic field which creates a small loss of efficiency. First, we need to understand that when a magnetic field changes across a surface there is an induced current (induced voltage or *emf*). Faradays Law of Electromagnetic Induction states that the *emf* induced in a loop (such as an electromagnet) is proportional to the rate of change of the magnetic flux through it.

$$\xi = -N \frac{d\phi}{dt} \quad (2.4.22)$$

This is the equation to govern the relationship between the change in magnetic fields and the induced current. ξ is the electromotive force (*emf* measured in volts), N is the number of turns in the coil and, of course, $\frac{d\phi}{dt}$ is the derivative of the magnetic

flux with relationship to time. Lenz's Law states that, when an electric current is induced in a conductor, the direction of the current is such that its magnetic effect will oppose the action that gives rise to the current. This explains why there is a negative sign in Faraday's Law above. The opposing force is opposite the direction of the magnetic flux; hence, where the resistance comes from. In the case of a SRM, the rotor produces eddy currents as it passes each electromagnet. These eddy currents cause a small resistance from the rotor to the electromagnets, an invisible "friction" if you will. A good way to observe this resistance is to drop a strong magnet down a non-magnetic tube, such as a neodymium cylindrical magnet down a copper tube. A copper tube can, after all, be thought of as the ultimate copper winding. The eddy currents produced as the magnet falls through the tube will act as an attraction between the magnet and the tube, adding resistance against the gravitational force, and will slow the magnet's fall through the tube.

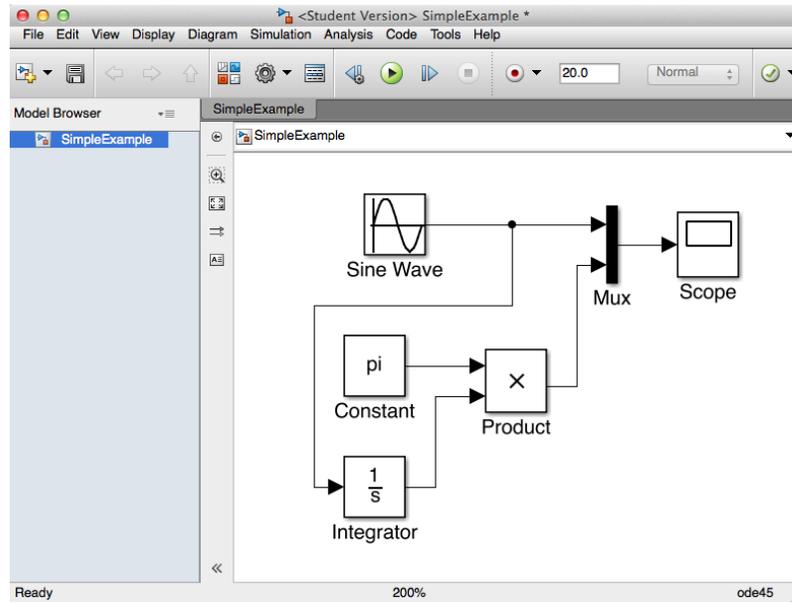
These are a few of the most important concepts and equations to keep in mind when designing an SRM.

CHAPTER 3

DESIGN IN SIMULINK AND ANALYSIS

3.1 Design of Three-Phase SRM

With the use of Simulink through MATLAB, an open loop control was developed for an SRM in order to test if an SRM has the ability to be a viable substitute for a gasoline engine on a motorcycle. Simulink is a block design building software; this means pulling different blocks from the libraries, setting parameters and linking them together. Below is a simple example of a standard sine wave and that sine wave multiplied by π . Below that is the output from the scope. The scope allows the output from the blocks to be displayed in a graphical interface. The sine waves run directly into the mux gateway which combines signals from other outputs into one graph. The integrator is a real-time integration of, in this case, the sine wave. The constant block set to π is multiplied with the integrator in the product block. Then, that signal is sent to the mux gateway which graphs it along with the sine wave. The mux gateway is sent to the scope so that the user can view the results via graph. This example had a 20 second test time and took less than a quarter second real time to complete; the more complex the model, the longer it takes to run. In comparison, the three and five-phase SRMs run much slower than real-time because of the complexity. This simple, straightforward example also has no sub blocks or linked blocks or solvers within any of the blocks. The three-phase SRM and five-phase SRM have several sub layers with linked functions and solvers.

Figure 13: *Simple Simulink Example*Figure 14: *Scope of Simple Example*

Next, we'll look at the development of a three-phase SRM and control in Simulink. Simulink contains several motors including DC Motors, Stepper Motors, Asynchronous Machine Units and even a Steam Turbine within its Power Library. The Power Library also contains a generic three-phase SRM, which is where the design begins. The components of the SRM model consist of the following:

Part	Description	Entry
Type	3 Phase	6/4
Machine Model	Specific Model	
Stator resistance	Ohm	.05
Inertia Momentum	J kg/m.m	5.780
Friction	N/m.s	.36
Initial Speed and Position	wo (rad/s) Theta θ (rad)	[0,0]
Magnetisation Characteristic Table	(MAT file)	'srm64_60kw.mat'
Rotor Angle Vector used in MAT File	Degrees	[0 10 20 30 40 45]
Stator Current Vector used in MAT File	(A)	0:25:450
Sample Time	Inherited	-1
Electromagnets	6	A1, A2, B1, B2, C1, C2
Mechanical Load Torque	TL Nm	45.89

Table 2: Three-Phase SRM Components

Lastly we have 'm' which is the outputs of the SRM. 'm' contains the following signals:

Symbol	Description	Unit
flux	Flux linkage	V/s
I	Stator current	A
Te	Electromagnetic torque	N/m
w	Rotor speed	rad/s
teta	Rotor position	rad

Table 3: SRM Output Components

The block itself is the following:

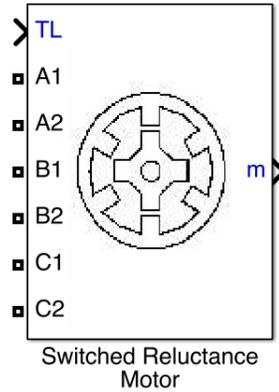


Figure 15: *Three-Phase SRM Block*

Some of the aspects of the design were modeled after current production motors and their outputs. Most of these factors have been taken to be either fair or less than fair in order to not give the SRMs any unfair advantage. This created a slight disadvantage but the results, shown later, are still good. For example, the company ZeroMotorcycles have an electric motorcycle commercially produced which has a maximum torque of 92 Nm. [ZeroMotorcycles use conventional DC Motors connected to the rear wheel using gearing, sprockets and a chain. This limits their performance.] SRMs are known for having very high torque but, for the sake of showing worst-case-scenario, the simulation is limited to having only 92 Nm torque.

For the purpose of this simulation, the maintained mechanical load torque used is

$$T_L = \frac{m_L g D (\sin(\alpha) + \mu \cos(\alpha))}{2\pi\eta} \quad (3.1.1)$$

where T_L is mechanical load torque, m_L is the weight in kg ($m_L = 181\text{kg}$ (average weight of sport motorcycle)), g is the gravitational constant 9.8m/s^2 , D is diameter

in meters, α is inclination angle (assuming a level road, $\alpha = 0$), μ is the friction coefficient (.36) and η is motor efficiency ($\eta = 90\%$).

$$T_L = \frac{181 \cdot 9.8 \cdot .4064(\sin(0) + .36\cos(0))}{2 \cdot \pi \cdot .9} = 45.89Nm$$

Torque is not usually considered a constant value as seen above. However, implementing the changing resistance into this design would be impossible with this software. Initial values must be chosen since it is an open loop control.

$$T = \frac{i^2}{2} \frac{dL}{d\theta}$$

Below is a visual of the torque.

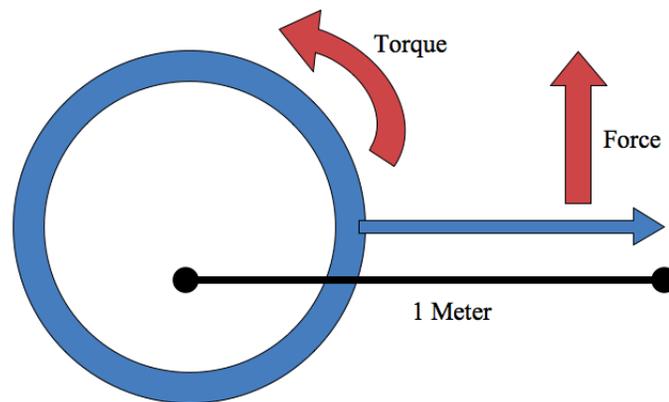


Figure 16: *Simple Torque*

The stator resistance of $.05\Omega$ was pulled from standard SRMs of this average operating voltage and flux. The stator resistance is the resistance by each phase winding. With a manipulation of Kirchoff's Voltage Law we can see that resistance is

$$R = \frac{v - \frac{dL(\theta,i)}{dt}}{I} \quad (3.1.2)$$

Like the torque, resistance is set to be a constant due to limitations of the software. However, the resistance used is the average operating resistance. A common depiction of the resistance for a three-phase SRM follows. (Not to be confused with the flux capacitor in Back to the Future)

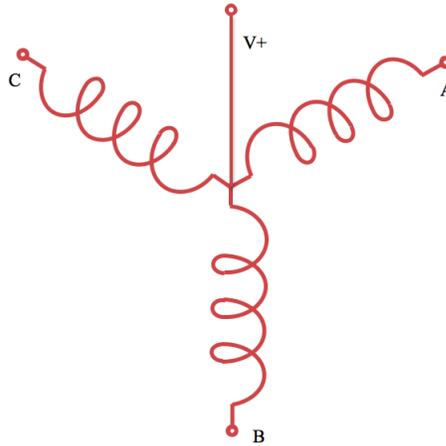


Figure 17: *Resistance*

Next is the Inertia Momentum of $5.780kg.m^2$. Inertia momentum is

$$J = m \cdot r^2 \quad (3.1.3)$$

where m is mass in kg and r is radius in meters. An average motorcycle tire ranges in weight from $7.7lbs$ ($3.5kg$) for smaller, 250cc engines to $15.4lbs$ ($7kg$) for 1200cc cruisers. The rear rims usually weigh between 13.2 to $37.5lbs$ or 6 to $17kg$. Suppose the mass of the motorcycle wheel without the weight of the stator (since only the rotor contributes to the rolling weight) is $77lbs$ or $35kg$ and the radius is $16'' = .4064meters$. The radius of $16''$ is standard for most sport bikes. The weight of $77lbs$ for a rear wheel is unheard of but is more than fair given that the weight of the rotor must be taken into account. $J = 35 \cdot .4064^2 = 5.780kg.m^2$.

Next is the friction coefficient. The friction coefficient of a skidding motorcycle tire on asphalt ranges from .9–1.2. There aren't units to a friction coefficient because it is a ratio of one material to another. Of course, we don't want a friction coefficient of a locked up tire skidding on asphalt because that's not realistic. We turn to McNally Associates who have performed several tests to find the friction coefficient of motorcycle wheels and came up with a range of .35 to .48 with a range from .35 to .38 after stabilizing. An SRM has very little friction because there are no brushes or permanent magnets within the motor, which gives it an advantage. For this input, a friction coefficient of .36 was chosen. This is a fair assumption and would most likely be less but, without a prototype, cannot be measured. The reason it would be less is that it is a direct drive and there are no gears, sprockets or chains adding friction. This sums up the inputs for the SRM block in Simulink.

The next most important part in the design is the power converter. As discussed earlier, one phase is ON and then OFF as the next comes ON in a circular motion pulling the rotor along and creating the mechanical force that is driving the tire. The mux gateway on the left hand side of the conversion is connected to a switch which controls when the power converter receives power. The converter is the part of the control design which translates the power input and sends it to the correct phases. We'll see later how each phase is tracked through the switch so that each phase is switched ON and OFF accordingly. Shown is an image from the three-phase including the switch on the left hand side, the power converters, and the constant power source. The constant power source was changed to a battery in the five-phase.

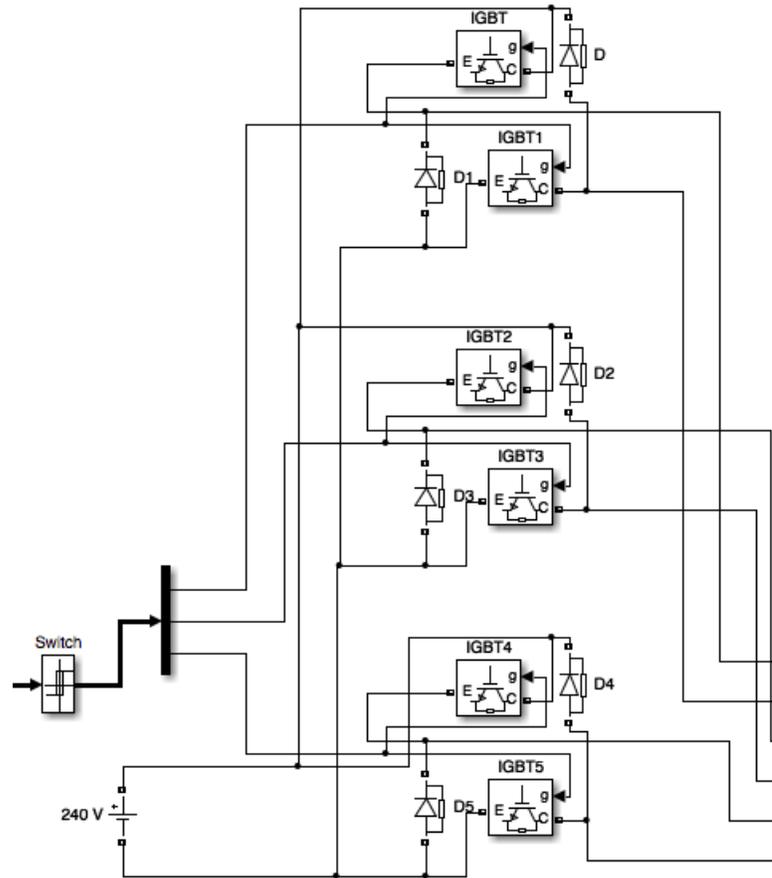


Figure 18: *Switch, Power Converter and Power Source*

IGBT stands for Insulated Gate Bipolar Transistor, very similar to MOSFETs but with the addition of a capacitor and handling positive charges instead of negative charges. This is the switch that handles the 240V change of current when switching the phases ON and OFF. The capacitor builds up the charge coming in at C . When the gate is open the IGBT emits the charge through E and when the gate is closed builds up 240V charge. The parts labeled ' D_i ' are Diodes which not only restrict the flow of the majority of the electricity to one direction, but also adds 1000Ω resistance

and allows only 0.8V forward. This is to prevent the 240V load from "back firing" and blowing up the IGBT. The diodes also help to dissipate the load across the circuit when off. This is how the change from 0 to 240 volts is controlled without overloading the circuit. These together form a type of Snubber Circuit, which is commonly applied to this type of circuit where there are large changes in voltage across the circuit that require only a small voltage to switch the gate on and off.

The hardest part to this design is controlling when to turn each phase ON and OFF. To do this we need some sort of feedback from the SRM into a converter outputting, to the switches, to the power converters, and back to the SRM. In Simulink the SRM starts at the same location every time which is why we can create an open loop system that runs the same way every time. Current (A) and Rotor Speed (rad/s) are used to determine when to switch phases ON and OFF. The goal is to take the rotor speed, incorporate time and have a single output of 0 or 1 for each phase. 0 for OFF and 1 for ON. This is the part of the design which does this:

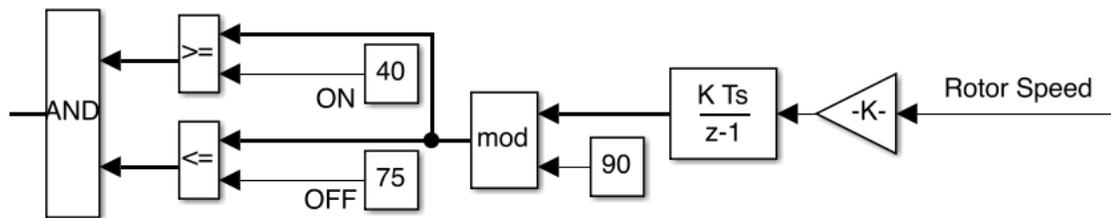


Figure 19: *Converter*

The first step is to change the input –radians per second– into degrees per second. One radian is $57.2959^\circ = \frac{180}{\pi}$. This is accomplished with an element-wise gain block with inherited time (-1) .

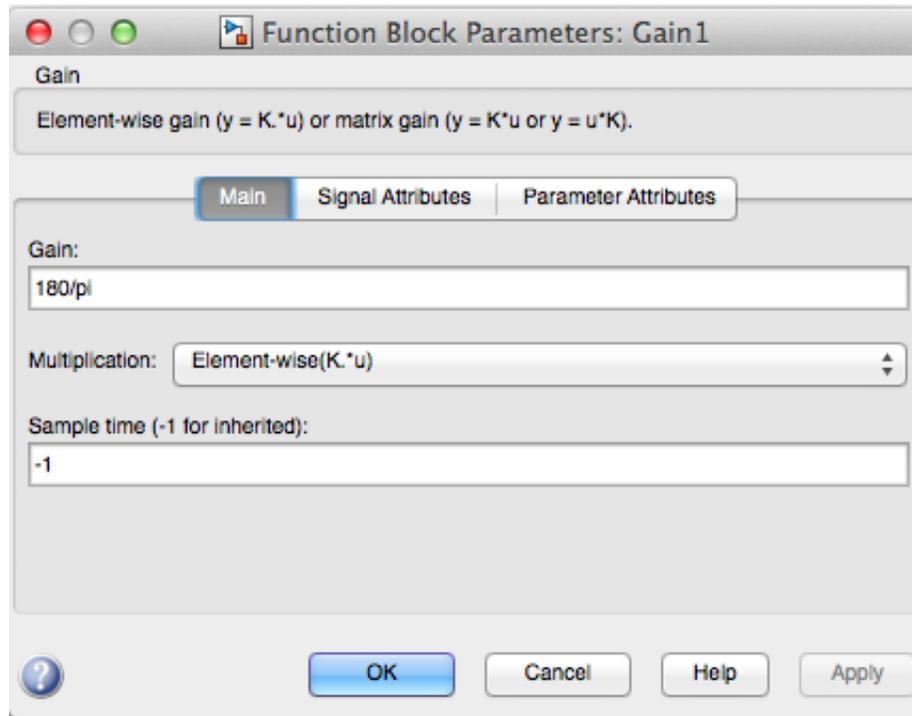


Figure 20: *Element Wise Gain Block Parameters*

The rotor speed in degrees then passes to the discrete time integration block. This integration uses the Forward Euler Method in order to avoid algebraic loops. This uses the following equation to integrate over time:

$$y(n) = y(n - 1) + K \cdot T \cdot u(n - 1) \quad (3.1.4)$$

where y is the function, u is the block input, K is the input gain value, n is the step and T is the block sample time. An important step here is splitting the deg/s signal back into three signals, one for each phase. This is done by setting the initial conditions to $[0 - 30 - 60]$ which sets the three phases to 0° , -30° and -60° respectively. The gain value K is default at 1 which multiplies the input by 1. This is left at 1 because the input doesn't initially need to be modified. Since we are running a discrete model, the

sample time is set to match T_s . This is important because it is an open system and may have very slight deviations in some of the outputs. Using T_s keeps the timing perfect. For example, if after 50 phase switches the rotor angle is off by a fraction of a degree, then the switching ON and OFF of phases becomes unstable. Using a fixed discrete T_s time keeps the timing correct and eliminates any variance. The Tustin solver was chosen over the Backward Euler solver in order to increase accuracy. Both are built in solvers; however, Tustin uses more data points to solve which produces more accurate results. Discrete time was chosen in order to speed up simulation of an already very slow system when run because of the complexity. The simulation runs about $1\frac{1}{4}$ minutes for every second of simulation.

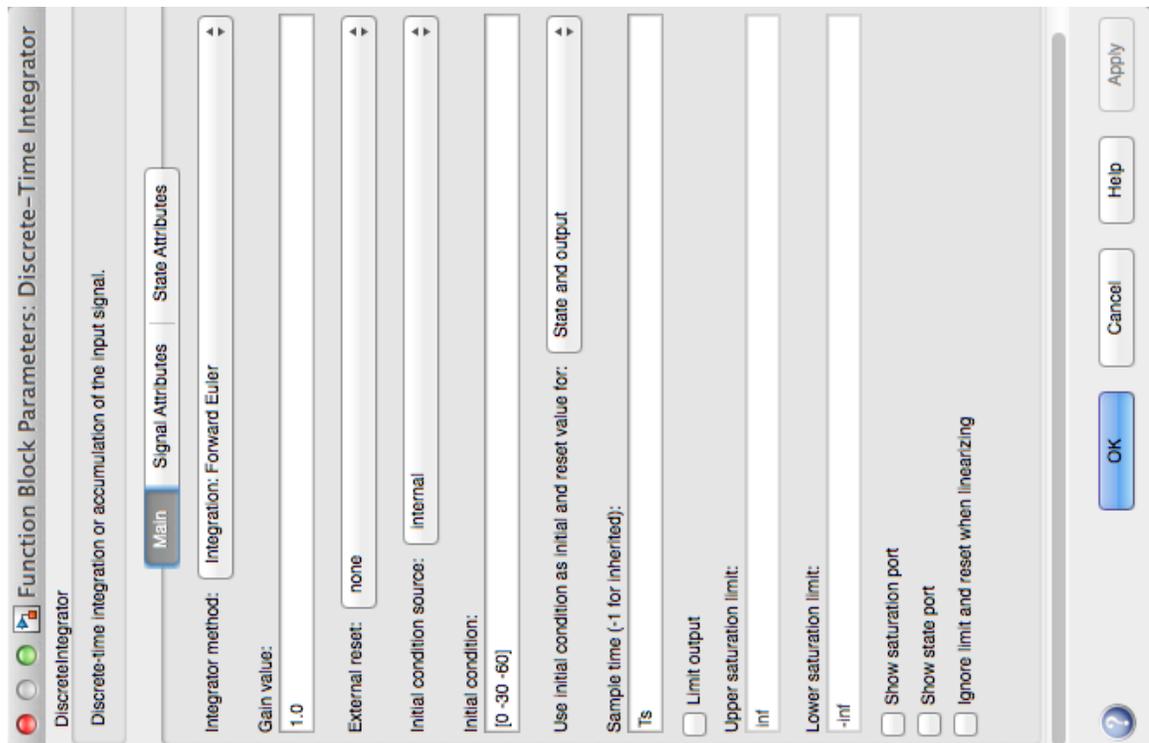


Figure 21: *Discrete Integrator Block Parameters*

Below we can see the change to degrees per second and also the integration of each phase separating them to 0° , -30° and -60° .

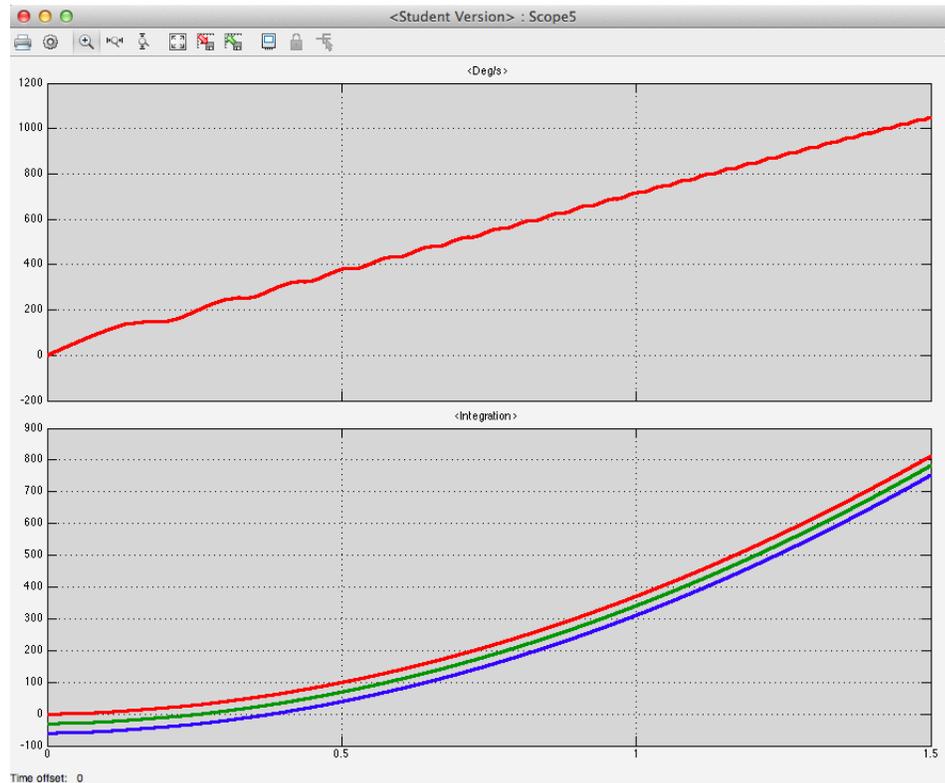


Figure 22: *Degrees and Integration*

The signal then passes to the math function block which, for this case, is set up to convert the output of the integrator block into positive numbers via modular arithmetic. Mod 90 is selected because there are four quadrants of the circle to which this can be applied to equivalently, and our ON/OFF angles are 40° and 75° . Using Mod 90 keeps each phase's outputs between 0 and 89. This block has inherited time (-1) since we are using the running time within these blocks to create real time feed back.

Next are two logic statements. "Is the turn ON angle 40° equal to or less than the input from the Mod 90 block" and "is the turn OFF angle 75° greater than or equal to the input from the Mod 90 block". This is where the computer decides when to turn ON and OFF each phase. The AND logic operator outputs 1 (TRUE) if and only if both input conditions are met. When a phase's signal into this logic block outputs TRUE, that phase is ON, otherwise it is OFF. Shown is the signal after passing through Mod 90 and below that is the signal output from the logic block. The output is what you would expect to see after applying the Forward Euler method.

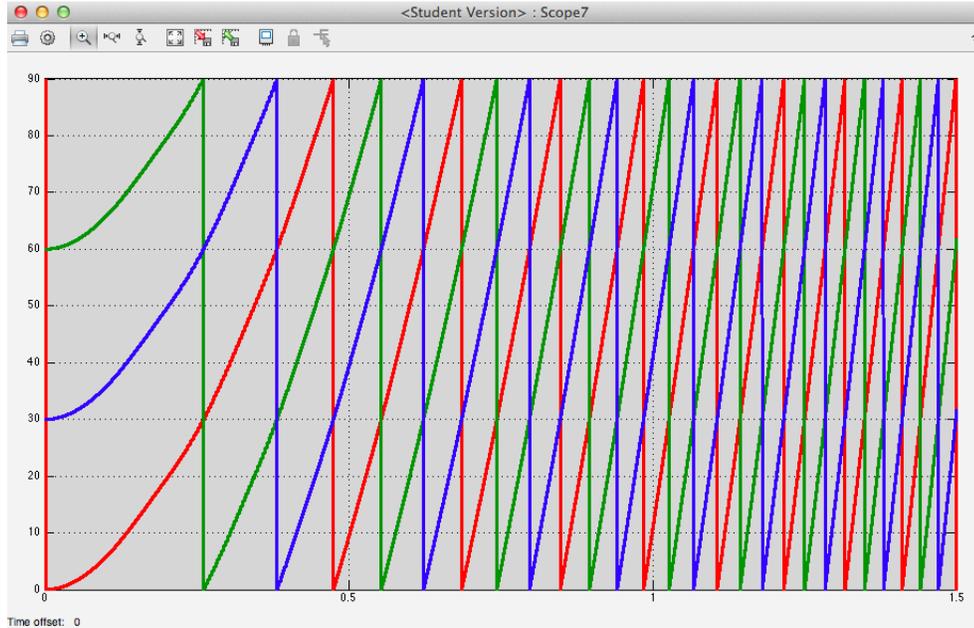


Figure 23: *Mod 90 Output*

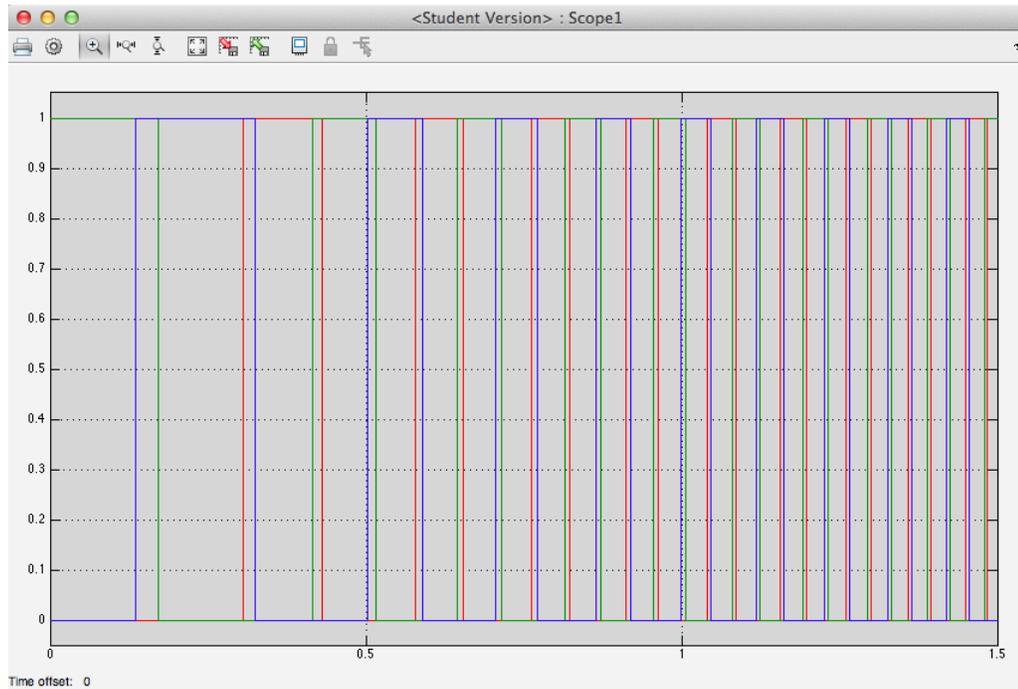


Figure 24: *Converter Output*

An intermediate step during development of this determines at what degree each electromagnet turns ON and OFF. Something to consider is that with using Simulink we do not know the physical size parameters of the electromagnets. This is another limitation of Simulink, so adjusting the ON/OFF angle is numerical analysis. If the size of the electromagnets was known, along with the spacing, finding ON/OFF angles would be much easier. So for the three-phase, there are six electromagnets placed every 60° around the circumference of the motor; that much we know. Assume that each electromagnet must be turned on within 30° on either side so that there is no overlapping magnetic flux on the rotor poles. Focusing on the electromagnet at 60° , this means that it will need to be ON and OFF somewhere between 30° and 90° . If 30° and 90° are used, this means that there are two rotor poles aligned at 120° and

300°. Trying this, we see that using 30° and 90° creates a oscillating effect of the rotor, as expected. This means it would start to rotate one way then be pulled back in the reverse direction and so on. This is easily seen visually through the scope. Notice how the values of the bottom three outputs fluctuate between positive and negative. This indicates that the rotor is switching directions. In the top graph it can also be seen clearly that only two phases are staying on for any amount of time. Since the rotor is aligned with the electromagnets at 120° and 300°, those are only on for a brief amount of time.

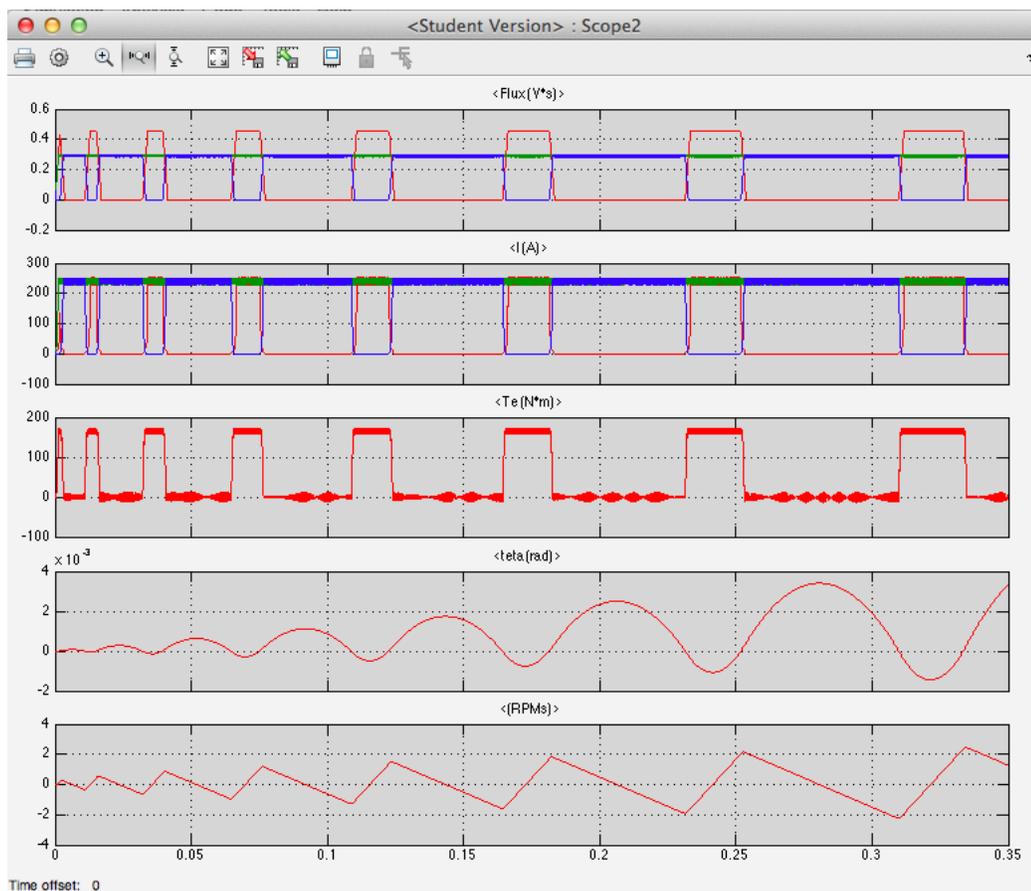


Figure 25: *Main Scope 30° 90°*

The next step is to split the difference between 30° and 60° , and 60° and 90° . The degrees of 45° and 75° were used.

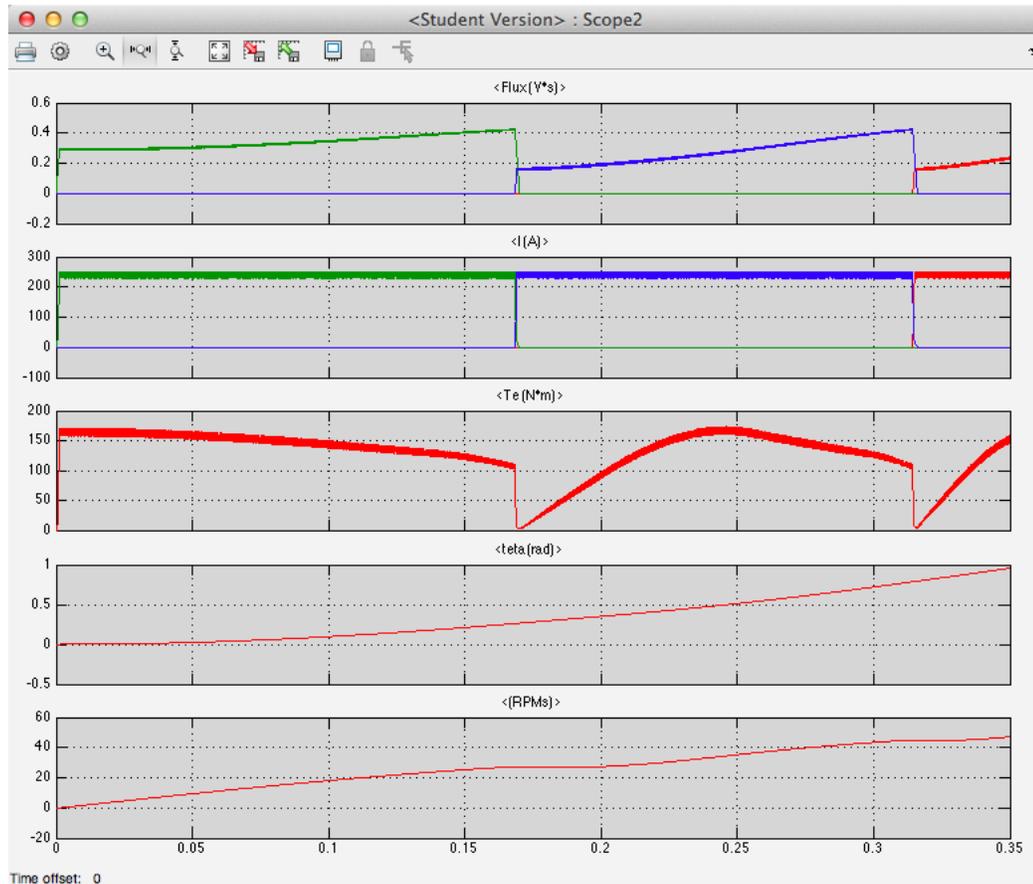


Figure 26: *Main Scope 45° 75°*

Recall the ideal flux changes from the introduction: The ON phase needs to turn OFF just as the next phase's flux begins to increase once ON. This implies the turn ON angle is too high if we keep the OFF angle the same. Changing 75° to 80° will produce a skewed flux which does not have the properties required. Observe below 45° and 80° are used first to illustrate that the flux changes required are not present. Following that, 40° and 75° are shown, which give the results of the flux changes

required.

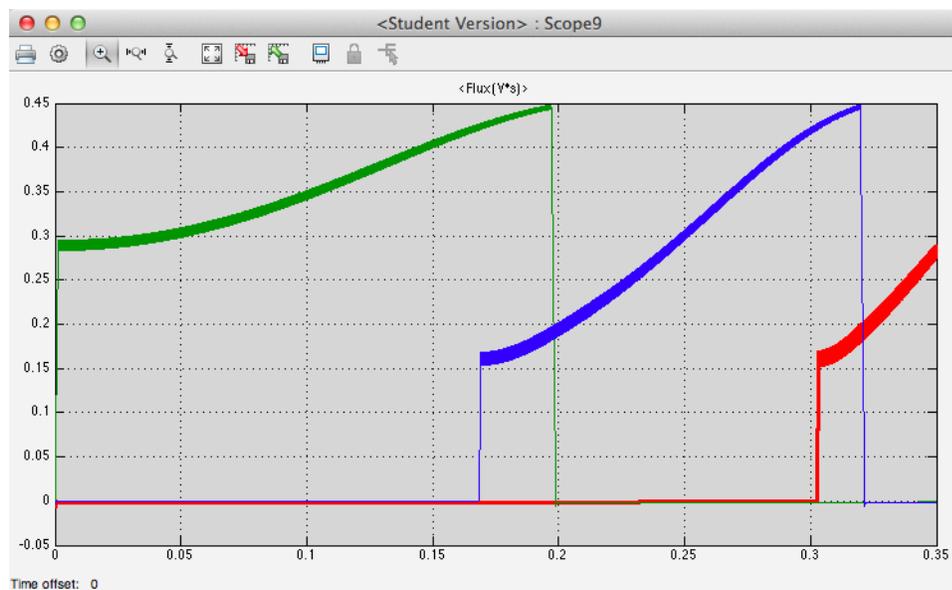


Figure 27: *Flux* 45° 80°

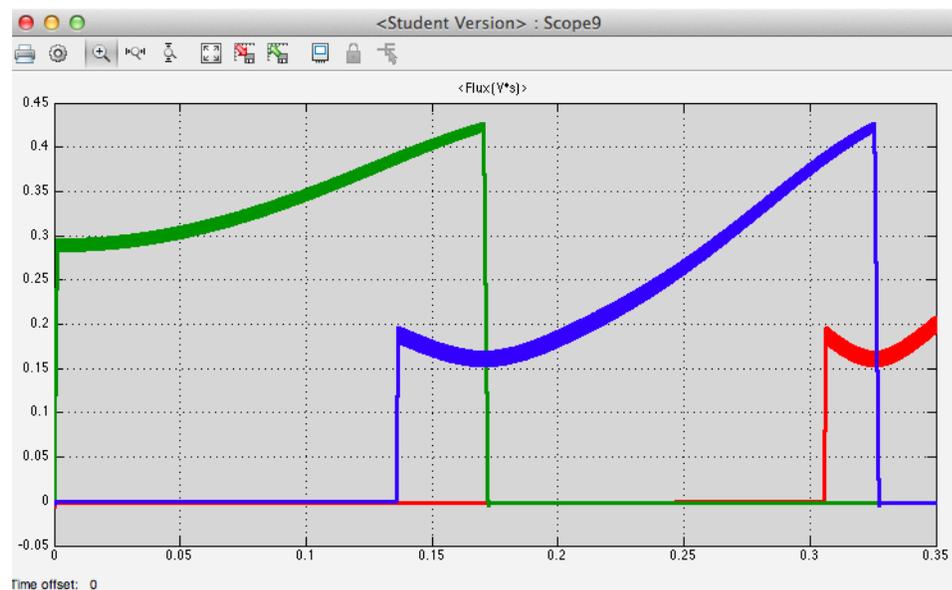


Figure 28: *Flux* 40° 75°

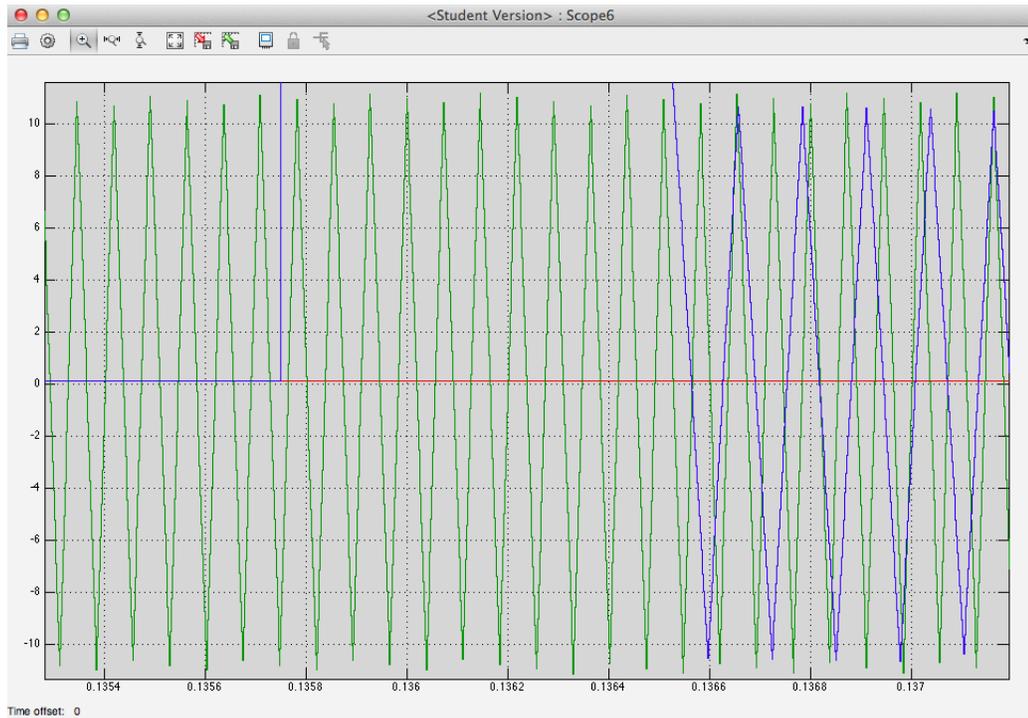


Figure 30: *Switch Zoomed-In*

With all of this connected, running and working, we have a running SRM model with parameters that are set to real-world specifications. This model is set to accelerate from zero to its maximum, and then to maintain its maximum. This is due to the integration method used to run the SRM. This gives us the acceleration from zero and the top speed. Note in the output, rad/s is multiplied by $\frac{30}{\pi}$ before reaching the scope; this translates rad/s into RPMs.

3.2 Analysis of Three-Phase

Because the three-phase simulation takes about $1\frac{1}{4}$ minutes for every 1 second of simulation, the simulated run time will be a maximum of 10 seconds. Trying to run it longer creates too much data and, without enough computational power, freezes Simulink. However 10 seconds is adequate to see trends in acceleration, speed and torque. Simulink does have a "rapid acceleration" mode which generates code to run the simulation much faster by finding general trends and applying those in place of individual values throughout. This mode is unfortunately not available in the student version.

```

csl =
    1854918483
    3755924718
    2415912422
    4147061770

EDU>> rtp = Simulink.BlockDiagram.buildRapidAcceleratorTarget('SRM3Phase')
### Build procedure for model: 'SRM3Phase' aborted due to an error.
Error using build_rapid_accel_target (line 137)
Unable to build a standalone executable to simulate the model 'SRM3Phase' in rapid
accelerator mode.

Error in sl (line 16)
[varargout{1:nargout}] = feval(varargin{:});

Error in Simulink.BlockDiagram.buildRapidAcceleratorTarget (line 39)
[setupAborted, rtp] = ....

Caused by:
Error using tlc c>DoTermRTWgen (line 2002)
Code generation is not available in Student Version

EDU>> |

```

Figure 32: *Rapid Acceleration*

The simulation is run for 1 second. Following is the main scope, scope after integration, the signals after conversion, Rad/s vs RPM's, and the input to the switch. Showing 1 second better illustrates the torque ripple and how it relates to the phases turning ON and OFF; this control design works for a computer but, if used on a prototype, small adjustments in timing would need to be taken into consideration.

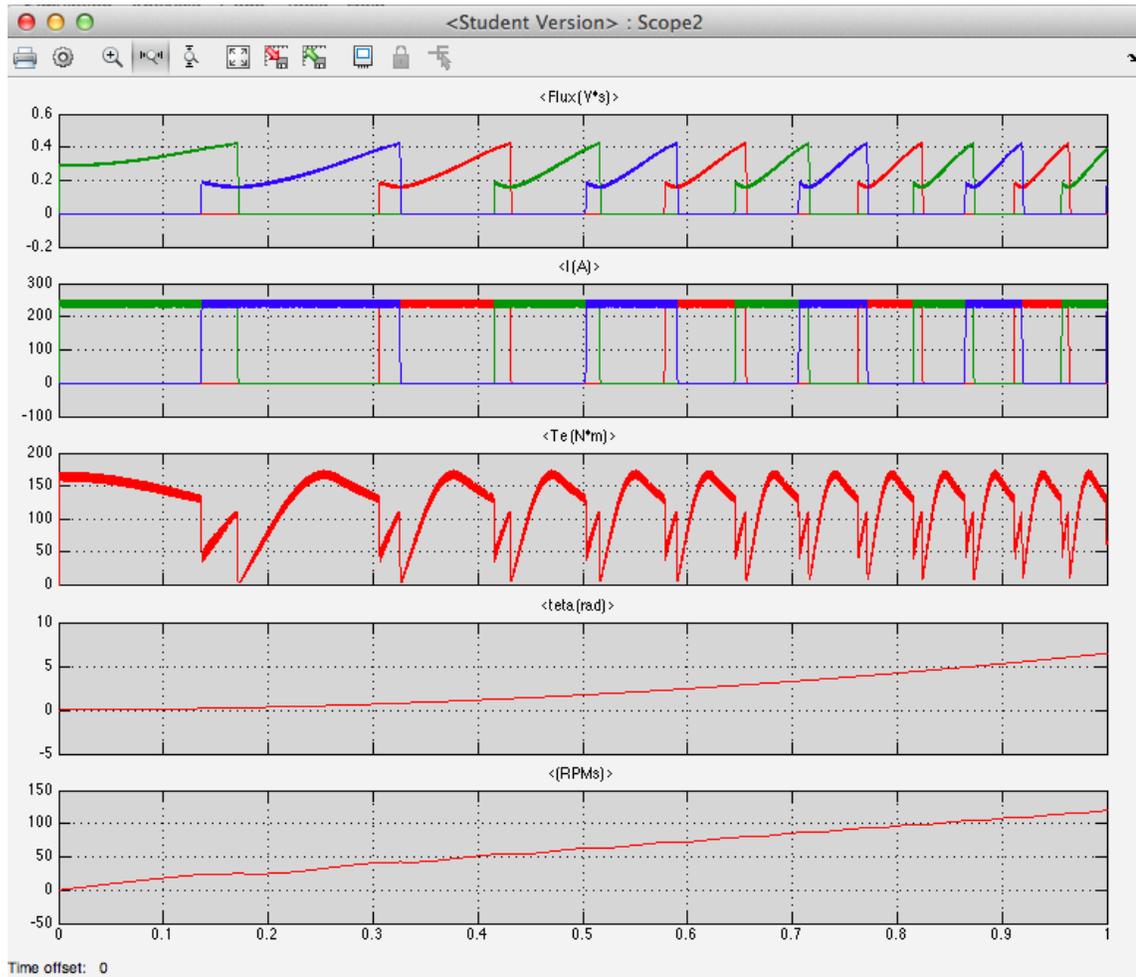


Figure 33: *Three-Phase One Second Main Scope*

A disadvantage to this control design is the three signals after integration will continue to increase and lengthen calculations until the speed stabilizes and becomes constant. On the positive side, the integration is limited by the top speed which limits the magnitude of the three signals.

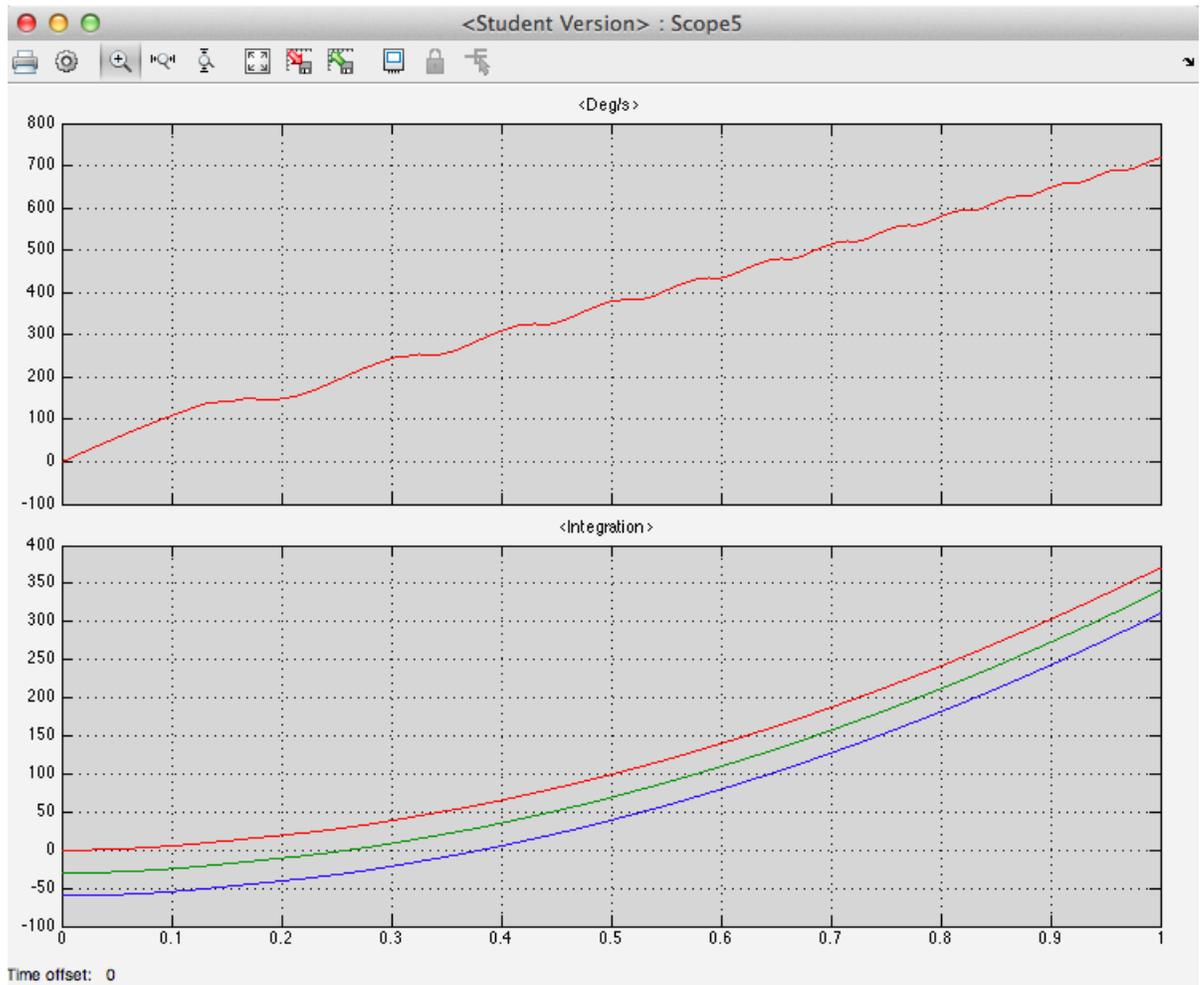


Figure 34: *Three-Phase One Second After Integration*

The signal coming out after the converter outputs 1 and 0, which correlates to ON and OFF respectfully. The vertical lines are tangent lines and are the instantaneous changes from 0 to 1 in the simulation. In the real world these would not be tangent lines because there would be a small amount of time to make that switch from OFF to ON and vice versa.

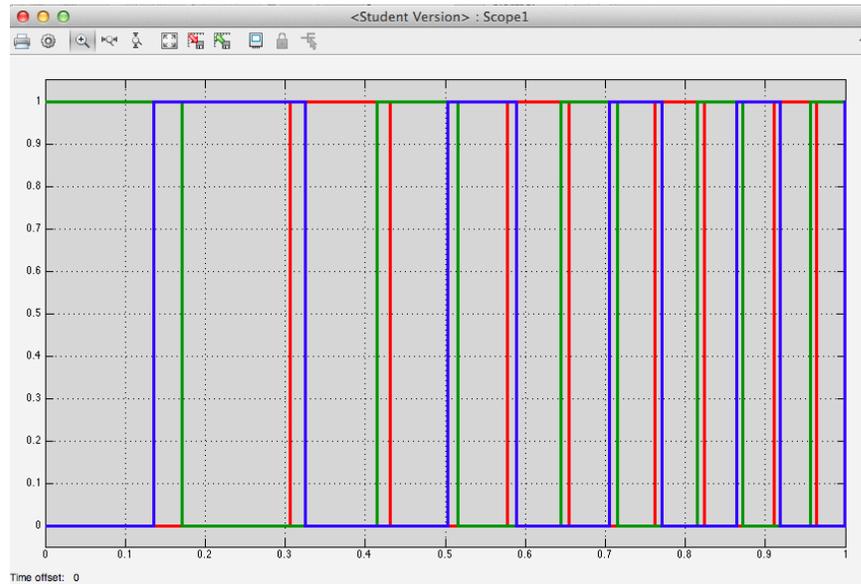


Figure 35: *Three-Phase One Second Converter*

Recall $\frac{\text{rad}}{\text{s}} \frac{30}{\pi} = \text{RPM}$. Radians per second and revolutions per second are represented in blue and burgundy respectively.

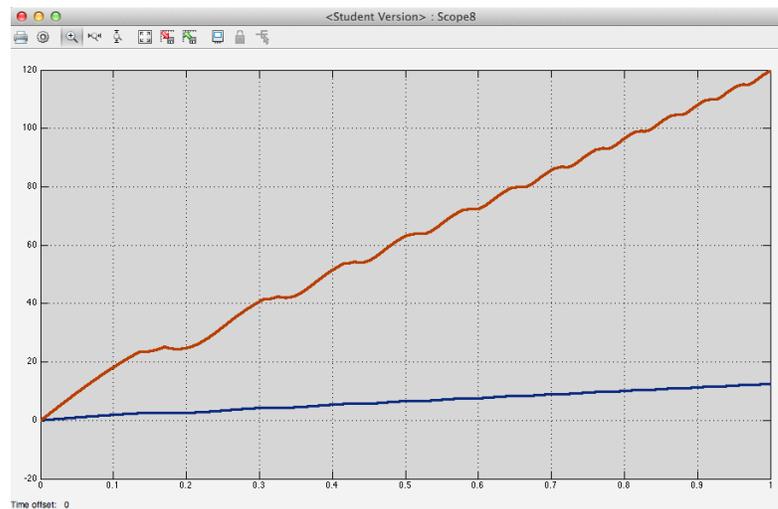


Figure 36: *Three-Phase One Second Rad/s vs RPMs*

Recall that the switch is set to turn the phases ON if the input signals of each phase (independent of each other) are between -10 and 10 , and OFF elsewhere. The switch scope clearly shows the correlation of subtracting the current output from the product of the signal of the converter and the constant 240 , representing the $240V$ power source.

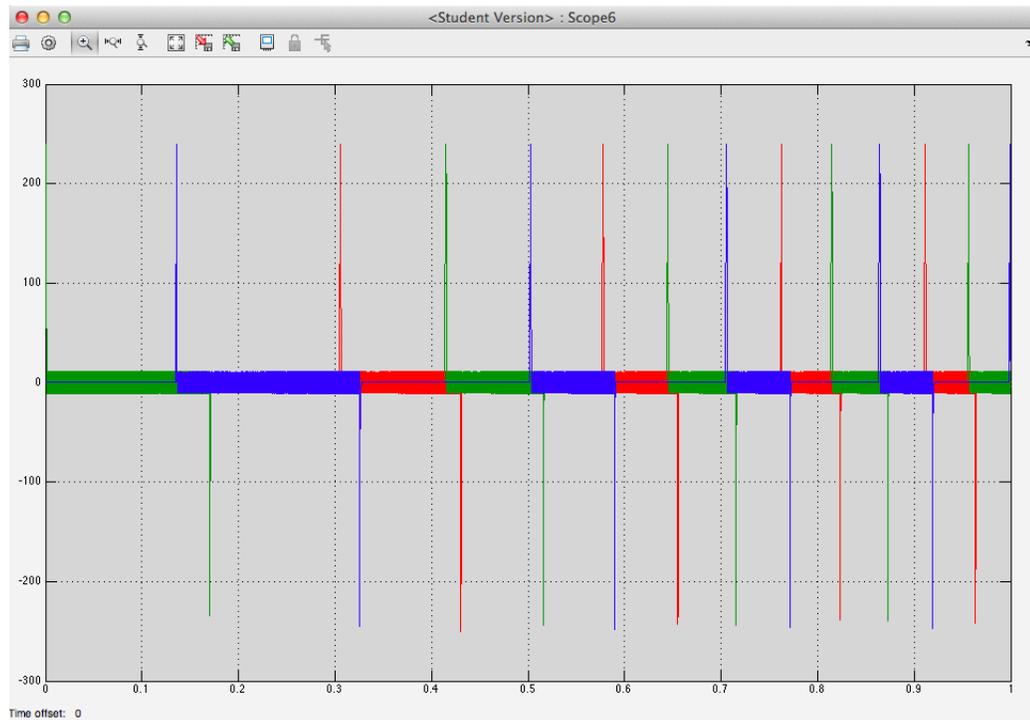


Figure 37: *Three-Phase One Second Switch*

From here the simulation was run for 5 seconds to better show how quickly the phases are being turned ON and OFF as time progresses. Following is the main scope from the 5 second simulation.

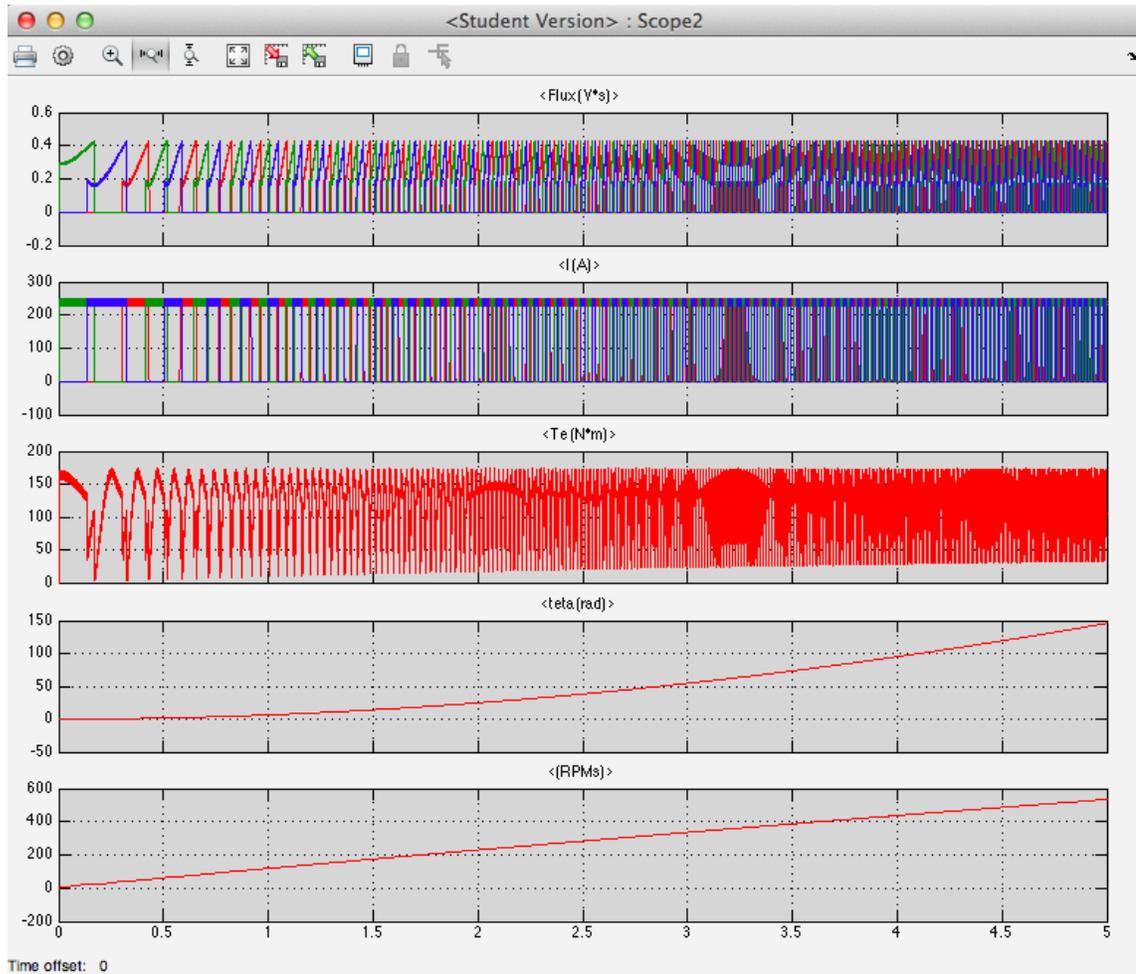


Figure 38: *Three-Phase Five Seconds Main Scope*

The simulation was then run for 10 seconds. Following is the RPM output and torque output. The RPMs reach roughly 950 after 10 seconds, which is roughly 45 mph. We won't be setting any speed records with this design; however, it would accelerate a motorcycle up to a decent speed around town. If we assume a constant acceleration, the 0 to 60mph time is 13.3 seconds. Comparing this to a few vehicles, we see that a typical 250cc motorcycle can accelerate from 0 to 60mph in 6 seconds, most

sport cars run between 4.5 to 6 seconds, and a 850cc Yamaha FZ-09 runs 2.7seconds. ZeroMotorcycles' motorcycles run 0 to 60 in 9.2 seconds. These lower run times can be attributed to gearing which this design does not have. If we were to add gearing the 0 – 60 time would be less but also add more resistance ultimately lowering the range.

One of the most important factors to consider is the torque ripple; a motorcycle can't be ridden if the torque makes it impossible to control. The torque for the first second is somewhat choppy in the three-phase, which is to be expected. "Choppy" meaning that it is not only oscillating from roughly 0 to 175Nm but there are also significant time gaps between 'pulls' on the rotor. However, even in a three-phase, the torque ripple becomes steady and decreases after that first second. "Steady" meaning that although the torque is rippling between roughly 20 and 175, it oscillates so quickly that the noticeable torque would be nearly constant to the rider. Note how, as time progresses, the graph becomes one solid color; this indicates that the oscillations happen fast enough to form a smooth curve. This is confirmed by observing at the acceleration of, in this case, the RPMs. Note how the acceleration remains a smooth curve. This indicates the felt torque ripple is –surprisingly– very little.

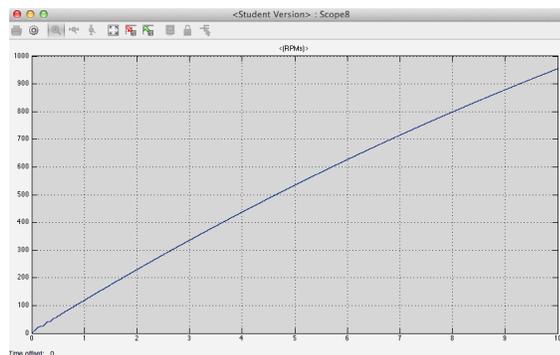


Figure 39: *Three-Phase Ten Seconds RPMs*

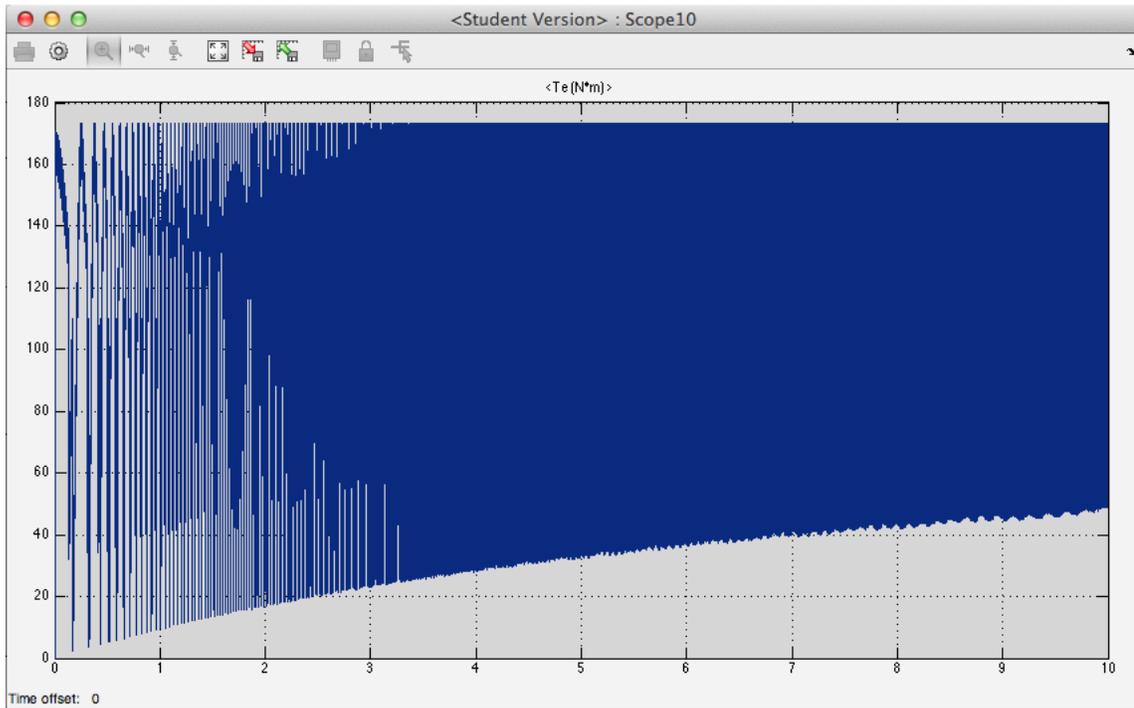


Figure 40: *Three-Phase Ten Seconds Torque*

As seen above, an SRM is a viable motor to be placed into the rear wheel of a motorcycle replacing the traditional gasoline engine! This is only a three-phase SRM and will accelerate to 60mph after 13.3 seconds; however, it is still feasible. The current design shows this in-wheel hub SRM is roughly equivalent to the power and acceleration typically found on 250cc mopeds. These are not the results I'd hoped for; nevertheless, they are results and provide us with an answer.

3.3 Design of Five-Phase SRM

Part	Description	Entry
Type	Five-Phase	10/8
Machine Model	Specific Model	
Stator resistance	Ohm	.05
Inertia Momentum	J kg/m.m	5.780
Friction	N/m.s	.36
Initial Speed and Position	wo (rad/s) Theta θ (rad)	[0,0]
Magnetisation Characteristic Table	(MAT file)	'srm64.60kw.mat'
Rotor Angle Vector used in MAT File	Degrees	[0 10 20 30 40 45]
Stator Current Vector used in MAT File	(A)	0:25:450
Sample Time	Inherited	-1
Electromagnets	10	A1, A2, B1, B2, C1, C2, D1, D2, E1, E2
Mechanical Load Torque	TL Nm	45.89

Table 4: 3 Phase SRM Components

The design of the five-phase SRM is a modified version of the three-phase SRM already developed. The SRM block has 10 electromagnets and a rotor with 8 poles. Shown are the parameters set for this block in the five-phase. Two additional block sections were added to the power converter because there are two more phases in the five-phase. Below are the parameters and an image of the five-phase SRM block.

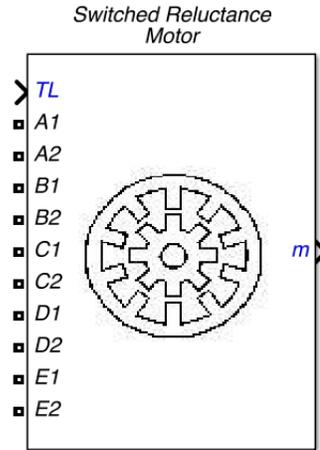


Figure 41: *Five-Phase SRM Block*

Within the discrete integrator block we now have initial conditions of [0 36 72 108 144], whereas the three-phase had [0 -30 -60]. These angles were selected because, similar to the three-phase, the electromagnets are 36° apart from each other in a five-phase. Positive angles were chosen this time to keep rotation positive in simulation. Negative degrees, as in the three-phase, resulted in the rotation being negative.

Taking the RPM output and multiplying by 60min, 4.186 (circumference in ft) and $\frac{1}{5280}$ (mile/ft), the output is now in MPH. Displays were added within the diagram to view the MPH as a continuous function during simulations and also to view the maximum MPH obtained as time progressed. These additions can be seen near the lower right of the complete diagram.

The turn ON and turn OFF angles had to be adjusted accordingly. The three-phase used ON at 40° and OFF at 75° . An easy solution to finding the ON/OFF angles of the five phase was to use ratios. $\frac{40}{60} = \frac{ON}{36} \Rightarrow ON = 24^\circ$ and $\frac{75}{60} = \frac{OFF}{36} \Rightarrow OFF = 45^\circ$, so the five phase ON angle was 24° and the OFF angle was 45° .

Also, for this simulation, a battery was added to model the motor running off a battery as it would on a motorcycle. The battery was modeled after the current production used in ZeroMotorcycle's S Series. The biggest limiting factor in any electric vehicle and the reason electric vehicles have always been second best to gasoline engines is the battery capabilities. Electric motors, for the most part, are far more efficient compared to gasoline engines; however, the battery technology is severely lacking. Below are the parameters of the battery I used. The cost is determined as follows. $Wh = \frac{V \cdot Ah}{1000} = \frac{240 \cdot 8.5}{1000} = 2.040Wh$. Averaging \$1000/Wh this brings the cost to \$2,040. This is mentioned because the cost of the battery and the battery's limitations are the most dampening aspects of commercialization of electric vehicles.



Figure 42: *Battery Block Parameters*

This is the five-phase diagram:

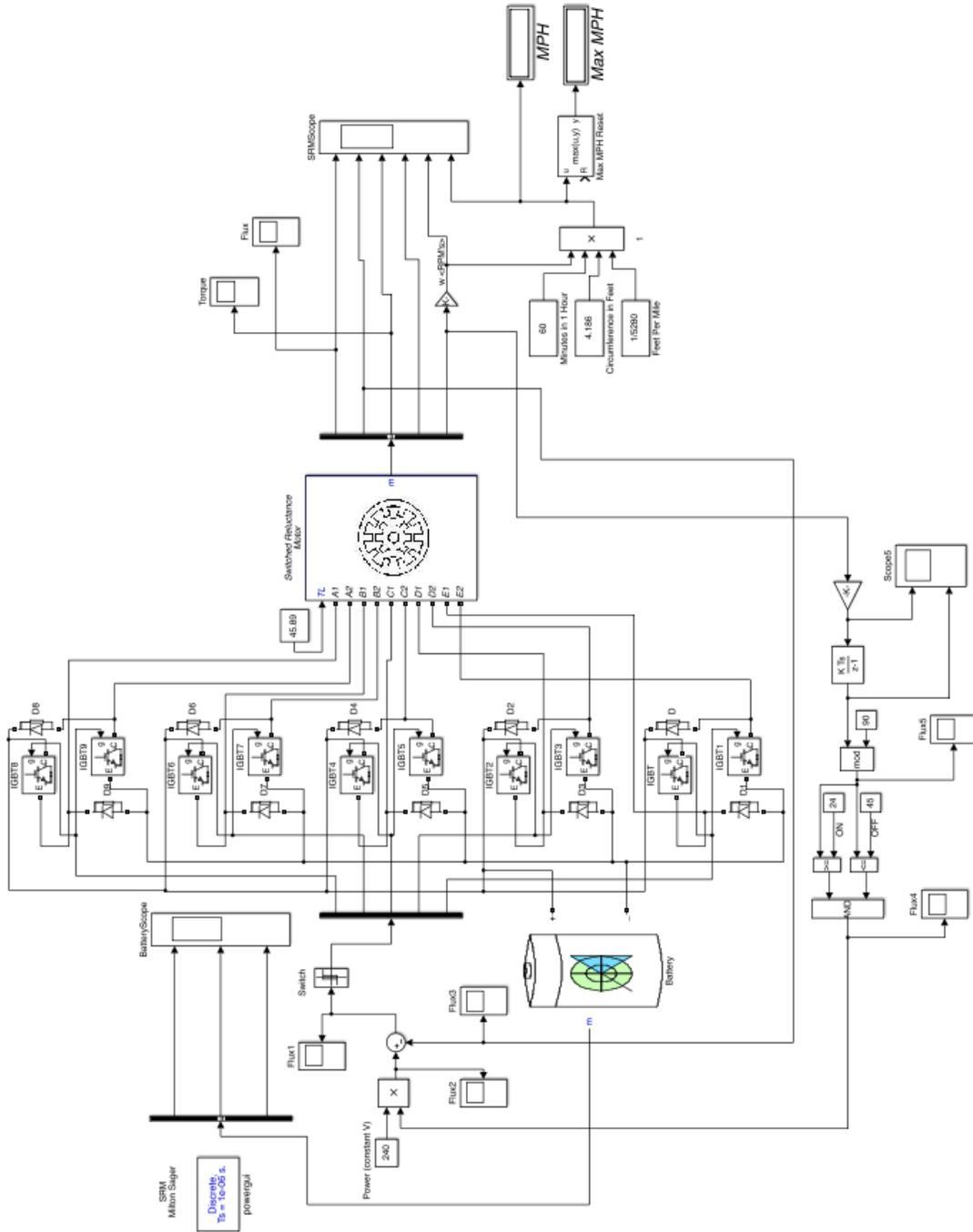


Figure 43: Five-Phase Diagram

3.4 Analysis of Five-Phase

The simulation is run for 1 second; this, again, is due to having no rapid acceleration mode and lack of computing power. Simulation of the five-phase takes roughly 2 minutes for every 1 second of simulation, and Simulink freezes if more than 10 seconds are attempted due to the amount of data. Below is the main scope, scope after integration, the signals after conversion, and the input to the switch.

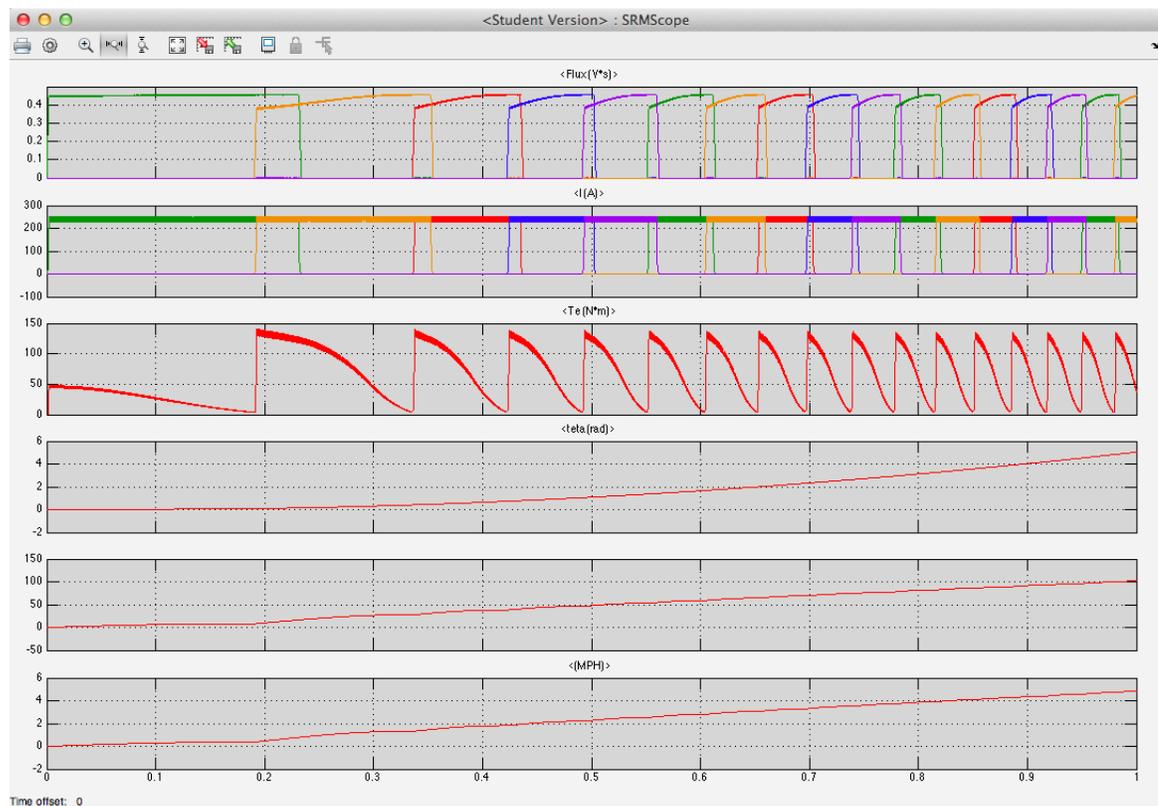


Figure 44: *Five-Phase One Second Main Scope*

Similar to the three-phase, a disadvantage in run-time is the continuous integration. However, just like the three-phase, this is limited when the motor reaches a constant speed.

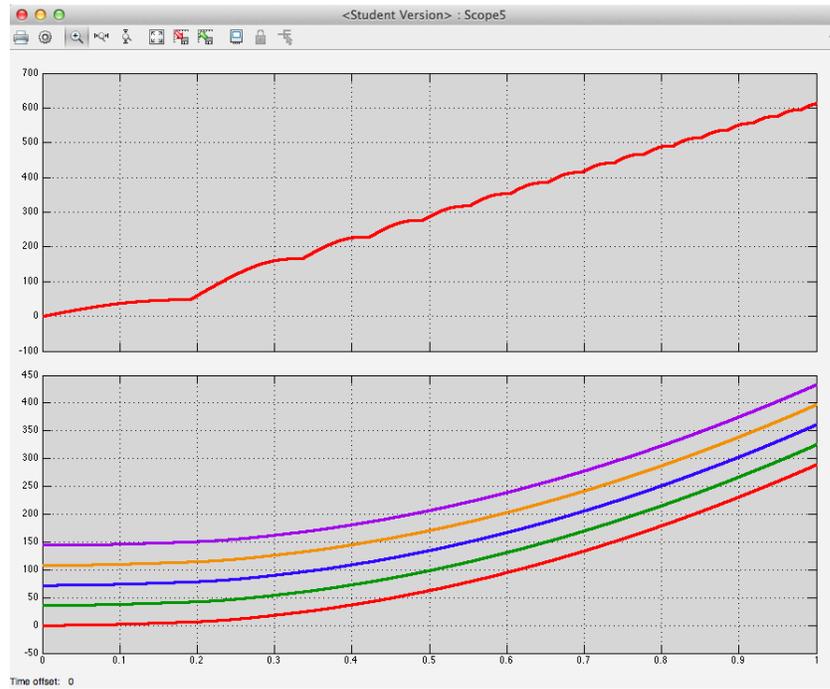


Figure 45: *Five-Phase One Second Integration*

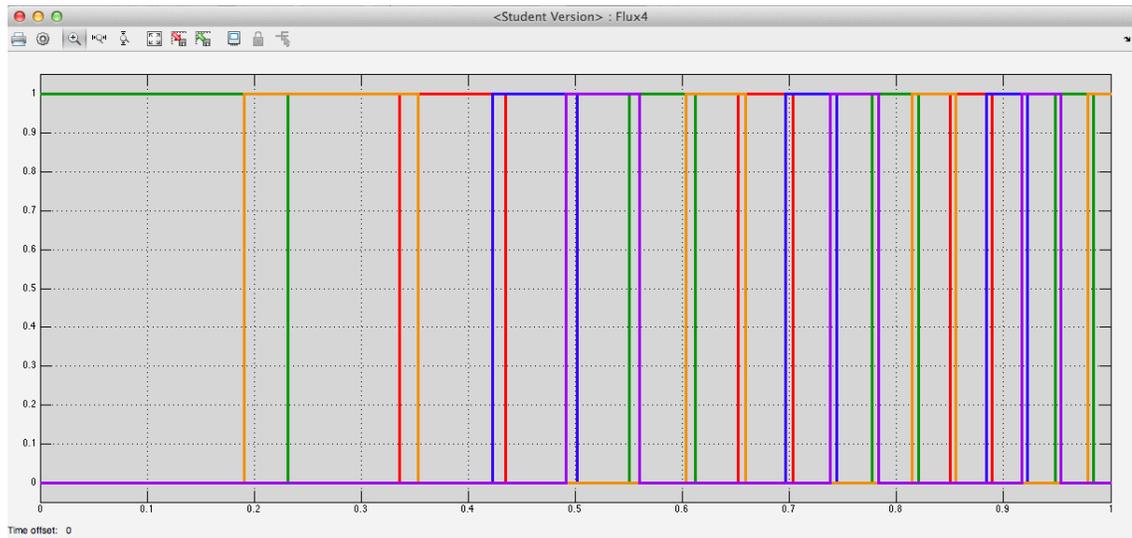


Figure 46: *Five-Phase One Second Converter*

The switch properties remain the same: ON if the phase input is between 10 and -10 , and OFF elsewhere.

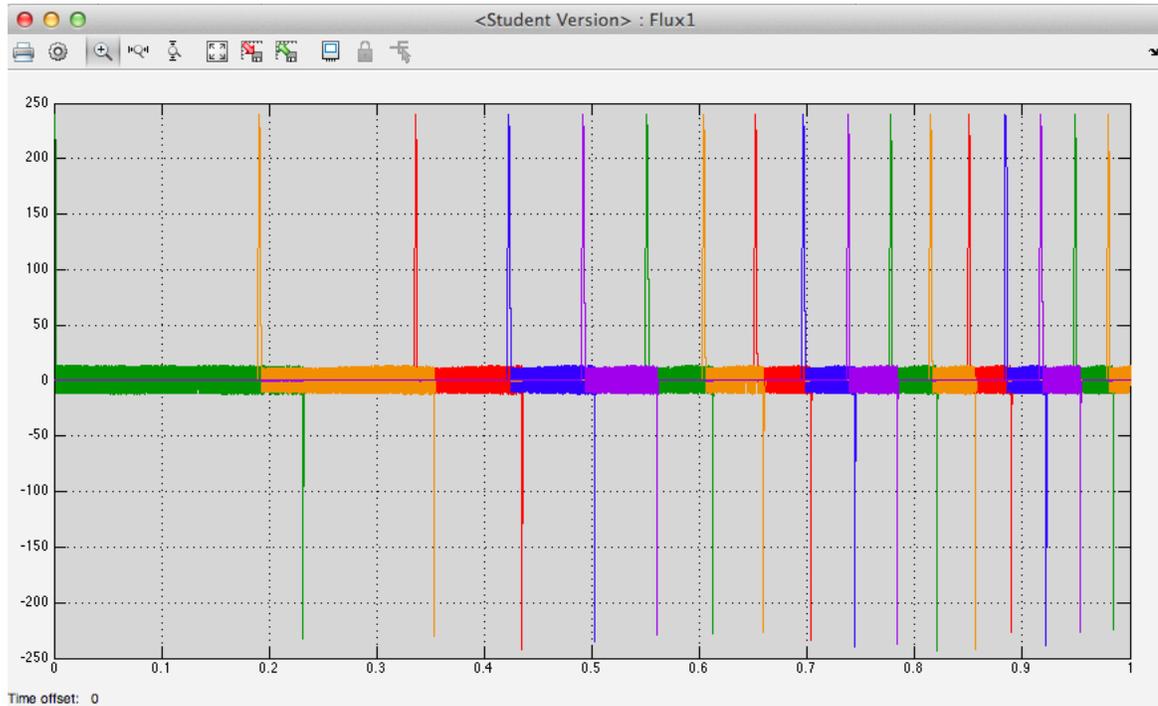


Figure 47: *Five-Phase One Second Switch*

The five-phase was then run for 10 seconds. The design also incorporates a battery whose output is included in the following graphs: the main scope, flux, battery scope [which includes (from top to bottom) the % power, Current and Volts], battery discharge characteristics, and the five-phase magnetization plots.

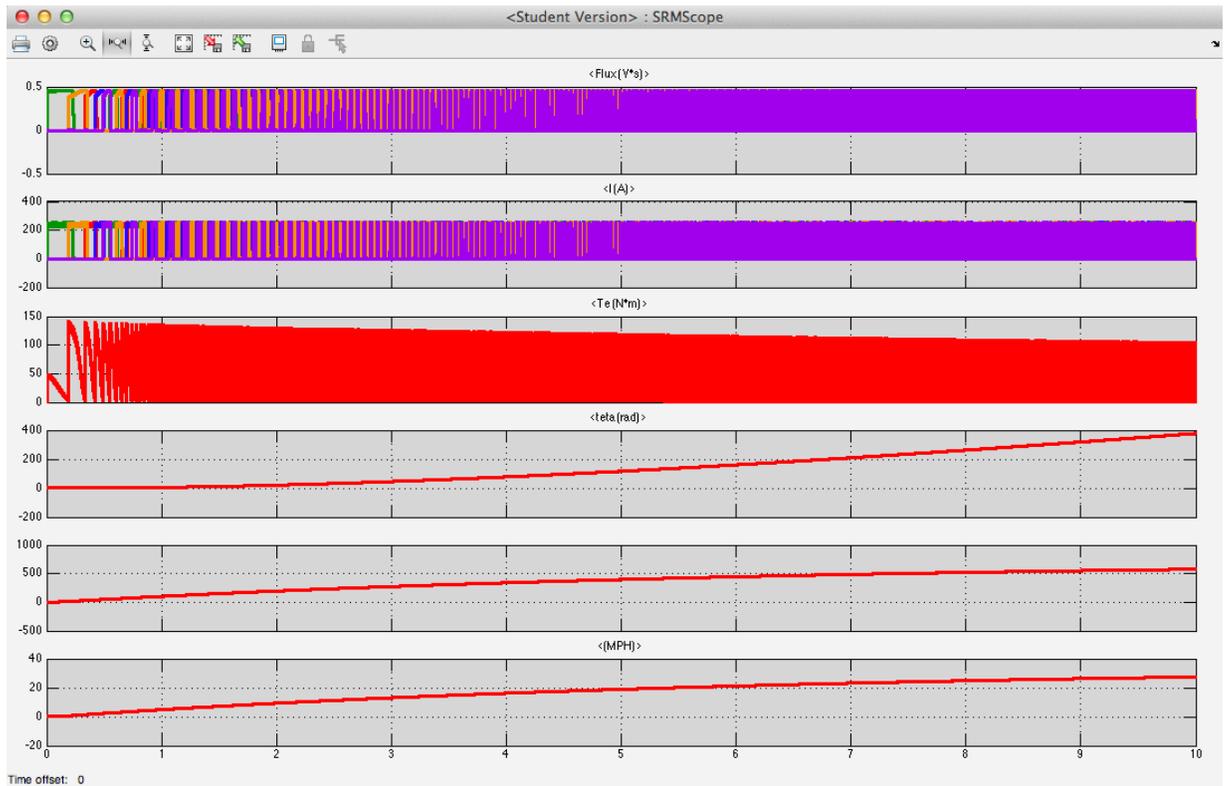


Figure 48: *Five-Phase Ten Seconds Main Scope*

After a 10 second simulation, the motor runs at roughly 28mph; slower acceleration than the three-phase, but much less torque ripple. The slower acceleration can be attributed to smaller gaps between the electromagnets which means less time "pulling" on the rotor between phases. This gives the rotor more time spent traveling between the phases with less "pull" force, thus less acceleration. Assuming a constant acceleration, this puts the five-phase 0 to 60mph trial at 21.4 seconds. The torque, however, now oscillates between 0 and 140Nm –40Nm less than the three-phase– and becomes steady after almost $\frac{1}{2}$ seconds. This results in a smoother but slower acceleration due to less torque.

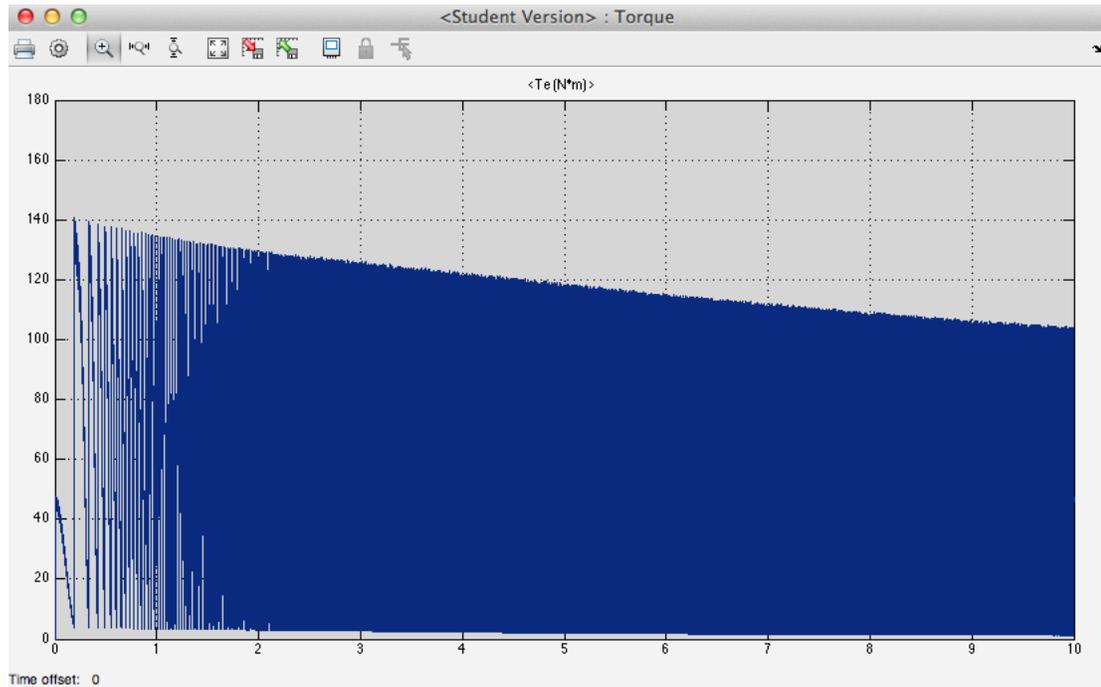


Figure 49: *Five-Phase Ten Seconds Torque*

The battery outputs indicate that, for the first 3 seconds of acceleration, the system has unstable drawing power and then levels to 240V. This can be attributed to all three IGBT's building up the 240V charges initially at the same time. The battery's discharge shows the battery in this system should sustain 240V for just over $2\frac{1}{2}$ hours. Neglecting the 21.4 second acceleration time to 60, this would imply a range of roughly 150 miles at 60mph before a recharge is required. This is the theoretical aspect. In the real world,

$$\text{HorsePower}(HP) = \frac{\text{Force} \cdot \text{Speed}}{\text{Weight}} \quad (3.4.1)$$

This means $HP = \frac{((\frac{1}{2} \cdot \rho \cdot V^2 \cdot C_d \cdot Ar) + (\text{weight} \cdot .005)) \cdot 88}{300}$ where ρ is a constant .002378, V^2 is velocity in ft/s (at 60mph), C_d is the drag coefficient of .2 and Ar is frontal area

in feet. And so we have, $HP = \frac{(7.366+1.5) \cdot 88}{300} = 2.6$. Since $1HP = .75KW$, $1.95kW$ are required at 60mph. This means the $2.04kW$ battery at 60mph with a 300lb load (rider and motorcycle) and 90% DOD would only last about $\frac{1.95}{2.04} \cdot .90 = .86$ hrs, this means a range of 51.6 miles at 60mph. Comparing this, ZeroMotorcycles range of their top line, the Street Fighter S, has a range of 64 miles at 55mph.

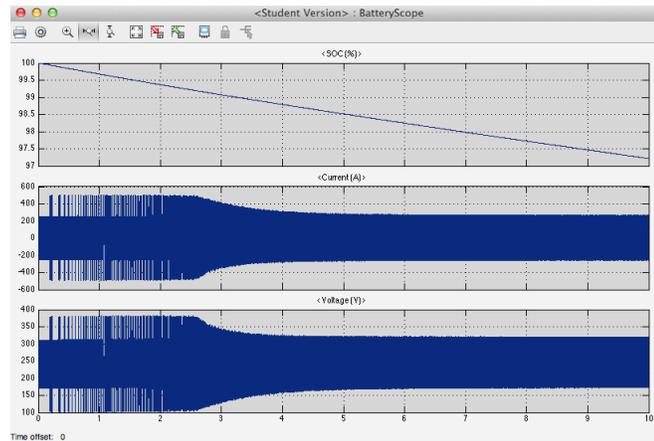


Figure 50: *Five-Phase Ten Seconds Battery Scope*

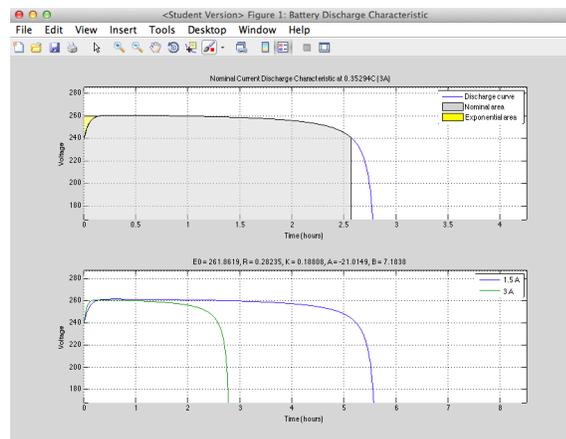


Figure 51: *Five-Phase Ten Seconds Battery Discharge Characteristics*

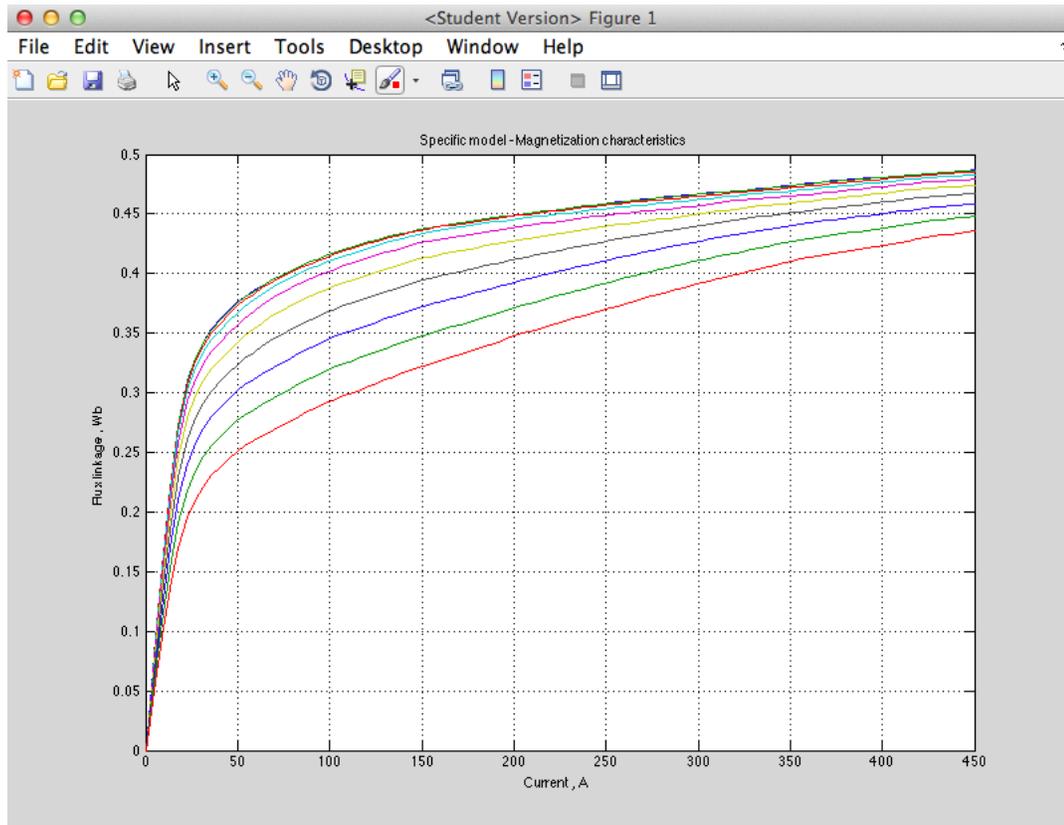


Figure 52: *Five-Phase Ten Seconds Magnetization Curves*

Just like the three-phase, these results indicate that this five-phase SRM is a viable replacement for the gasoline engine! The five-phase has less acceleration and less torque than the three-phase, which was a disappointing result. Further studies of this would need to be completed to find the optimal ratio of an SRM to yield the best performance given the limitations of current battery options. Any further investigation would need to be with other software because Simulink can only handle up to a five-phase SRM.

CHAPTER 4

BUILDING THE THREE-PHASE

4.1 Materials and Cost

My original electromagnets were constructed by first welding two washers, each measuring $1\frac{1}{2}$ inches in diameter, to the ends of a steel rod, measuring $1\frac{1}{2}$ inches long and $\frac{1}{2}$ inches in diameter, in order to create a makeshift iron core spool. The core was then wrapped with approximately 85 feet of 14 gauge magnet wire, leaving a foot of wire on either end of the wrapping. Magnet wire is different from conventional wire because it is coated in a very thin layer of insulation whereas traditional insulated wire has almost as much insulating in thickness as the wire itself. Magnet wire is preferred in electromagnets because the thin insulation layer maximizes the number of turns the wire makes; more turns results in greater current rotation, creating a stronger electromagnet. The approximate number of turns in each of my electromagnets was 330. Unfortunately, these did not work as well as expected and prefabricated electromagnets had to be ordered. These electromagnets are rated for 12V and have 55lbs of lifting force with very little internal resistance.

The following costs listed are only the costs of the parts used in the build. Other parts were used for experimentation but were ultimately not used in the build.

Item	Cost
8 Electromagnets	\$127.92
Power Supply	\$58.76
Circuit Board Base	\$27.39
Toggle Switches	\$26.45
$\frac{3}{4}$ " Plywood	\$24.86
Step Down Voltage	\$19.64
2 Steel Sheets	\$16.57
Momentary Switches	\$14.97
Wire	\$12.74
LEDs	\$10.84
Washers, Bolts, Nuts ect	\$10.00
2 Plexiglass Sheets	\$8.59
Aluminum Sheet	\$7.86
Power Switches	\$6.25
MOSFETs	\$3.95
Resistors	\$3.40
Microchip PIC	\$2.45
9V Battery	\$2.25
Total*	\$384.89

Table 5: Hardware Expenses

*price of tools purchased not included

4.2 Construction

Coming from a theoretical math background, building an SRM posed a difficult – however, interesting– challenge. A three-phase model was chosen because it would show how an SRM works but wouldn't be overly complicated to construct. The ultimate goal of fitting an SRM into the rear wheel of a motorcycle guided my design. Rough plans were created for the sake of visualization, and the design changed several times throughout the development.

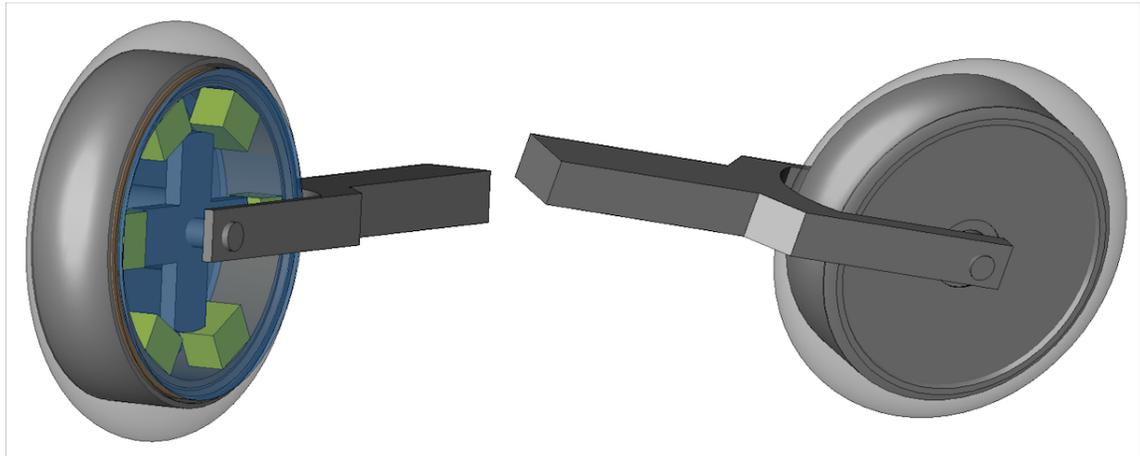


Figure 53: *Three-Phase Design Front*

The mechanical design and electrical design of the motor and control unit follow.

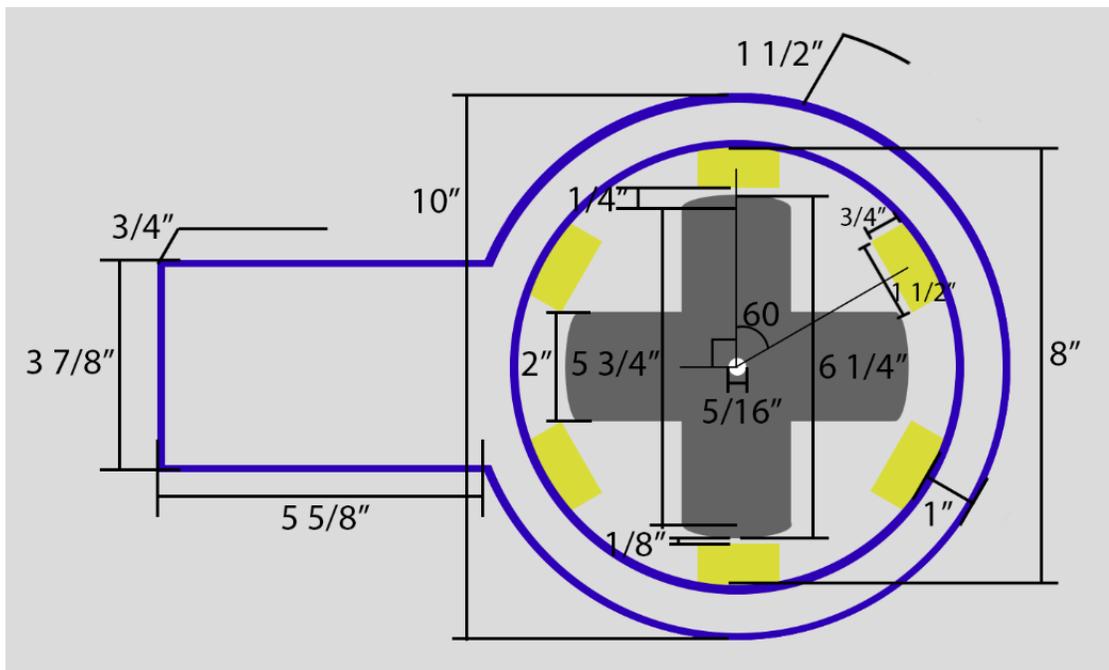


Figure 54: *Three-Phase Design Measurements*

The electromagnets are wired together in phases with corresponding light emitting diodes (LEDs.) This allows the user to view which phase is ON. There are four connections from the motor to the control unit; one contains the positive charge for all of the LEDs and electromagnets, and each of the other three is the negative charge corresponding to each of the three phases labeled by LED color [Green = A, Red = B and Yellow = C]. The LEDs are connected to the individual electromagnets using $2.2K\Omega$ resistors and $75V_{max}$ diodes. The diodes were added to ensure there was no inductive kick back of electricity through the circuit, similar to the way diodes were used in the simulation. Without the diodes, the kick back would cause all the LEDs to blink as each switch was turned OFF.



Figure 56: *LED Assembly*

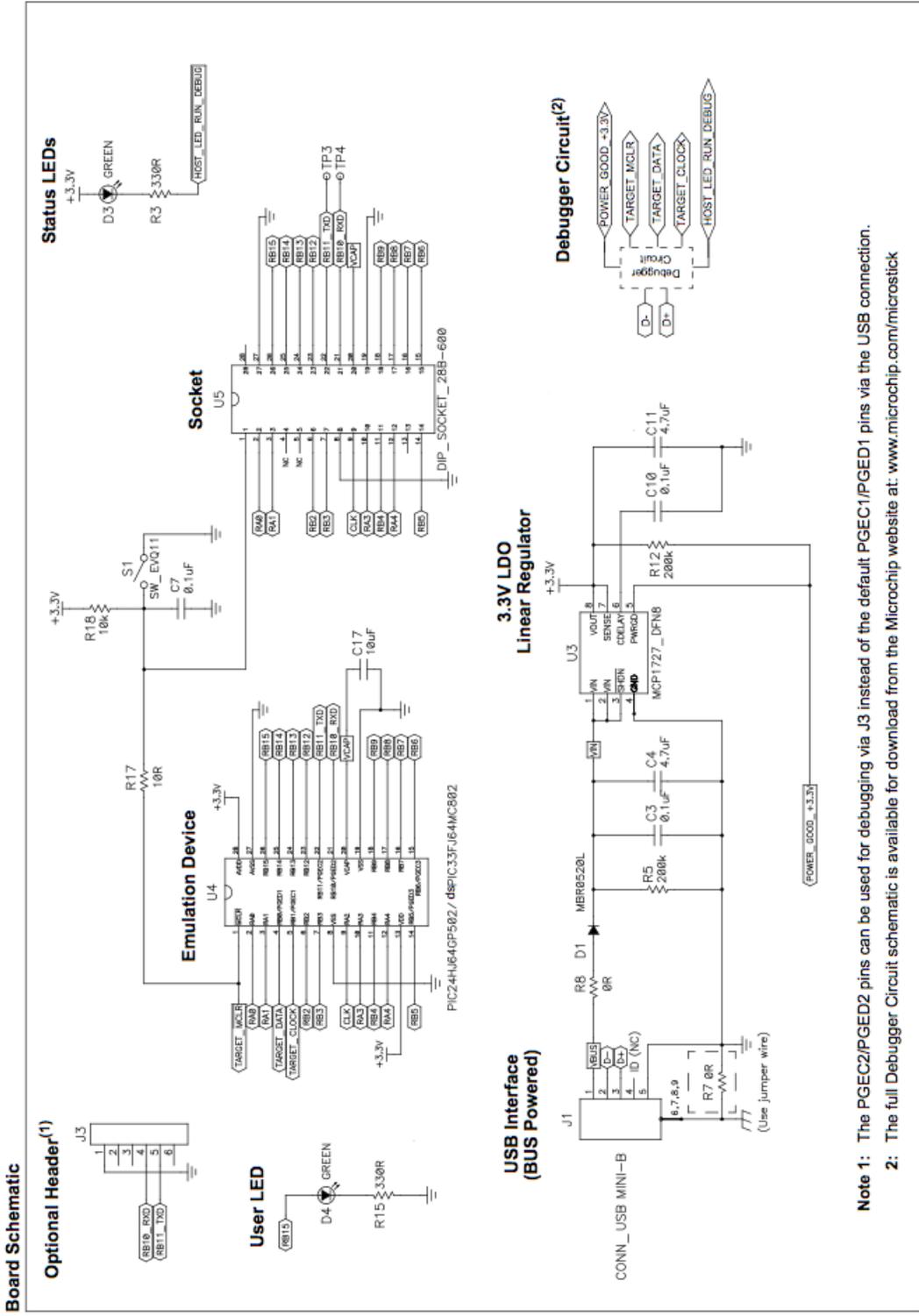


Figure 57: *Three-Phase Built*

Some of the challenges included learning how to solder, knowing what kind of wire to work with, cutting with precision and even welding (the final design required no welding). $\frac{3}{4}$ " plywood was used for the frame and plexiglass was used to hold the LEDs in place. 22awg braided copper wire was used for the motor and 18awg single strand copper wire was used for the to control unit. A SPST (single pole single throw) Bat Handle Toggle Switch [On-Off 20A] is the 'kill switch' to the whole circuit. Three SPST Push Button Momentary Switches [On/Off 6A] act as the manual button control, and six SPDT (single pole double throw) Miniature Toggle Switches [On-Off-On 6A] change the control to either manual or computer driven.

The microchip used to run the SRM is a PIC24HJ64GP502 on a microstick from MicroChip Development. The microstick allows for the chip to be plugged into the computer, programmed, and then run on it's own. The software MPLAB X was used

to create the program on the microchip. An isolated power source from a 9V battery was stepped down to 3.3V and used to run the microchip. The PIC24HJ64GP502 is connected to three MOSFETs (metal oxide semiconductor field-effect transistors) which act as the switches for the electricity. A MOSFET has three components the source, drain and gate. The negative charge runs from the electromagnets to the drain then to the ground through the source. The gate is what acts as the switch. When a small positive charge (5V) is passed to the gate the MOSFET is on and the negative current can flow. When zero charge (0V) is applied to the gate the MOSFET is off and current cannot flow. The microcontroller sends a positive charge to each MOSFET (connected to each phase) rapidly in succession which in turn runs the SRM. A 6" IC Breadboard Socket was used to connect the microstick, MOSFETs and 9V power source together. The PIC24s schematic, control computer assembly and whole unit follows.



Note 1: The PGEC2/PGED2 pins can be used for debugging via J3 instead of the default PGEC1/PGED1 pins via the USB connection.
2: The full Debugger Circuit schematic is available for download from the Microchip website at: www.microchip.com/microstick

Figure 58: PIC24HJ64GP502 Schematic

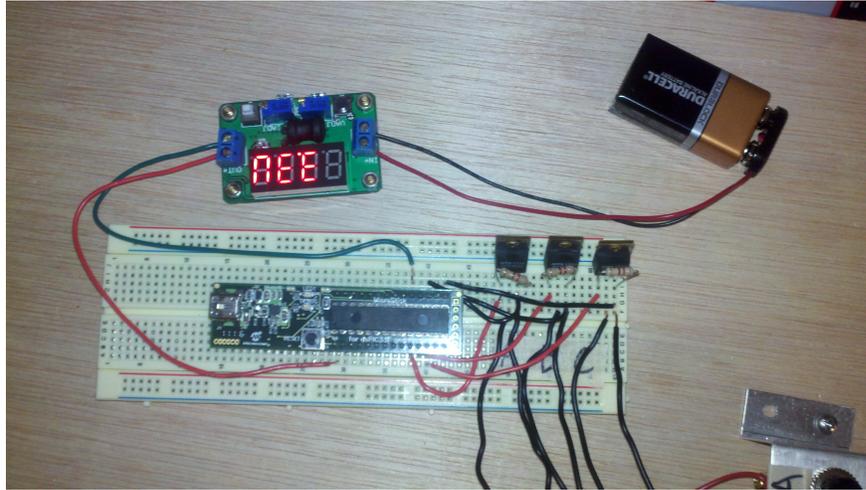


Figure 59: *Control Computer*

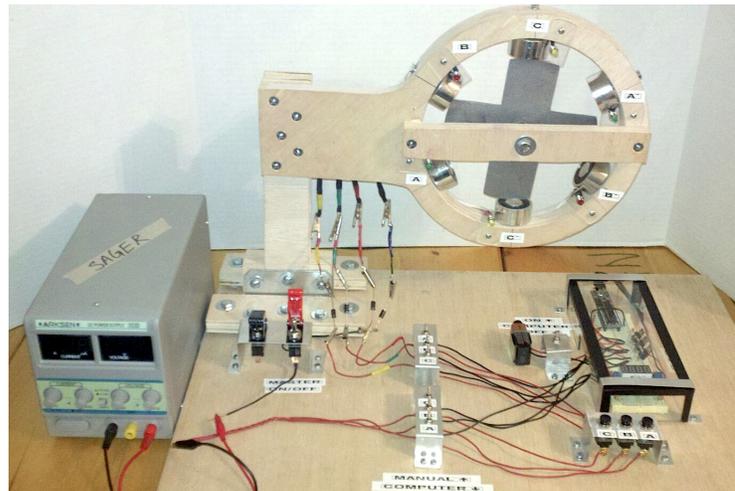


Figure 60: *Complete Build*

The microchip runs the following code to run the SRM. The code is on a timer and does not adjust with rotor position which causes the rotor to be started manually. Once at speed the timing keeps the rotor spinning at roughly 57 RPM.

Three_Phase_SRM_Code.c

3/16/14, 12:31 AM

```

/*****
 * © 2014 Milton W. Sager III
 *
 * FileName:      main_led.c
 * Dependencies:  p24HJ64GP502.h
 * Processor:     PIC24H
 * Compiler:      MPLAB® C30 v2.01
 *
 *This software turns each phase ON and OFF with a delay
 *inbetween each. This design has no sensors and the SRM
 * must be started manually.
 *
 *****/

#include "p24hxxx.h"          /* generic header for PIC24H family
 */

/*****

set device configuration values

 *****/
#ifdef __PIC24HJ64GP502__
_FOSCSEL(FNOSC_FRC);          // set oscillator mode for FRC ~ 8 Mhz
_FOSC(FCKSM_CSDCMD & OSCIOFNC_ON & POSCMD_NONE); // use OSCIO pin for RA3
_FWDT(FWDTEN_OFF);          // turn off watchdog
#elif defined(__dsPIC33FJ64MC802__)
_FOSCSEL(FNOSC_FRC);
_FOSC(FCKSM_CSDCMD & OSCIOFNC_ON & POSCMD_NONE);
_FWDT(FWDTEN_OFF);
#endif

#define PERIOD 0xFFFF          // sets the default interval flash rate
#define FLASH_RATE 5          // smaller value yields faster rate
    (1-100)
#define FOREVER 1              // endless
#define Delay_MS(ms)
#define Sleep(ms)

/* function prototypes */
void InitTimer1();
void delay(void)
{
    int i, j;
    for(i=0; i<8000; i++)
    {
        for(j=0; j<2; j++)
            /* it's a timer delay */}}

/* globals */
unsigned int Counter = 0;
volatile unsigned int timer_expired;

/*****

main entry point

```

```

*****/

int main ( void )
{

    /* Initialize ports */
    //LATA = 0x0000;           // set latch levels
    //TRISA = 0x0000;         // set IO as outputs
    //LATB = 0x0000;         // set latch levels
    //TRISB = 0x0000;         // set IO as outputs
    TRISAbits.TRISA0 = 0; // RA0 Phase C
    TRISAbits.TRISA4 = 0; // RA4 Phase A
    TRISBbits.TRISB4 = 0; // RB4 Phase B

    InitTimer1();           // start the timer

    int i=1;

    /* endless loop*/
    while (i=1)
    {
        if (timer_expired && Counter == FLASH_RATE )
        {
            LATAbits.LATA4 = 1;
            LATBbits.LATB4 = 0;
            LATAbits.LATA0 = 0;
            delay();
            LATAbits.LATA4 = 0;
            LATBbits.LATB4 = 1;
            LATAbits.LATA0 = 0;
            delay();
            LATAbits.LATA4 = 0;
            LATBbits.LATB4 = 0;
            LATAbits.LATA0 = 1;
            delay();
            Counter = 0;
            timer_expired = 0;
        }

        // or do something else
        Nop();
        Nop();
        Nop();
    }
}

/*-----*/
Function Name: InitTimer1
Description: Initialize Timer1 for 1 second intervals
Inputs:      None
Returns:     None
/*-----*/

void InitTimer1( void )
{

```

```

T1CON = 0;          /* ensure Timer 1 is in reset state */
IFS0bits.T1IF = 0; /* reset Timer 1 interrupt flag */
IPC0bits.T1IP = 4; /* set Timer1 interrupt priority level to 4
*/
IEC0bits.T1IE = 1; /* enable Timer 1 interrupt */
PR1 = PERIOD;      /* set Timer 1 period register */
T1CONbits.TCKPS1 = 0; /* select Timer1 Input Clock
Prescale */
T1CONbits.TCS = 0; /* select external timer clock */
T1CONbits.TON = 1; /* enable Timer 1 and start the count */
}

/*-----
Function Name: _T1Interrupt
Description:   Timer1 Interrupt Handler
Inputs:       None
Returns:      None
-----*/
void __attribute__((interrupt, auto_psv)) _T1Interrupt( void )
{

    timer_expired = 1; /* flag */
    Counter++;        /* keep a running counter */
    IFS0bits.T1IF = 0; /* reset timer interrupt flag */
}

```

CHAPTER 5

WHERE TO GO FROM HERE

5.1 Starting the SRM

Recall the aforementioned hurdle of the rotor's starting direction. The only difference in driving direction is which way the rotor initially begins to spin. The initial solution to this problem, because the user is on a motorcycle, would be for the rider to push off and begin the motorcycle moving just a little. Sounds like a viable option, right? Only until it is recalled that the world isn't flat; often, a rider will find himself starting on an incline. There must be a solution that does not require the rider to do anything but turn the throttle. The solution is to turn ON two specific phases corresponding to the rotor's position with respect to the electromagnets. One phase is ON only for a moment while the other would be the start of the normal acceleration. In this way it can be guaranteed that the rotor will start spinning in the direction desired. Shown is a representation of which two phases to switch ON depending on the rotor position using a five-phase SRM. Not surprisingly, there is a pattern that repeats itself. Below that, on the left is an image of the correspondingly labeled five-phase SRM, and on the right an example of the rotor being between 18 and 26 degrees. Note how Phase C is the closest to alignment with any rotor pole. This is why Phase C is momentarily switched ON with Phase B to give a clockwise, positive rotation. This is, of course, all dependent on the size and spacing of the electromagnets and rotor poles.

R1 Start Angle (Degrees)	R1 End Angle (Degrees)	Rotor Pole Aligned with Phase	ON	Momentarily ON
1	8	R1 = A	D	E
9	17	R4 = E	C	D
18	26	R3 = D	B	C
27	35	R2 = C	A	B
36	44	R1 = B	E	A
45	53	R4 = A'	D	E
54	62	R3 = E	C	D
63	71	R2 = D	B	C
72	80	R1 = C	A	B
81	89	R4 = B'	E	A
90	98	R3 = A'	D	E
99	107	R2 = E	C	D
108	116	R1 = D	B	C
117	125	R4 = C'	A	B
126	134	R3 = B'	E	A
135	143	R2 = A'	D	E
144	152	R1 = E	C	D
153	161	R4 = D'	B	C
162	170	R3 = C'	A	B
171	179	R2 = B'	E	A
180	188	R1 = A'	D	E
189	197	R4 = E'	C	D
198	206	R3 = D'	B	C
207	215	R2 = C'	A	B
216	224	R1 = B'	E	A
225	233	R4 = A	D	E
234	242	R3 = E'	C	D
243	251	R2 = D'	B	C
252	260	R1 = C'	A	B
261	269	R4 = B	E	A
270	278	R3 = A	D	E
279	287	R2 = E'	C	D
288	296	R1 = D'	B	C
297	305	R4 = C	A	B
306	314	R3 = B	E	A
315	323	R2 = A	D	E
324	332	R1 = E'	C	D
333	341	R4 = D	B	C
342	350	R3 = C	A	B
351	359	R2 = B	E	A

Figure 61: Start of Five-Phase Angles Chart

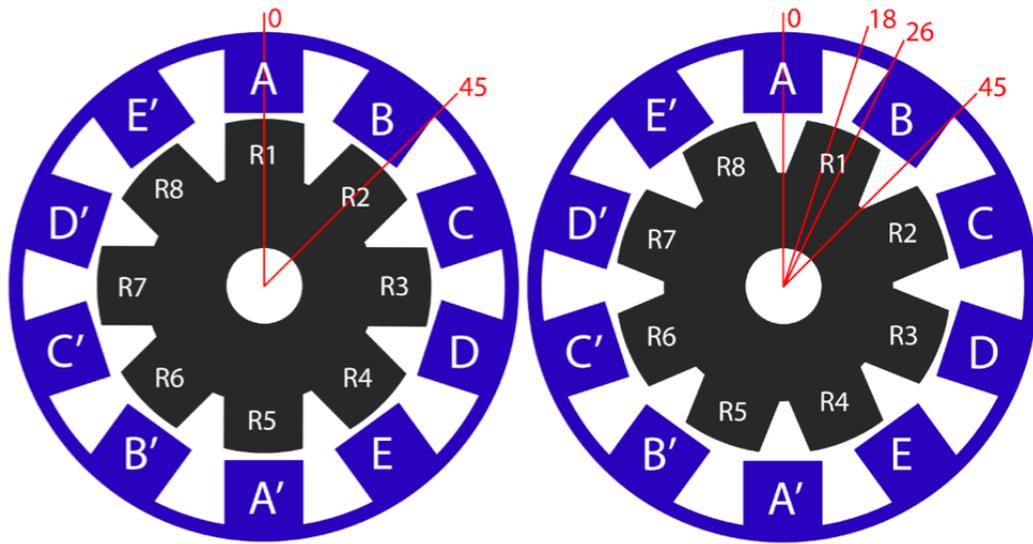


Figure 62: *Example of Start Angles*

5.2 Balance and Riding of Motorcycle

A factor that I stumbled upon while building the three-phase model is stabilization. Traditional electric motors have small rotors which do not affect stability but limit speed which, in turn, requires the use of gearing. That said, the direct-drive design of the SRM should incorporate the largest possible rotor in order to maximize RPMs. In building the three-phase it was discovered that the rotor acted somewhat like a gyroscope when spinning at high enough speeds. This means that the motorcycle would be just as –if not a little more– stable at higher speeds than traditional motorcycles. This also means that taking curves or turns at higher speeds would require more effort as the SRM would want to remain in an upright position.

Coasting means having zero magnetic friction; thus, maintaining a constant speed may only require intermittent usage of alternating phases thereby reducing battery

consumption which would extend battery life! Once at desired speed, the motor could run and maintain that speed (at least on a flat road or slight decline) with only a few phases switching ON instead of all of them. This was not addressed in this paper but should be investigated further.

5.3 Building the Motorcycle

Since traditional motorcycles do not have reverse –as discussed earlier– the prototype could be given reverse capabilities. Also, since motorcycles have cable-driven brakes, the braking system is not affected by the removal of the gasoline motor and is, therefore, not a problem to consider. The shift lever would be removed as it would be unnecessary. The clutch lever would be kept as a fail-safe; engaging the clutch lever would not only switch all electromagnets off in the event of an emergency and allow the motorcycle to be brought to a controlled stop, but would also turn the regenerative braking off (if regenerative braking is something that is added). Turn signals and lights would remain as they are since they run off the battery already. This leaves the removal of the gas tank, gasoline engine, transmission, sprockets, chain, etc. which would be replaced by batteries, the control computer and, of course, the SRM.

5.4 Regenerative Braking

The possibility of incorporating regenerative braking into the design, to return some of the energy back into the batteries when braking, is something to be considered. Energy cannot be created or destroyed, only used or lost; when a vehicle brakes there is a terrible loss of energy to the heat of the brake pads and discs. Regenerative braking introduces an alternator connected to the front wheel which, when turned

on (when braking), would act as a generator sending power back to the batteries via capacitors. Regenerative braking serves two purposes: returning some of the energy to the batteries, and significantly slowing the tire without the need for brake pads. This would reduce the wear on the pads and extend their life, as well as extending the run time of the battery.

CHAPTER 6

FINAL THOUGHTS

6.1 Personal Hurdles

One of the first hurdles of the design process was finding software that could viably simulate the motor. The best software on the market today is ANSYS which costs \$1,000 for a one year student license. ANSYS allows for the building of almost anything mechanical, electrical or otherwise imaginable device based in real world physics. One could not only simulate custom designs and analyze them with a wide variety of tools, but one could also visualize the design using 3D graphics; this would be very helpful for those who may not be able to imagine what something looks like when staring at a circuit design filled with blocks, lines, numbers and letters. Sadly, I was unable to obtain this software; fortunately, I found an affordable alternative, MATLAB with Simulink. Simulink is similar to ANSYS in that it can simulate designs, but is not as expansive. Simulating a five-phase SRM is the maximum that can be achieved in Simulink due to a restrictive block, which can be seen in the simulated design. Final costs are listed as follows:

Item	Description	Cost
Matlab and Simulink (Student Version)		\$108.66
SimPowerSystems Library		\$31.83
SimScape Library		\$31.83
SimMechanics Library		\$31.83
3D Simulator Library		\$31.83
MATLAB Report Generator		\$31.83
Simulink Report Generator		\$31.83
Total		\$299.64

Table 6: Software Expenses

Another hurdle, similar to learning how to use Simulink, was learning to use ViaCad8. This was used to design a visual of the original design, which undertook drastic changes as more was learned about mechanics and SRMs. It was also used to make a visual of the final design of the three-phase scale model.

The most irritating hurdle –which stands as more of a warning for anyone wishing to work on a project like this– was the processing power of my computer. I often found that I could only run one program or one simulation at a time, which lengthens the amount of time it takes to do anything. It was particularly frustrating when programs that were running froze up while trying to do even simple tasks. This also ties into Simulink’s limited simulation capabilities. Simulink runs simulations in real time. This also ties back into the rapid accelerator mode mentioned earlier.

My greatest hurdle by far was that I come from a purely theoretical math background with little to no mechanical, electrical, or other real world experience in applying mathematics. This meant learning a great deal about mechanics and electrical circuits, including all of the terminology related to these subjects. The real-world application of math is the majority of this thesis; it meant taking the math learned from undergraduate and masters’ programs and applying it to an idea in the real world. This required taking days here and there to learn about topics that were necessary for this design – topics that may not even be included in this paper. This was a true test of taking math and applying it to the real world. It was exciting, though very challenging. Just one example was defining *Degrees*. What does it mean to say 360° of an electrical current and what role does it play? Since 360° in an electrical cycle is not always 360° as it would be in a standard circle, it poses a hurdle in the programming aspect of a SRM. For example, in a three-phase SRM which contains six electromagnets 360° , or the number of degrees in order to complete one *cycle*,

is actually $\frac{360}{6}^\circ = 60^\circ$. That means for every 60° of the arc the rotor travels, it is completing one 360° electrical cycle. Many other terms have been learned for this project.

The last hurdle was building a three-phase SRM. Choosing sizing, materials and how to connect everything was an unknown. This is where things like microcontrollers and MOSFETs were learned about. A great deal of time went into researching what materials were needed and how to connect them. From there it was a matter of learning how to program the microcontroller, compile the code and then run the code.

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