Brushless DC Motor Design and Build

A Senior Project

presented to

the Faculty of the Electrical Engineering Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

by

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ABSTRACT:

The objective of the project was to design and built a quarter horsepower, brushless, direct current (BLDC), permanent magnet, three phase electric motor. Using knowledge acquired from various magnetic design and power classes the motor would be built using these theories and practices. This project required a lot of research as to the extent of what was possible and what could be achieved within two quarters. The primary goal and focus was to be able to make a fully functioning motor. Once it was determined what type of material to make the stator and other portions of the motor out of, a reasonable size and power output was estimated. Using a general radial flux motor concept, the design was refined through calculations while keeping in mind the limitations of machining. This proved to be very difficult given the type of material that had to be machined. After many checks and calculations were made the final design was approved and parts were ordered. Using this radial flux motor design, all parts were manufactured using various machines; lathes, end mills, band saws, CNC Mills, etc, from one single piece of bar stock steel . To power the design a Stellaris, Texas Instrument, three phase BLDC motor controller was used. The motor was then modified to accommodate the Hall Effect sensors necessary to operate the controller. As will be shown throughout the report, many difficulties and frustrations were encountered during design and machining of the motor. It will be thoroughly explained through this report that the theories and practices in both magnetic design and electrical circuit theory can be manipulated into a device that changes electrical energy into mechanical energy.

Tables and Figures

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Introduction:

The concepts behind converting electrical energy into mechanical energy have been known since the late 1820's when the first electric motor was successfully tested. These concepts over the years have been improved upon, but for the most part have remained the same. This applies to the design of electric motors. Over the years there have been many upon many design changes to improve efficiency and output power, however the theories and practices that make them work have remained constant. Behind every electric motor used today these basic and fundamental magnetic and electrical properties hold constant and are demonstrated through this project.

Electric motors are everywhere in the world today. The world as we know it exists because of the electric motor. From the Hoover dam to your laptop computer there is an electric motor serving a purpose. From the beginning, motors have been used to improve the everyday life of people on Earth. They generate thousands upon thousands of kilowatts of electricity to power homes, factories, tv's, computers, lights, microwaves, etc. They allow for one man to move thousands of pounds of material from one place to another replacing the need for twenty men to do the same job, just by using a simple hydraulic system with a motor. In today's world electric motors power cars that can go from zero to sixty miles/hr in no more than a few seconds. Motors are essential to today's way of life and make life easier as we know it.

As of today there are over 15 types of various DC and AC motors that all serve the purpose of converting electrical energy into mechanical energy or vice versa. Of these many different designs one design in particular was chosen for this project. It displays the basic magnetic and electrical principles as mentioned earlier and is composed of a design that fits the overall goal of this project.

The brushless direct current (BLDC) permanent magnet motor was chosen to demonstrate the theories and practices behind electric motors. These particular types of motors are known for their high durability due to simplicity in design, and high RPM capabilities. BLDC motors have both small and large applications. For example, in every computer there is a hard drive. A hard drive consists of a spinning disk that is powered by a small BLDC motor to rotate the hard drive disks at very fast speeds. On the other hand with the newly developed hybrid cars coming out along with a small fuel efficient engine there are typically two or even four BLDC motors located on either the axel or each individual wheel. Both of these motors are similar to this design in that they both run off of permanent magnets. This particular design is in between these two extreme (small, large) type of motors. The design although simple was made extremely difficult when all aspects of a motor were to be taken into account and designed from scratch. The goal was a twenty four volt, quarter horsepower design.

All of the following was done with help from various people including professors, machinists and text books. I would encourage who ever reads this report to understand the importance of electric motors in today's world and how this project was made to gain a better understanding of the complete engineering process from understanding concepts to the actual testing of a motor.

Requirements:

To design and build a twenty four volt, brushless permanent magnet, DC motor from scratch. To gain a higher understanding of the general principles behind these machines and the various designs that can accommodate them. To test and troubleshoot the design and explain reasons for possible failures in the motor. This project is not required to work but an understanding of why failure could have occurred must be explained. Explain the various troubles and difficulties that were experienced throughout the project and how the project was developed in full.

Design:

In order to understand how the motor was to be designed, the theories in magnetics had to be understood. Once these theories were understood it was simple to understand how a motor converts electrical energy to mechanical energy. In figure 1.0 below there are basic variables that were used throughout the project.

- "H" : Magnetic Field Strength (Amps Per Meter)
- "B" : Magnetic Flux Density (Tesla)
- "μ" : Permeability (Henry per meter; $\mu = \mu_o \times \mu_r$)
- "ϕ" : Flux (Weber)
    - Equivalent to Electrical Current "I" (Amps)
- "Ɍ" : Reluctance (Amp. turns per Weber)
    - Equivalent to Electrical Resistance "R" (Ω-Ohms)
- "F" : Magneto motive force (A-t)
    - Equivalent to Electrical Voltage "V" (Volts)
- "N" : Turns per winding (Turns)

(Magentic Properties follow the same Electrical "Ohms Law")

Electrical Circuit: V=I*R *Magnetic Circuit:* F= ϕ* Ɍ

Figure 1.0: Table of Variables in Magnetics [4]

If these variables are understood then one can understand the concepts behind an electric motor. Magnetic variables react in the same way as electrical variables. For example in electrical systems voltage is the result from the product of current and resistance. This applies to magnetics as well, where Magneto motive force is the result of the product of flux and reluctance.

It is understood that current is the flow of electrons through a material. With relation to magnetics what is flux then? Flux is the flow of a magnetic field that passes through a material. So then what is magnetic field? Magnetic field is a type of force that is found in magnets. When two magnets are put side by side depending on what poles are facing each other, they will either attract or retract from each other. That force that brings them together or apart is resulted by the magnetic field. Magneto motive force is a physical force that is a type of potential similar to electric potential. This force as stated earlier is the result of flux multiplied by reluctance. Reluctance is a materials resistance to the flow of flux. However unlike electrical resistance where energy is dissipated, magnetic reluctance stores energy in a material. This will play a key role in the limitations of the motor later on.

Now that a basic understanding of magnetic terms is understood, where does the conversion from electrical to mechanical energy take place? A current carrying wire induces a magnetic field in the area around it. If a wire is wrapped around a piece of material in a coil, that material (from the magnetic field provided by the wire) will have flux flow through it. Depending on the reluctance of the material there will be a Magneto motive force expressed. This force can be used to attract or repel other magnetic forces, such as a magnet or other coiled wires that express the same type of force. This is where the conversion from electrical to mechanical energy takes place.

So now that it is understood how a current carrying wire can induce magnetic fields and Magneto motive forces, how can this be manipulated to essentially turn a rotor. There are many design possibilities for this as shown in the motor family tree on in appendices E. However given that this project was to be designed and made all by hand, a simple motor design had to be chosen. Some motors are very complex, although the theories behind them are all the same. Others like the one chosen are relatively simple to design and build. Brushless permanent magnet DC motors are among the most reliable and simple machines that anyone can buy or make.

An entire series of books can be written on all of the different designs of motors and their advantages and disadvantages. For this project a focus will be brought upon several factors that influenced the final design. Brushless motors, are known for there very high torque, reliability and durability. They are known for having long lives and rarely failing. What is the difference between brushed and brushless motors? Please observe the image below for a better description of a multiple phase brushed motor. When observing the picture the two "Graphite Brushes" shown at the bottom and upper left portion of the picture are

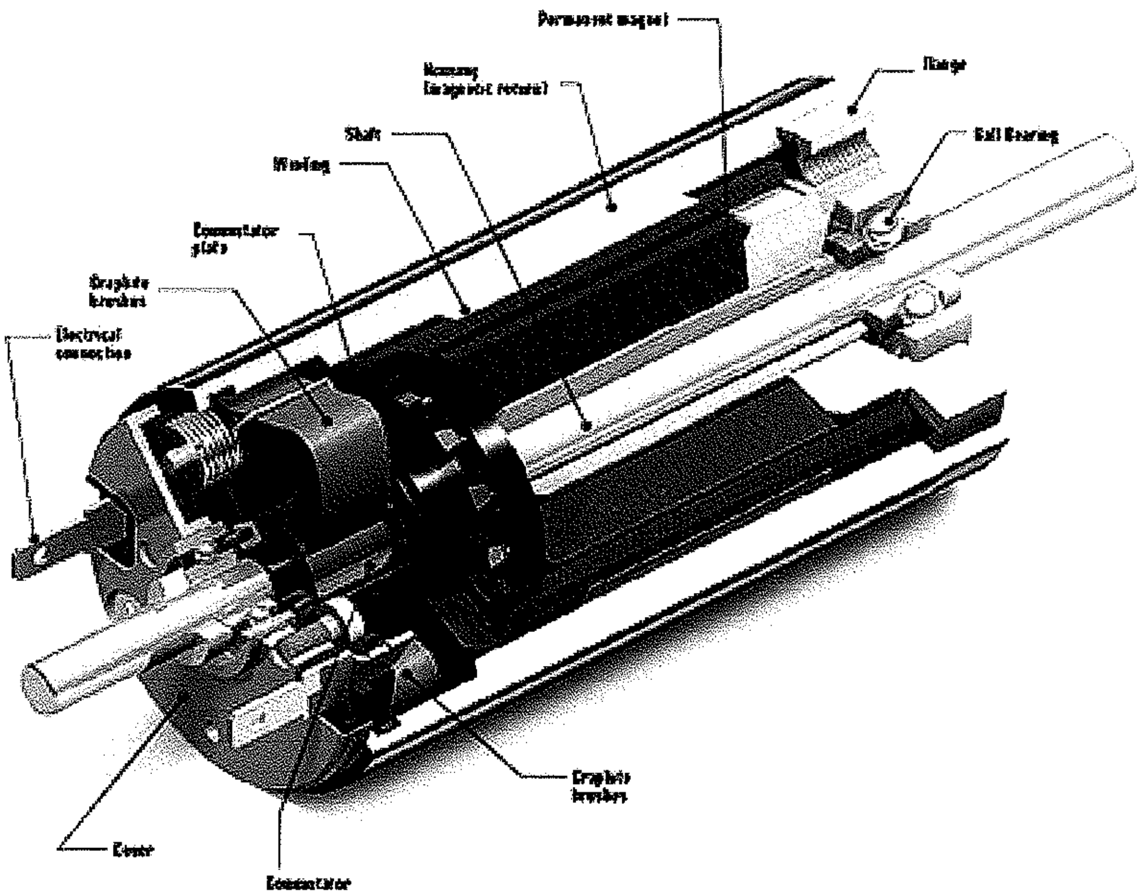

Figure 1.1: Example of Small Brushed DC Motor [1]

shown rubbing up against the copper "Commutator". It can also be noticed that these "Graphite Brushes" are attached to the "Electrical Connections" (Positive and Negative) in the front of the motor. Notice that the copper "Commutator" is divided into many different sections. These sections, which are connected in pairs by a copper coil, each represent a phase of the motor. If looked at from the point of view of current the following will be observed. When an electric potential is applied across the "Electrical Connections" current flows through the motor, more importantly current flows through the windings in the motor. The use of the "Graphite Brushes" is to complete the connection from both "Electrical Connections" by rubbing up against the "Commutator". The "Commutator", rotating along with the rotor, completes the connection for each different set of windings in the stator. The "Commutator" is therefore changes the phases of the motor.

This design was one possibility however the big difficulty with this type of motor is the "Commutator". Making the "Commutator" and getting the brushes positioned properly and connecting each phase correctly is difficult to do. Therefore a brushed motor was not an option. Observed below in Figure 1.2 a brushless DC motor design can be seen. It can be observed that this particular design has an electronic portion to it.

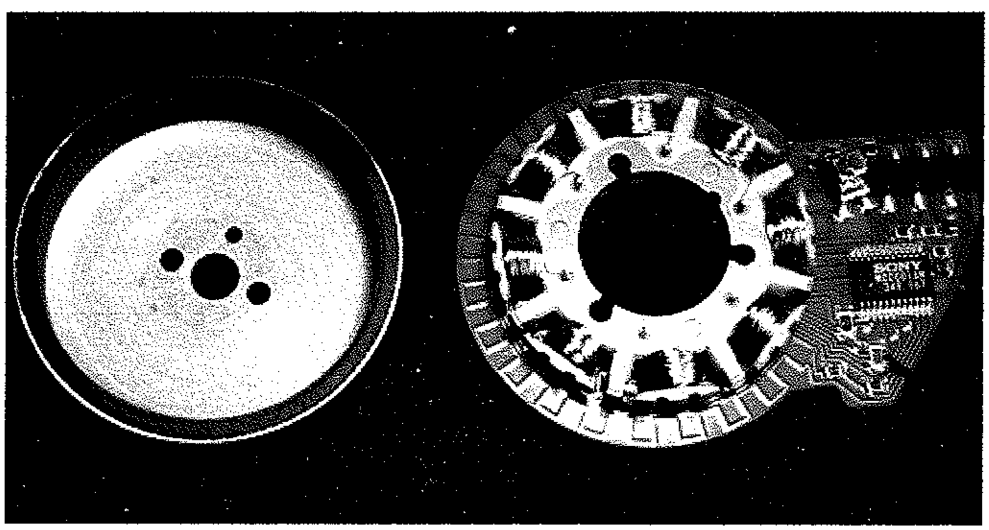

Figure 1.2: Example of Brushless DC motor Design [2]

Unlike a brushed motor where each motor phase is opened and closed mechanically, a brushless motor needs an electronic controller to change the phases of the motor. The electronics are fairly simple to make and can be bought given that many different types of controllers are available. Choosing a brushless design allowed more options and allowed for easier manufacturing of the motor.

The permanent magnets used in the design also allowed for greater ease in the manufacturing of the motor. In both of the above figures permanent magnets can be found on the rotor portion. However there are other motor designs where both the stator and rotor have windings in them. Remember how previously explained, a current carrying wire induces magnetic fields. In cases where no permanent magnets are used these windings induce magnetic fields that act like magnets. Again this is another design that was not used because assembly of the rotor with the windings would be very difficult.

So the reasons for building a BLDC, permanent magnet motor are for the simplicity of the motor. The next was step is to find a general design that could be manufactured given the available machinery. There are two main types of BLDC motors, Radial Flux and Axial flux as can be Observed in Figure 1.3 below.

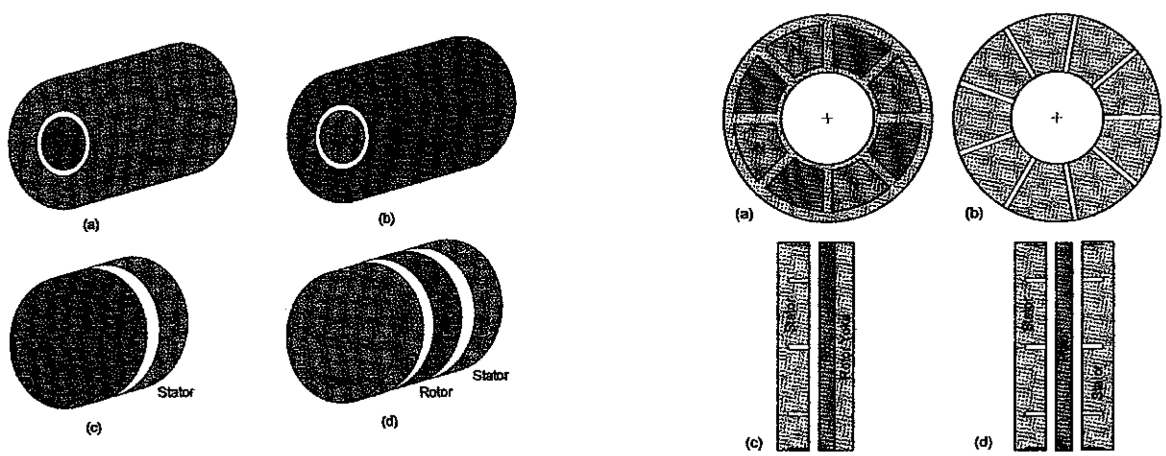

Figure 1.3: Radial and Axial Flux Motors (Left), Axial Flux motor (Right) [3]

The difference between them is the flow of flux. In a radial design, shown in the left image parts “a” and “b”, the flux flows radially around the stator, where with axial flux located on the right image, flux flows axially along the axis of the stator. Examine Figure 1.4 below and the flux flow of an radial flux design can be seen.

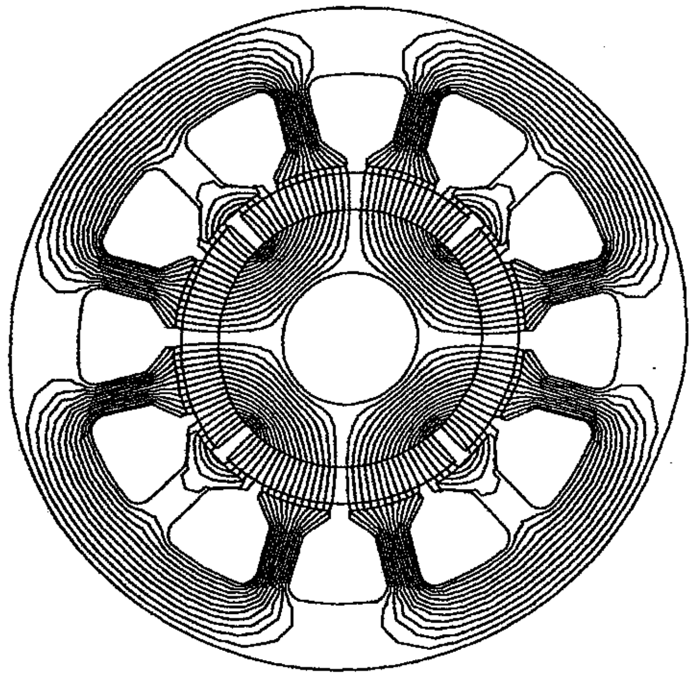

Figure 1.4: Flow of Flux in a Radial Flux Design [3]

As can be observed this is a 4 pole (permanent magnets on the rotor in the middle), 12 tooth design. Flux can be seen traveling radially through the motor. These particular designs are typically used for common low power machines such as fans or remote control plane motors. The designs in Figure 1.3 (Right) are typically used in larger applications for cars such as the Toyota Prius's Hybrid electric drives. For this particular project a radial flux motor was more suitable because the motor could get the same power output as an axial flux motor by making it longer instead of wider unlike the axial flux. This is important because the machines that would be used are better at cutting longer pieces than they are wider pieces. The machines that are available are simply designed this way. The design would be very limited if an axial flux design were used.

The most challenging part of this project was going to be the stator, it was going to be the most difficult to machine and the design itself made the windings difficult to wind. None the less the reason for the design chosen as shown below in Figure 1.5 is due to its simplicity and its some what machine friendly design.

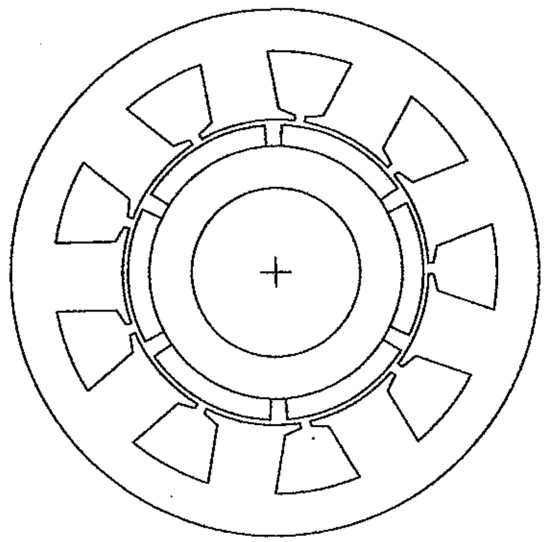

Figure 1.5: Radial Flux Motor Design Chosen [3]

With this particular stator design, the rotor design can be changed if necessary. There were only nine teeth which would cut down on machining time. Some other designs would require up to 36 teeth. This would take a very long time to machine and even more time to do the windings. In addition as will be shown later the size of wire that was going to be used will be larger therefore the gaps between each tooth had to be quite large to accommodate for a reasonable amount of turns and wire size.

Next was the actual rotor design that had to be chosen. Rotor designs vary quite a lot. As seen in Figure 1.6 below, it can be observed how many different possibilities there are with this type of radial flux motor. Of all of these designs the easiest to manufacture are models A through C. These particular models offer the greatest flexibility as far as what type and size of magnets to use. Surface mounted permanent magnets can provide the greatest magnetic field because nothing is blocking the field path. In model F for example, the magnets are embedded inside the rotor which results in decreased magnetic field given by the magnets. Design A was chosen out of all of all of the different designs.

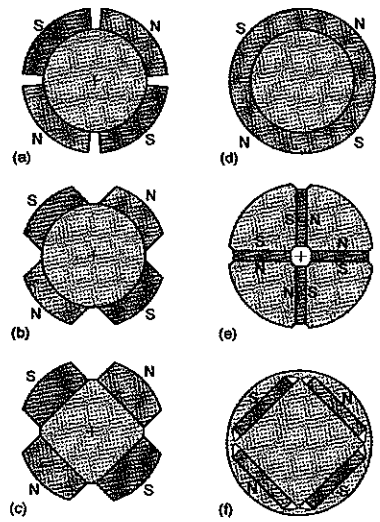

Figure 1.6: Possible Permanent Magnet Rotor designs [3]

Now that a general shape/design for the motor has been established the type of material going to be used needs to be found. Below in Figure 1.7 shows a magnetic field strength "H" vs. flux density "B" curves. Then in Figure 1.8, there is a list of materials and their material composition. The type of material used plays a key role in determining the maximum output power of the motor.

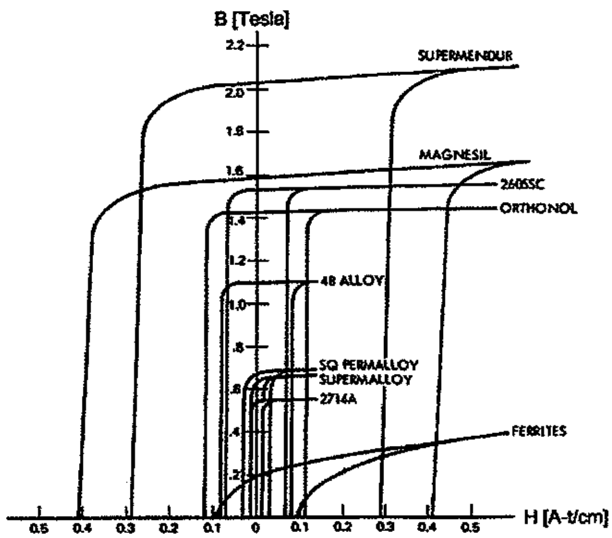

Figure 1.7: H vs. B graph [4]

Magnetic Core Material Characteristics

Trade Name	Composition	Saturated Flux Density* [T]	DC Coercive force, [AMP-Turn/cm]	Squareness Ratio B_r/B_s	Material Density** [g/cm^3]	Curie Temperature [°C]	Weight factor
Supermendur	49% Co						
	49% Fe	1.9-2.2	0.18-0.44	0.9-1.0	8.15	930	1.066
Permendur	2% V						
Magnesil	3% Si	1.5-1.8	0.5-0.75	0.75-0.85	7.63	750	1.00
Silectron	97% Fe						
Supersil							
Deltamax	50% Ni	1.4-1.6	0.125-0.25	0.94-1.0	8.24	500	1.079
Orthonol	50% Fe						
49 Sq Mu							
Allegheny 4750	48% Ni	1.15-1.4	0.062-0.187	0.80-0.92	8.19	480	1.073
48 Alloy	52% Fe						
Carpenter 49							
4-79 Permalloy	79% Ni	0.66-0.82	0.025-0.82	0.80-1.0	8.73	460	1.144
Sp Permalloy	17% Fe						
80 Sq Mu 79							
Supermalloy	78% Ni	0.65-0.82	0.0037-0.01	0.40-0.70	8.76	400	1.148
	17% Fe						
	5% Mo						
Ferrites							
F	Mn	0.45-0.50	0.25	0.30-0.50	4.8	250	0.629
N27	Zn						
3C8							

*Tesla = 10^4 Gauss
**g/cm^3 = 0.036 lb/in^3

Figure 1.8: Core Material Properties [4]

With these two figures an idea of what type of material needs to be used can be established. Remember as stated earlier with greater flux there is greater Magneto motive force, which essentially results in greater magnetic field strength. The goal is to maximize flux. In order to maximize flux, the more flux density is needed. Flux Density "B" is the amount of flux per unit area. In other words the greater the flux density the greater magnetic field can be generated inside the motor. The greater the magnetic field the stronger force the magnets have to be attracted or repelled. In Figure 1.7 it can be noted how the different materials can handle flux. Examining Figure 1.8 shows how materials with large amounts of Nickel "Ni" allow for greater flux density. What always needs to be kept in mind is the machinability and durability of the material being use. In addition, what also needs to be accounted for is the availability of these materials. Typically these materials are found in inductors, transformers and motors in prefabricated shapes. The design chosen requires these materials to be available in a round bar in large quantities. The material needs to be available in a round bar so the proper parts can be machined. All the types of materials listed in Figures 1.7 and 1.8 were not available in the dimensions or quantity that was desired. Typically these materials are shipped in large quantities to big manufacturers of transformers, motors, etc. In other words a material had to be found that was reasonably priced and could give the desired flux density.

Every material has a flux density limit. Meaning that when the material can not handle any more flux traveling through it the material has reached its saturation point. Observe the Figure 1.9 below to better understand saturation.

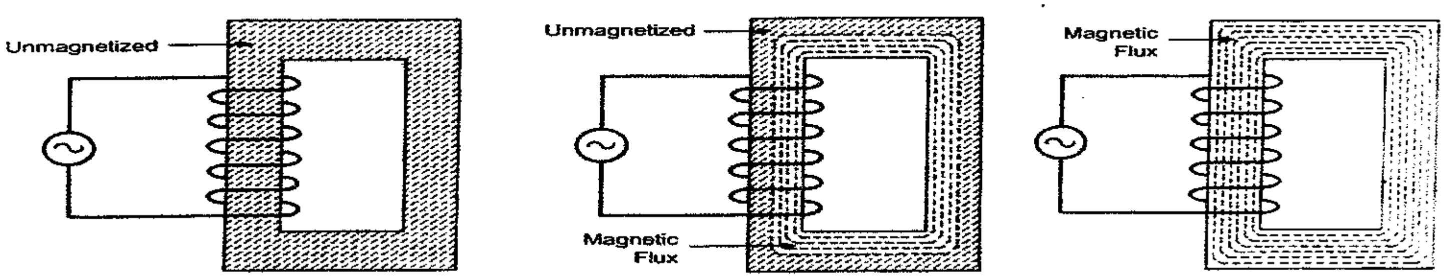

Figure 1.9: Core Saturation Example [4]

When the core is "Unmagnetized" as shown to the left there is not current traveling through the coil. The middle picture shows what the material looks like when there is a specified current through the coil. The current through the coil creates a magnetic field which then magnetizes the core which creates flux. Let's say just as an example the middle figure has a current of three amps running though the coil. Then at right figure that current is increased to six amps. The right figure shows that the material is handling the maximum amount of flux it can handle at six amps. The magneto motive force is at a maximum because flux is at a maximum. Flux is at a maximum because flux density is at a maximum. This core is now in saturation. Even if current through the coil where to be increased to nine amps, flux through the core would remain the same. Since flux remains the same so does the Magneto motive force. In light of these facts a 4340 alloy steel with the material list shown in Appendices D was chosen for the stator material. This alloy steel was available in multiple bar sizes and contained some nickel content in it as desired. Max flux density through this material was estimated at a rating between .05 to .1 Teslas. This is far below what normal materials are made out of but given the cost and the availability of the material it was one of the only options. The next step was to determine the size of the motor which was determined through various equations.

Using the variables shown in Figure 1.1 the following equations where used to determine various sizes and values. Figure 1.10 below shows the bulk of equations used.

$$B = \mu H$$

1. Used to find Flux Density (H is Field Intensity)

$$F = \phi R$$

2. As Shown Earlier

$$T = kD^2 L$$

3. T is equal to torque, D is Diameter and L is Length, k is a motor Constant

$$R \equiv \frac{1}{P} = \frac{l}{\mu A}$$

4. R is equal to reluctance and A is area

$$P_e = k_e h^2 f^2 B^2$$

5. P is power, f is frequency and k is the motor constant

$$\phi = \frac{Ni}{R}$$

6. Equation to find flux

$$B_m = B_r + \mu_R \mu_o H_m$$

7. Bm is Flux density of the magnet, Br is Flux density of rotor

$$\phi = B_m A_m = B_r A_m + \mu_R \mu_o A_m H_m$$

8. Flux of the permanent magnets

$$\lambda = \frac{N^2}{R} i$$

9. Equation to find Flux Linkage of the coil

$$e = \frac{d(Li)}{dt} = L\frac{di}{dt} + i\frac{dL}{dt}$$

10. Induced voltage

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} - \frac{1}{2}\phi^2 \frac{dR}{d\theta} + Ni\frac{d\phi}{d\theta}$$

11. More accurate equation to solve for torque

$$L_g = \frac{2\pi\mu_o L_{st} R_{ro}}{g + \frac{l_m}{\mu_R C_\phi}} N^2$$

12. Inductance for Air gap

$$K_m = \frac{2NB_g L_{st} R_{ro} I}{\sqrt{I^2 (2R_{slot})}} = \frac{2NB_g L_{st} R_{ro}}{\sqrt{2\rho L_{st} N / A_{wb}}} = \frac{B_g R_{ro}}{\sqrt{\rho}} \sqrt{V_{wb}}$$

13. Motor constant K used in various other equations such as the Torque equation

$$T_{cog} = -\frac{1}{2}\phi^2 \frac{dR}{d\theta}$$

14. Cogging torque

Figure 1.10: Equations used to determine motor ratings and dimensions [3]

Instead of going through all of the derivations and calculations of each equation it would be better to understand the factors that influence the output power of the motor. Ultimately through the calculations of using the above equations the motors dimensions were found and can be found in Appendices A.

Several other factors needed to be accounted for before any construction of the motor could be started. First is Fringing effect. As shown in the Figure 1.11 below the effect can be better explained.

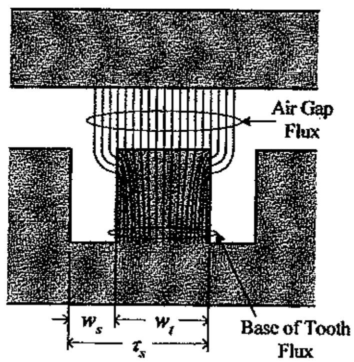

Figure 1.11: Fringing Effect [4]

When flux leaves the core material and flows through air there are a lot of loses. When flux travels through the material core it is compressed and losses are reduced. However when flux is introduced to air it is diluted due to a factor called fringing effect. As shown in Figure 1.11 when flux leaves the stator and move through air to the rotor, moving from bottom to top, some flux will spread. This reduction in flux density results in less physical force on the rotor. This is avoided by keeping the air gap between the stator and the rotor at a minimum. Professionally made motors have an air gap of less than 1 mm. The closer the rotor is to the stator the more power can be achieved. For this particular project an air gap 1-4 mm would be acceptable. This particular factor is completely dependent upon how well the motor is machined.

Eddy currents are another factor of loss in the motor. Eddy currents are the result of induced voltage cause by an alternating magnetic field which results in induced currents called Eddy Current in the core or in this motor design the stator. Observe Figure 1.12 below to see how Eddy currents can be reduced.

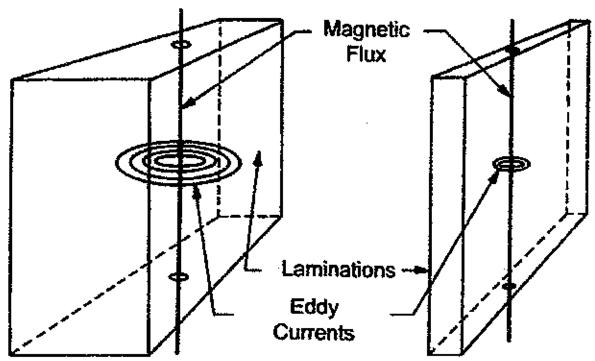

Figure 1.12: Eddy Current Example [4]

As can be seen Eddy currents are reduced by slicing that larger core into many smaller slices. Eddy Current cause heat loss which essential take away from the possible output power of the motor. By using laminated slices the motor reduces Eddy Currents which reduce heat loss, which increase possible output power. With these laminations the thinner they are the better. Again due to machining capabilities the smallest slices that could be machined were a quarter of an inch thick. Typically professionally made motors have laminations that are no more than half of a millimeter thick. With this project, the laminations were going to be a quarter of an inch thick. Losses would still be high but still be slightly reduced due the laminations. Laminations are normally put together by some sort of adhesive or are bolted together. The laminations in professional motors are separated by a very thin layer of steel so the core material doesn't touch each other which would inherently defeat the purpose of the laminations if they did touch each other. To prevent the laminations from touching each other in this design it was decided to use a material called Kapton's tape. This is a special type of tape that is an insulator that is typically used in circuit boards however this particular type of tape would serve the purpose of separating the laminations apart from each other. The laminations would be taped in Kapton's tape and put together using an epoxy.

Two more factors still remain, the type of magnets and the size of the wire being used. Motors can be made using any type of magnet, either that be the less powerful ferrite magnets or the more powerful neodymium magnets. Given that the stator material that was going to be used would experience very heavy losses as well as decreased magnet field, a stronger magnet would need to be used to account for all of the losses. To meet this demand neodymium arc magnets where used with an N50 rating. The N in the N50 rating means neodymium. The number following the N is the grade of neodymium used. Currently the highest rating is N52. The N50 magnets that were going to be used would be sufficient enough. They have an output power of about 1000 gauss in the center of the magnet which equates to 0.1 Tesla. This would be adequate given that my stator cannot output any more than 0.1 Tesla's given the stator material.

The last factor that needs to be accounted for is the size of the wire. For this particular motor, given that the windings would be done by hand, it was preferable to do a thicker gauge wire so more current could flow at the cost of less turns. The type of motor controller that was going to be used could output up to twelve amps at thirty six volts. Taking into account the amount of room that would be available between the teeth, a wire gauge size twenty three with a fussing current rating of thirty five amps, which is more than will ever be put through the motor, was used. The amount of turns would be maximized given space for the wire which was estimated at twenty turns leaving a fill factor of about 80%.

Ultimately that was it. The motor took a very long time to design. The biggest factors that limited the motor were cost and how the motor would be machined. There are other factors that influence the motor such as magnets not having the same Tesla levels across their whole surface. The strongest levels only being in the middle of the magnet. There are other factors such as proximity effect with layered wires which also influence motor losses. However the topics that have been discussed are the main influences of losses and how the motor works. The other more minimal influences were not given that much attention to during the design although they do have some effect.

The ratings of the motor ended up being designed to be a quarter horsepower, twenty four volt, three to four amp motor. Meaning at three to four amps a quarter horse power should be able to be achieved. Again all of these ratings are dependent upon how well the motor is machined and how the stator material reacts to flux.

Development and Construction:

Developments and Construction of this project was by far the most difficult and time consuming portion of the build. This project was built by using various machines and tools to machine the 4340 steel into the desired parts required. One factor that has to be accounted for is what can be done given the machines capability. Some design features had to be changed due to the limitations of the machines. In addition to these limitations there is also a factor of error involved in the finished parts which proved to be detrimental to some testing required in the end. Before any machining was to begin more research had to be done to be sure that the required design was possible.

When machining metals, these metals either machine well, machine ok, or are bad to machine. What this means is how hard or how tough the metal is. For example, aluminum is a very light weight and soft metal. Aluminum can be machined very well due to the fact that it can be cut, chip or drilled easily by hand or by machine. Steel is a much harder and tougher material than aluminum. With steel it is very difficult to cut, chip or drill through. When something is difficult to machine what is meant is that the cutting tool used to machine the steel cannot handle deep cuts very fast. For example if a bar of aluminum needed to be shorted in it's diameter, a lathe with a carbide bit would turn (reduce the diameter) of the bar down to the desired diameter. Carbide is an extremely hard material that is harder than aluminum and steel. Because it is so hard it can cut through steel and aluminum. When cutting a bar of aluminum, each pass can take off on average up to 0.15 of an inch depending on what speed the lathe is rotating the bar and what speed your are cutting the bar. Observe Figure 2.0 below to see how the lathe is set up.

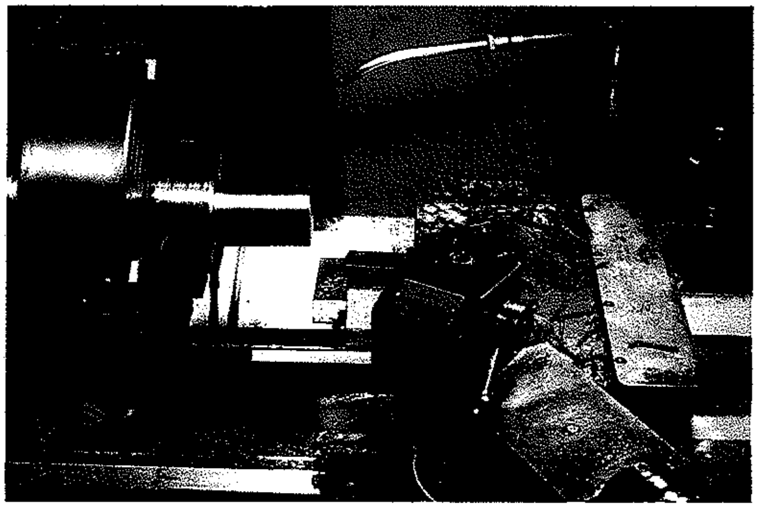

Figure 2.0: (Chuck on the Left, Cutting Tool Inserted in Middle Tool Holder)

This may not seem like a lot. However take into account that in seven passes the bar has been reduced in diameter by more than one whole inch. This will take you no more than twenty to twenty five minutes to turn down that whole inch of metal. When you compare this to a much harder material such as steel things are drastically different. Where as with aluminum you can take off about 0.15" per pass with steel you can only take off on average about 0.025". Even at this depth of cut the carbide cutting bits wear down relatively fast. When these bits wear down they do not cut well and sometimes jam the bar being cut. When the bar gets jammed the parts shifts on the chuck, therefore the part has to be reset and aligned properly again. During machining of the steel this happened consistently. Brand new carbide bits were being broken and the steel had to be reset on the chuck all the time because the part would constantly jam in the lathe. Taking into account setup time and with the carbide bits constantly breaking, along with the part (steel bar) constantly getting jammed in the lathe over 60 hours were spent just getting the parts turned down to the right diameter. This does not include time spent on cutting the steel with the band saw, or making the rotor with the end mill or machining the individual stator slices with the CNC mill.

The machining of the rotor took about 10 hours to do on the end mill. End mills are very different machines compared to lathes. Please observe Figure 2.1 below and examine how the end mill is setup.

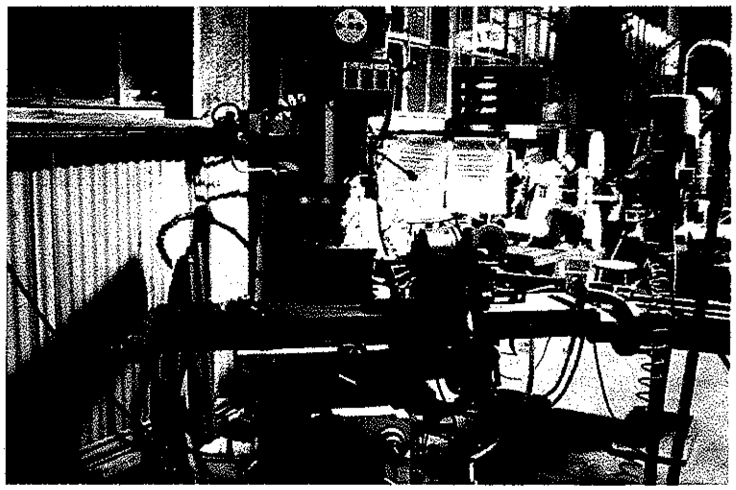

Figure 2.1: (Cutting tool in drill chuck)

Using the end mill to cut the grooves in the rotor went rather well. With the exception of the grooves being slightly off set from each other the rotor turned out nicely. The only difficulty being that setup for the mill took a lot longer than setup for the lathe. Reason being that the groves in the rotor had to be machined with a lot of accuracy and extra attention had to be taken for exact measurements.

The CNC mill is very similar to an end Mill. The only difference being that the CNC mill is computerized and makes the cuts automatically where as the end mill is all done by hand. The CNC mill was used to make the individual stator slices. After the bar of steel was turned down to its proper diameter and the inside diameter was drilled and bored out, the bar was cut into twelve different slices for the stator. Reasons for this were explained previously. With these twelve different disks the CNC machine was going to cut out all of the different teeth in each disk. However in order for this CNC machine to work it has to be programmed what to cut. This is done by using a program called Solid Works. Solid works is a 3D animation program that simulates the desired shape and cuts the CNC mill will perform. A good 14 hours was spent programming in Solid Works to program the CNC mill. Once the program was complete the CNC mill did the rest of the work. After about an hour and half of setup time the CNC mill just follows the Solid Works simulation and cuts out the desired shape. Please observe Figure 2.2 below to see the final shape.

Figure 2.2: (Stator Laminations after CNC mill)

All twelve pieces took about seven hours to cut with the machine. After each part was completed they were polished and removed of all sharp edges.

The end caps which hold the entire motor together can be observed in Appendices A. These end caps hold the bearings for the rotor and hold the stator in the center. The end caps were very straight forward to make, using the lathe to cut the steel each was made carefully and slowly. The only issues that occurred were just carbide bits breaking as usual and just having to take a long time to cut the steel. Ultimately both end caps were made and fit both the stator and the rotor perfectly.

Other miscellaneous parts were made such as the rotor extensions. These were made for two separate reasons. The longer extension observed in Figure 2.3 below, was used for the Hall Effect sensors needed for the control board.

Figure 2.3: (Displays one rotor extension, Rotor on top, Extension on bottom)

The Hall Effect sensors are used to indicate the location of the rotor so the control board can determine which phase of the motor to activate. Hall Effect sensors are activated using the South Pole of magnets. When in the presence of a South Pole they output a low voltage signal to the controller. The extension had magnets epoxied to it in a particular order. The other extension was used for accessories. You could attach this other side to anything from a fan to a wheel. Whatever the motor needed to turn this would be where it is connected. These parts did not take long to make. They both, combined, took a total of four hours to make on the lathe. There were no real issues or problem associated with these parts.

Lastly, since all of the parts were done being machined it was time for final assembly. First and foremost the stator had to be built. In order to reduce eddy current as explained under the design section the stator would be made out of the twelve slices one quarter inch thick. The original design called for much thinner slices however due to manufacturing limitations the thinnest the slices could be were one quarter inch. Before the slices were epoxied together they were layered in a non conductive tape called kaptons tape. This tape is typically used for circuit board to prevent contacts from touching each other. This tape was in fact a perfect insulator between each stator slice which reduced eddy currents. The main goal was to make sure that the stator was straight and all of the slices were aligned correctly. Please view the Figure 2.4 to see stator.

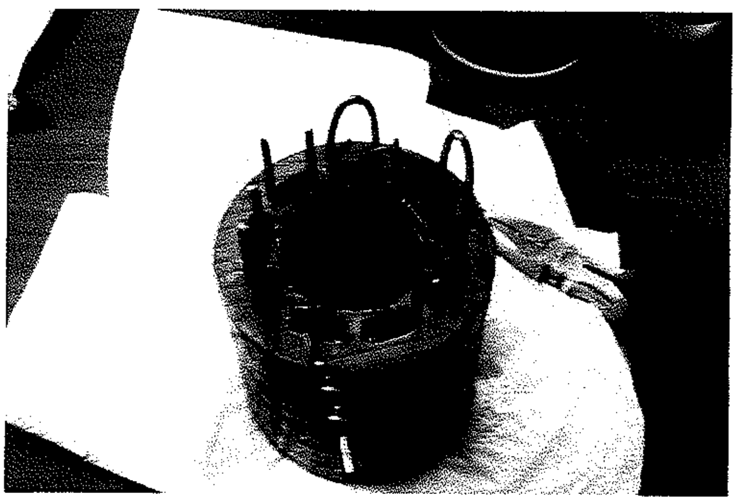

Figure 2.4: (Stator assembly, used epoxy and clothes hanger for alignment)

To align the slices correctly flexible clothes hangers were used and fit inside each tooth. Each layer was then epoxied to each other to make the complete stator. After a full day of drying, the stator was finished and ready to be wound.

The windings for the stator proved to be much more difficult than anticipated. The windings are key to the success of the motor. If any shorts in the windings are present then the motor will not be able to run. Winding the rotor took a lot of time, 9 hours for the whole motor. Typically manufactures of motors have machines that wind the stators of the motor automatically. However in my case, since this is a custom design there would be not chance to have a machine wind the stator. Winding was very tedious, I choose the amount of turns based on fill factor and how many turns the stator teeth could handle as explained previously. The process was slow and arduous but was eventually completed despite drawbacks. As will be explained later, errors were encounter when the motor was initially wound.

Lastly the magnets had to be attached to the rotor. By themselves the magnets would stick to the rotor however when the stator would be magnetized the magnets would shift and possibly crack due to the magnetization force from the stator. Using epoxy again the rotor magnets were arranged by North and South poles accordingly. After this final assembly of the rotor the motor was ready to be tested.

The concepts behind electric motors are fairly simple to understand. However to implementing these concepts into a working design proved to be far more difficult than ever anticipated.

TESTING:

Once the motor was finally built and assembled it was time to see if the motor would run. First and foremost because the motor would use an electronic controller, the operation of the controller and its various capabilities were tested. The controller came in a design kit which included a small three phase, brushless, DC motor. With this motor the operation of the controller was mastered through various tests at different settings.

This particular Texas Instruments, Stellaris BLDC motor controller has three main settings. These settings are based upon the input received from the Hall Effect sensors. Remember the purpose of these Hall Effect sensors is to monitor the position of the rotor so the controller can turn on which ever phase is necessary. The settings are for either a sinusoidal wave input or a trapezoidal waveform. The type of Hall Effect sensors utilized us a trapezoidal waveform output which would be an input to the controller. Hence the sinusoidal setting was never used. Lastly there is one more setting. If sensor less mode is selected the controller ignores any input from the Hall Effect sensors. In this setting the user defines starting bus voltage, ending bus voltage, desired RPM and the time the motor will take to reach up to that max RPM. In other words the controller automatically changes the phases on the motor in a forward or reverse fashion. Ideally the motor should work in the trapezoidal setting so both speed and voltage can be adjusted accordingly. As shown in the design portion section, the motor was built to run off of 24 volts at or around anywhere between three to six amps.

First initial tests resulted in failure. Adjusting the motor for various voltages and speeds, as well as testing in both trapezoidal and sensor less settings, the motor only turned about an eighth of a turn. This was occurring with a 24 volts bus voltage at half of an amp. Two concerns had to be addressed. First and foremost, is there a short in one of the phases of the motor? If there is a short this could account for such a low current draw from the motor. After about eight hours of testing nothing was working. The next day the motor was taken apart and examined.

After testing for shorts in the motor as it turned out there were multiple phase to phase shorts in the stator. This was possible because during the initial windings of the stator it was noted that each phase windings were rubbing up against each other. In other words phase A windings were rubbing up against phase B windings. There was the problem. Shorts between phases result in catastrophic failure of the motor. When there is a phase to phase short the motor is no longer a three phase but two phase motor. Even if just one phase was shorted the rotor would stick at that phase. With a single phase short the flux density through the core drops greatly. With extremely low flux density there is minimum magnetic field around the rotor which in turn doesn't allow the rotor to rotate. The stator was then rewound with extra care. While taking off the old windings the tares in the wire laminations although very small were visible. It was apparent why the shorts had occurred. The second time the windings were wound extra caution was taken. In addition to reduce phase to phase shorts less turns were used as well. Originally 18 turns were calculated and used and that was reduced to 10 turns. After another 6 hours of winding the stator was complete.

Test two again resulted in failure. The stator had been checked and rechecked for shorts and all was ok. However the same problem occurred. The rotor shifted only about a quarter of a turn. This was again at 24 volts and the motor would only draw about half of an amp according to the controller. After many of hours of trouble shooting an outside source of help had to be sought. Going to the TI website and posting a blog about the issue, a TI representative listed some possible issues. Of all of the possible issues mentioned only one stood out. The TI representative had asked if the power supply to the controller was sufficient enough for the motor. The power supply that was currently being used was just the stock supply for the controller. This supply was rated at 24 volts at .75 amps. Here was the big problem. The motor was given enough voltage but was being limited by the supply current. This was a silly mistake that should have been addressed before testing. Now the only trick was to find a power supply that would meet the 24 volt and three to six amp requirements.

After a few days of testing with various supplies and sources a desktop computer power supply rated at 12 volts at 8 amps was found. Although the voltage was half of what the motor was designed for, current was the key. What ever voltage the supply was not supplying could be made up with a higher current through the wire. With this supply lots of testing and adjustments took place. Then finally the motor was working. Using the sensor less setting on the controller the motor was successfully rotating at about 200 to 350 RPM. Success had finally been achieved.

There are a couple things that need to be noted about the motor. As stated earlier a huge portion of this project was the manufacturing of the motor. On big concern prior to testing the motor was whether or not the rotor was machined well enough so that when the rotor spins vibrations would be minimal and rotation would be smooth. This was accomplished for one side of the rotor. The rotor extension with the magnets on it runs smoothly with little vibrations. However the rotor extension on the other side is fairly rough and wobbly. This is attributed to the fact that when the rotor was being threaded on that side the threads were set at an angle. This was unintentional but sometimes happens during machining.

Although the motor was running there were other issues. The motor only works under this sensor less setting. The unfortunate fact is that under this setting there is a time limit as to how long the motor can run for. The maximum amount of time is about thirty seconds then the motor shuts down. The sensor less setting is meant to gradually increase the speed of the motor. It slowly increases voltage and gives the motor a chance to rotate. After the motor reaches its final voltage as set by the user, the motor should continue to spin at that speed and can then be adjusted to other speeds. However once the motor reaches this user set voltage the motor shuts down. The motor shuts off because of a controller error. The controller registers a "Watchdog" error. This error means that the controller is shutting down the motor because the motor is not rotating. However this is not true given that the motor is rotating but the controller doesn't think it is. The controller does not recognize any current being drawn by the motor. This was very confusing because when testing with other power sources the motor would draw up to eight amps as indicated by the source. This is the reason why the trapezoidal setting doesn't work. Since according to the controller the motor is not drawing any current then the motor must not be rotating.

This is the biggest issue with the motor. The controller has so many safety features on it to protect itself from burning itself out that it doesn't give the motor a chance to work. Under the trapezoidal setting if the controller doesn't recognize that the motor is drawing any current then the controller thinks something is wrong and will shutdown. Under the sensor less setting the controller pays not attention to what current the motor is drawing until the user set voltage is reached. Once the user set voltage is reached the controller examines whether or not the motor is running by examining the current draw, and if there is no current draw then the motor is shutdown. After lots of trouble shooting to figure out a way to disable the safety features on the controller the same results occurred.

Actual output of the motor was difficult to measure given that the controller doesn't measure what it is outputting and connecting other devices to the motor given the wobbling rotor connection made output testing very difficult. However Figures 3.0 – 3.3 below show various output measurements. Keep in mind that the speed measurements are some what estimated given the rotor was machined out of alignment and was difficult to measure speed accurately. Accounting for losses it was estimated that the actual horse power of the motor was 0.15. All of the data from the graphs below were taken using a Hewlett Packard, 6574A, DC power supply. The ratings on the supply are as follows: 0-60 V, 0-35 A. The test was done while the controller was in a sensor less setting. The controller was set to speed up the motor form 0 RPM to 520 RPM over the course of thirty seconds. The DC bus voltage of the motor would be set to 30V with a current limit set at 8 amps.

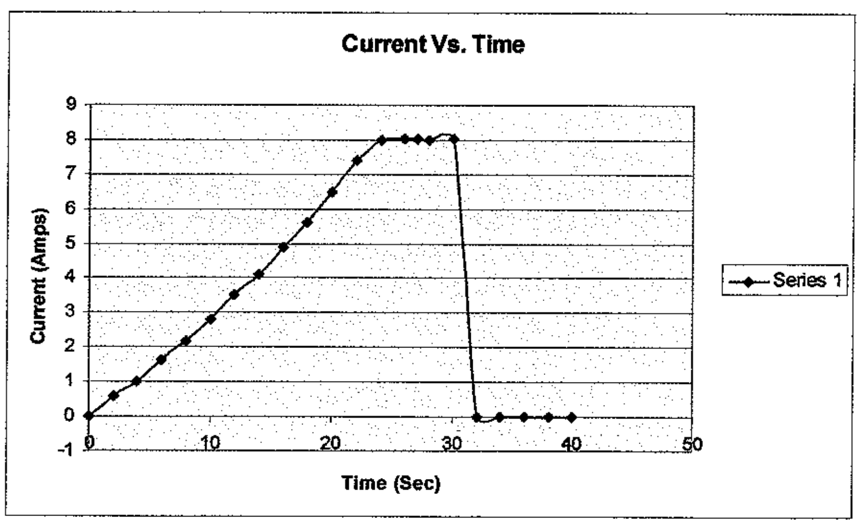

Figure 3.0: Current Vs. Time

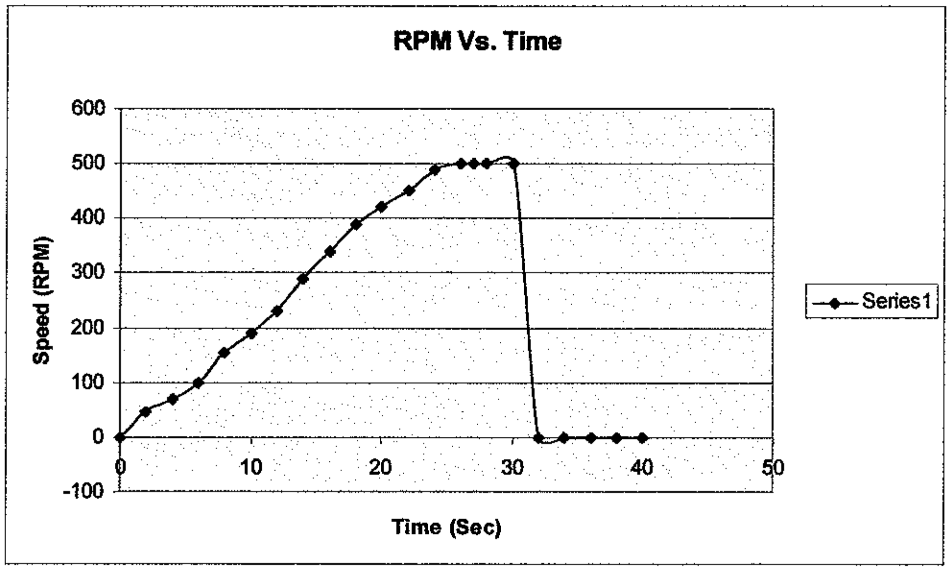

Figure 3.1: RPM Vs. Time

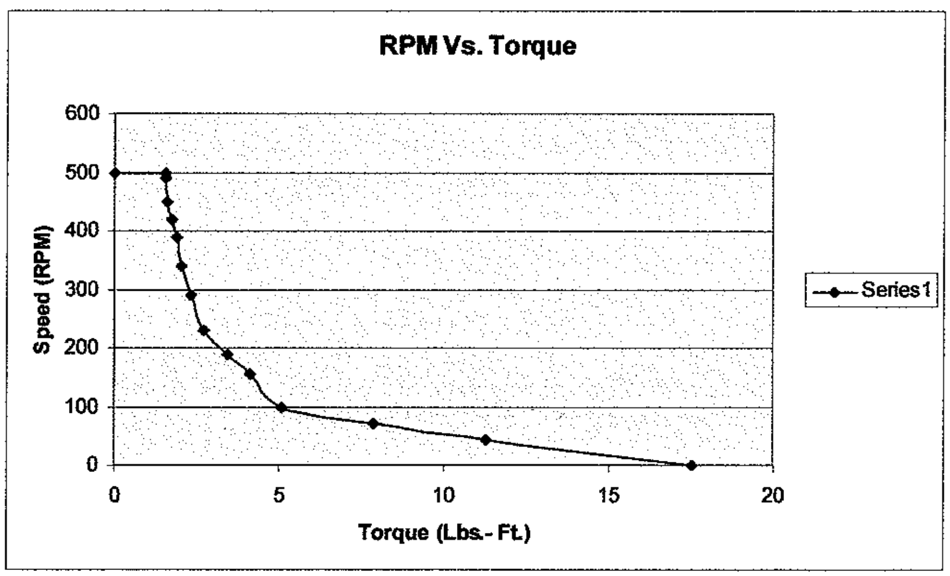

Figure 3.2: RPM Vs. Torque

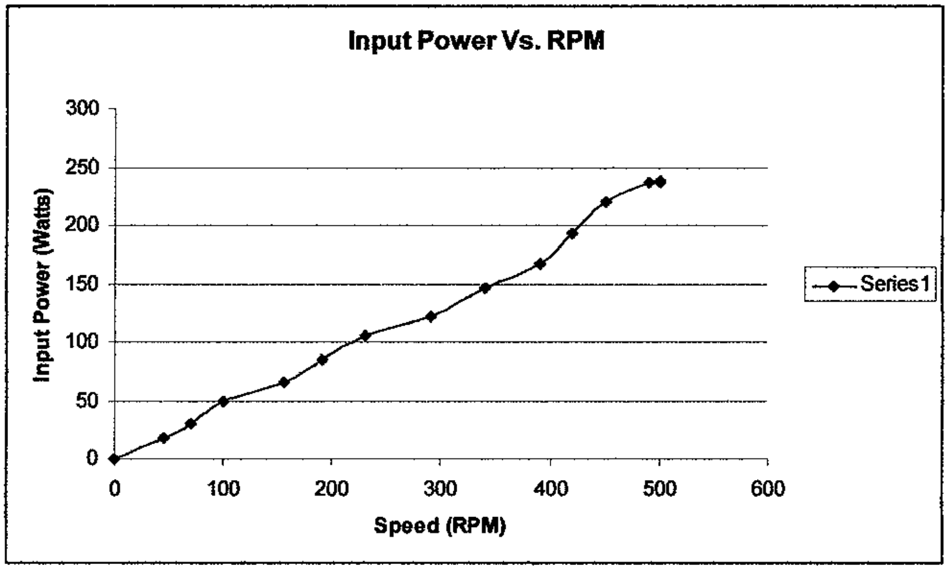

Figure 3.3: Input Power Vs. RPM

Conclusion and Recommendations:

Ultimately the complete engineering process of designing and building a permanent magnet BLDC motor was completed and resulted in a success. Although output of the motor was not what the motor was designed for, the fact that the motor ran shows a solid understanding of how an electric motor works. Also just as with many engineering projects the whole design took twice as long to build at four times the price. Despite these facts the project was well worth it and helped me understand what the entire engineering process is about and just how difficult it can be.

The most disappointing portion of this project was that the controller not functioning properly. The motor was not driven to its full potential due to the limitations of the controller. Looking back, despite what hardships may have been encountered when using a brushed system it may have been the better choice. Using a brushed system would have gotten rid all of the "Safety Features" of an electronic controller. In a different kind of way it would have allowed more freedom as far as input power.

Despite the issues with the controller, just as with any project there were plenty of difficulties and frustrations. However in the end it worked which was by far the most satisfying part of this project. The motor was at least designed well enough to work to some extent if not to its designed full extent.

To any future persons who would attempt any sort of project like this I would say, plan to spend lots and lots of time both troubleshooting and designing. In addition be prepared to spend a lot more money than anticipated. However the reward for a successful design will far out weight any hardships encountered during the process.

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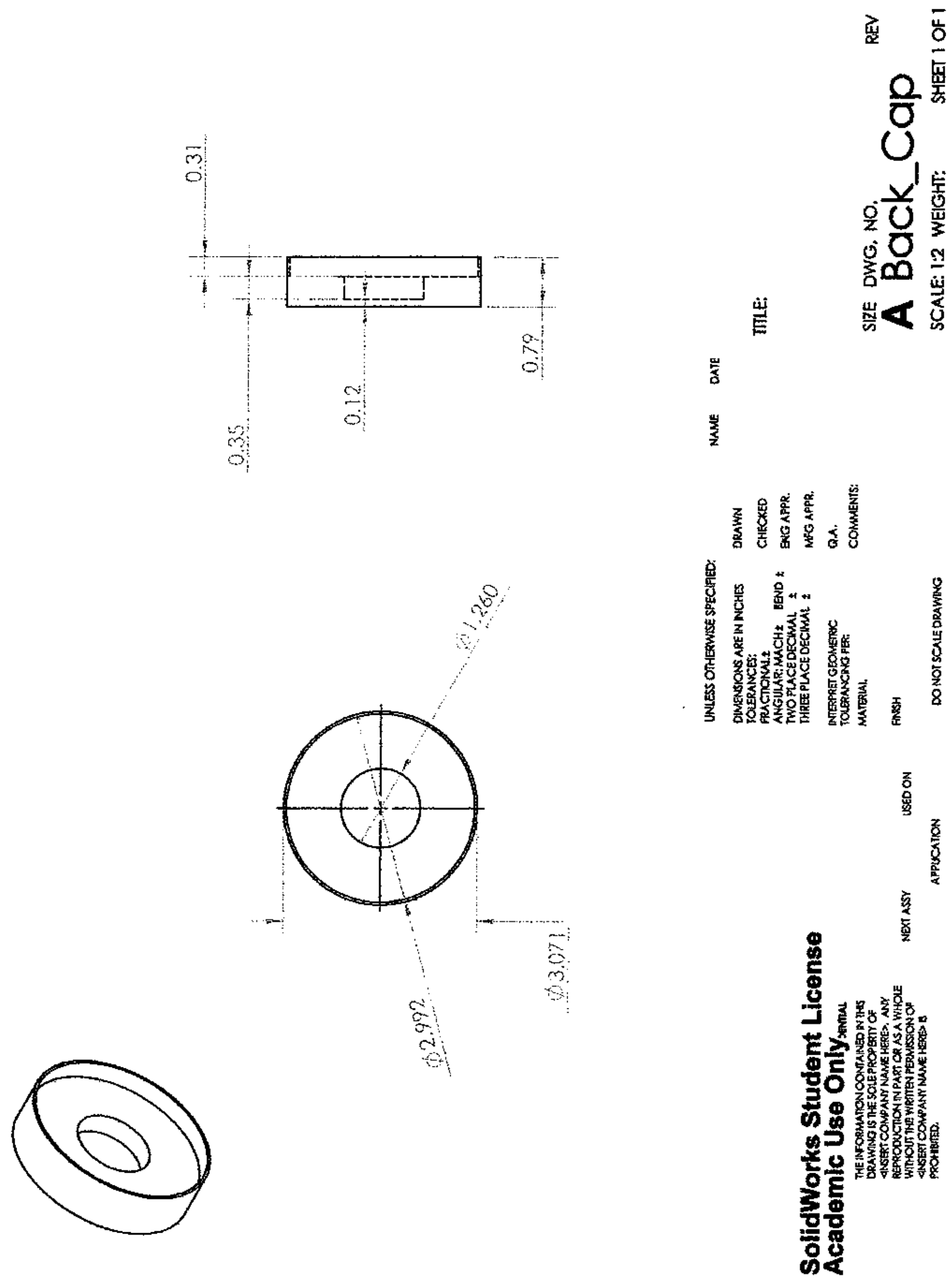
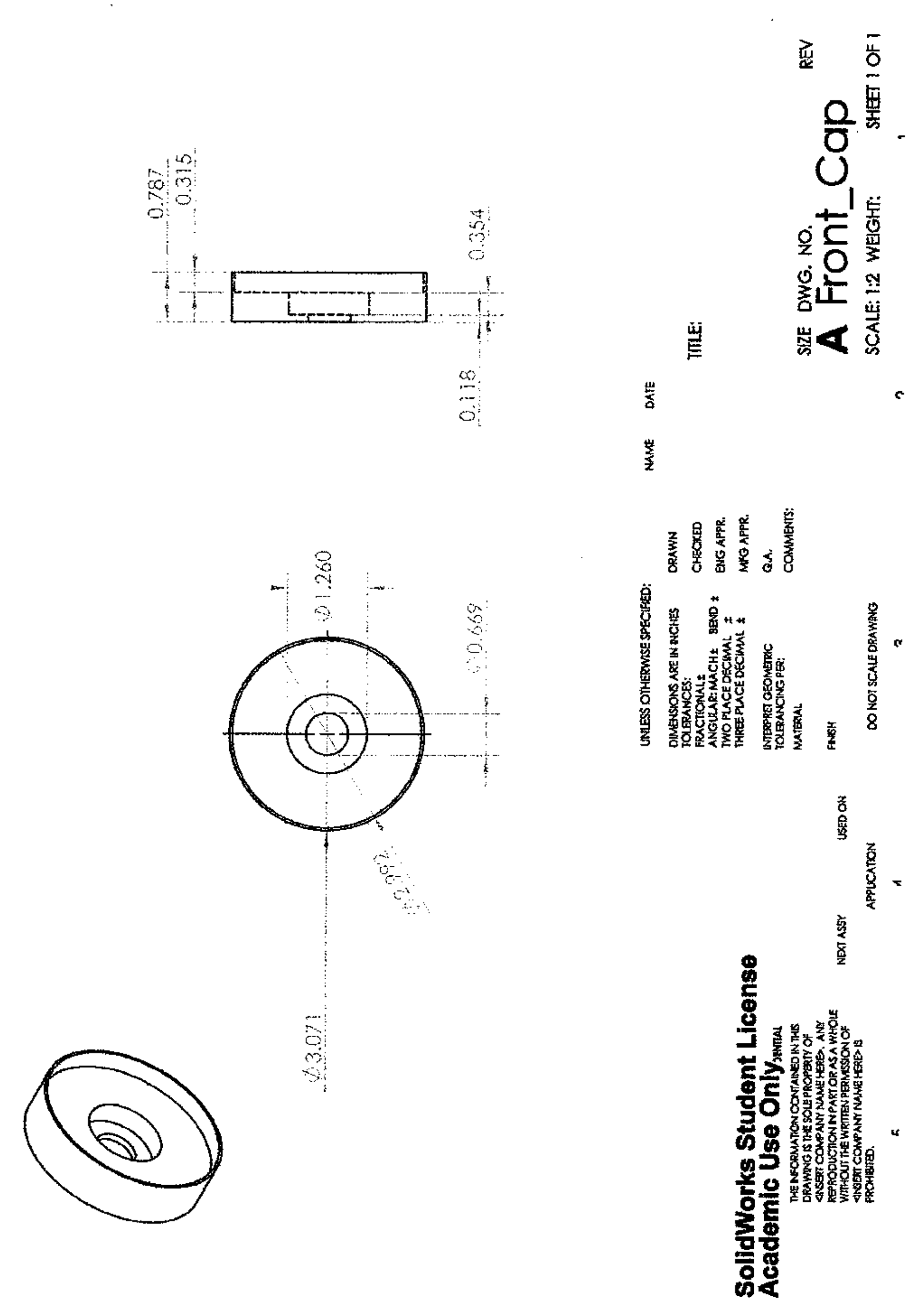
APPENDECIES A:

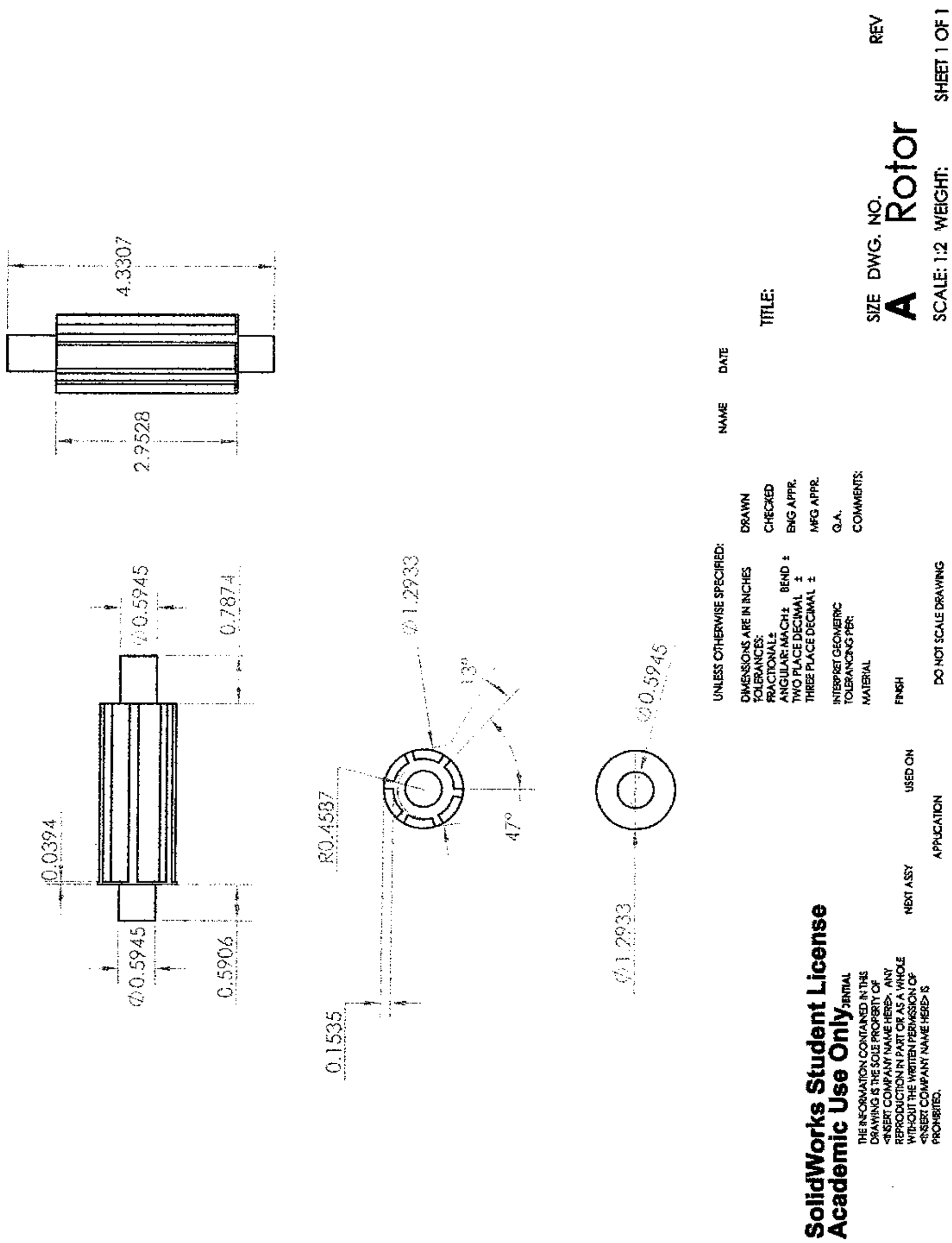
Details of Back End Cap:



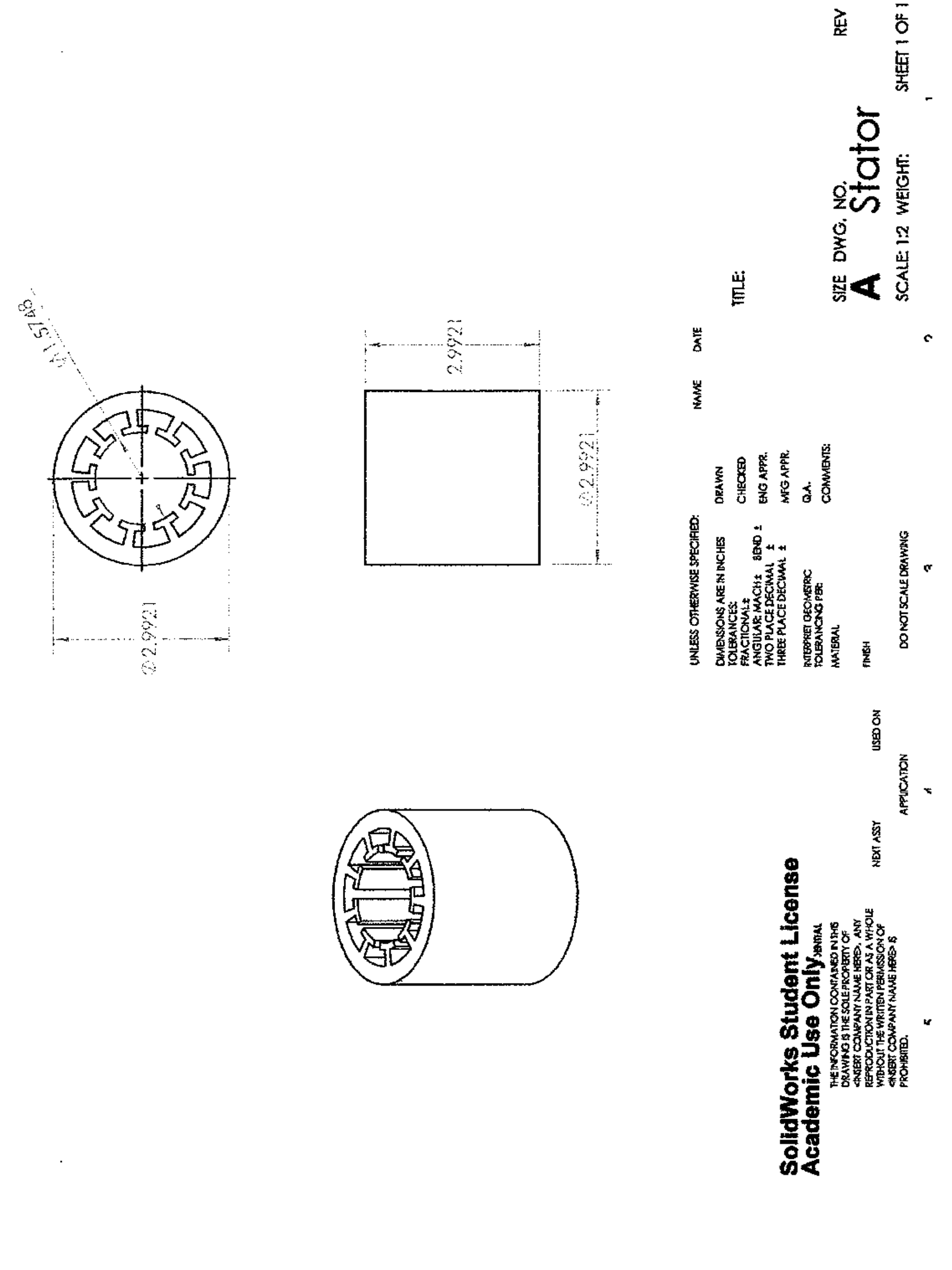
Details of Front End Cap:



Details of Rotor:

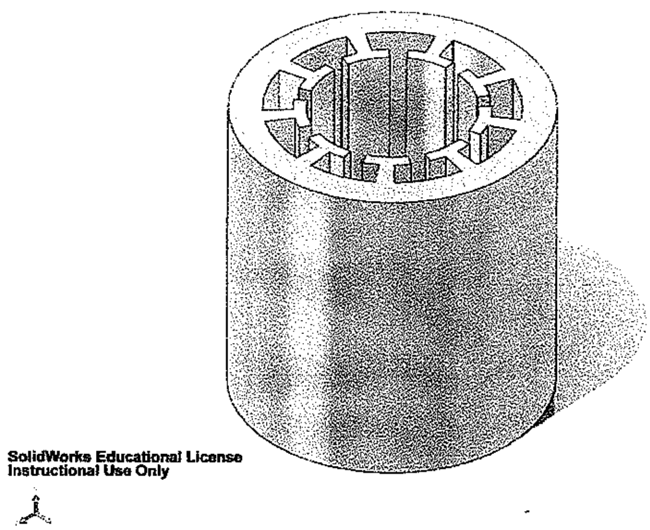


Details of Stator:

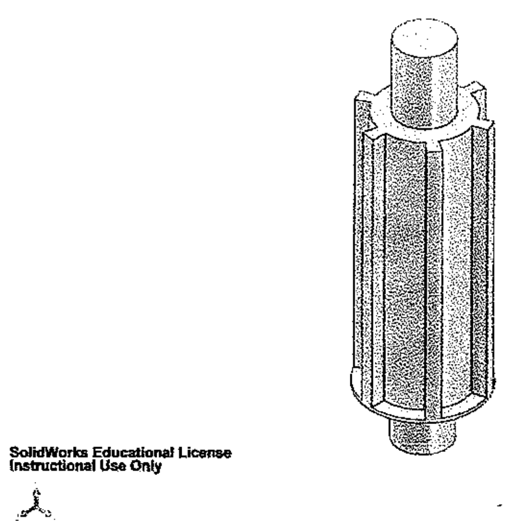


APPENDECIES B:

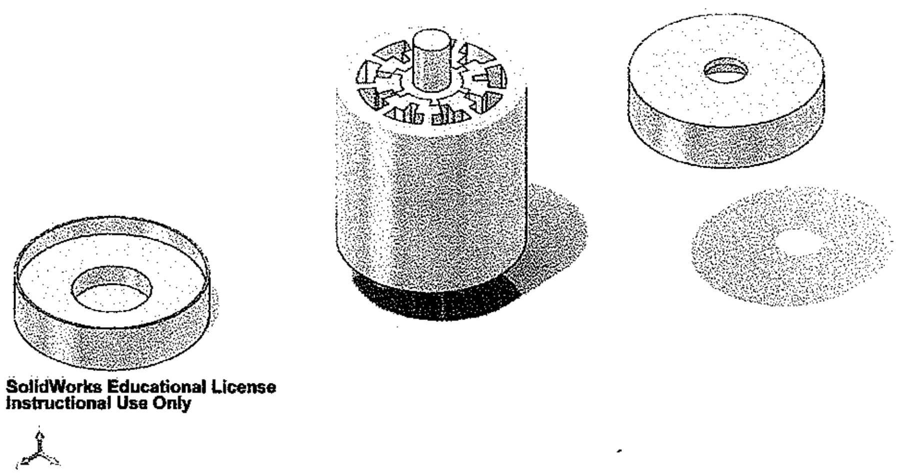
3D Model of Stator:



3D Model of Rotor:

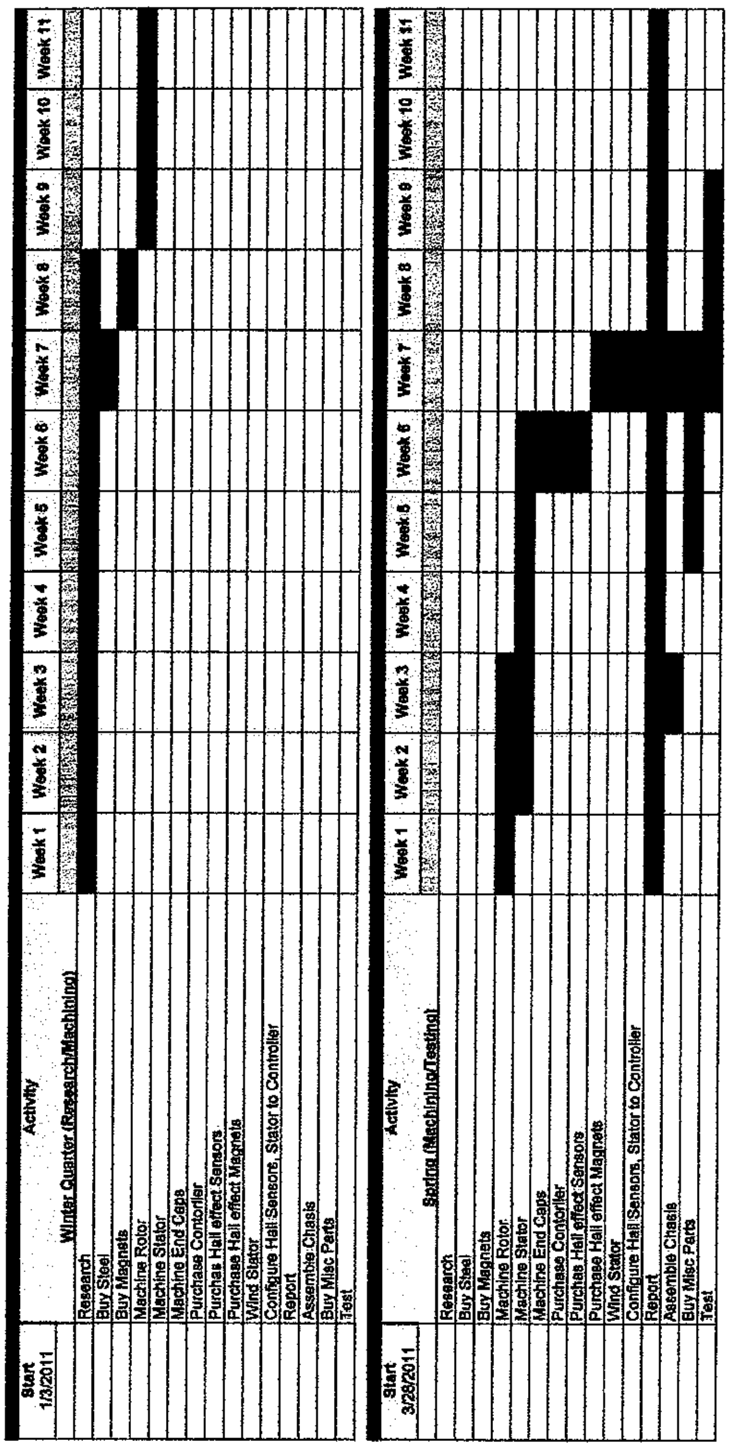


3D Model of Full Assembly:



APPENDECIES C:

Time Schedule:



Total Hours Worked	Research	Machining	Building	Testing	Report	Total
	40 Hrs	82 Hrs	18 Hrs	24 Hrs	22 Hrs	186 Hrs

APPENDECIES D:

Material Data Sheet [5]:

AISI 4340 Steel, normalized, 100 mm (4 in.) round

Categories: Metal; Ferrous Metal; Alloy Steel; AISI 4000 Series Steel; Low Alloy Steel; Carbon Steel; Medium Carbon Steel

Material Notes: AISI 4340 has a favorable response to heat treatment (usually oil quenching followed by tempering) and exhibits a good combination of ductility and strength when treated thusly. Uses include piston pins, bearings, ordnance, gears, dies, and pressure vessels.

Key Words: alloy steels, UNS G43400, AMS 5331, AMS 6359, AMS 6414, AMS 6415, ASTM A322, ASTM A331, ASTM A505, ASTM A519, ASTM A547, ASTM A646, MIL SPEC MIL-S-16974, B.S. 817 M 40 (UK), SAE J404, SAE J412, SAE J770, DIN 1.6565, JIS SNCM 8, IS 1570 40Ni2Cr1Mo28, IS 1570 40NiCr1Mo15

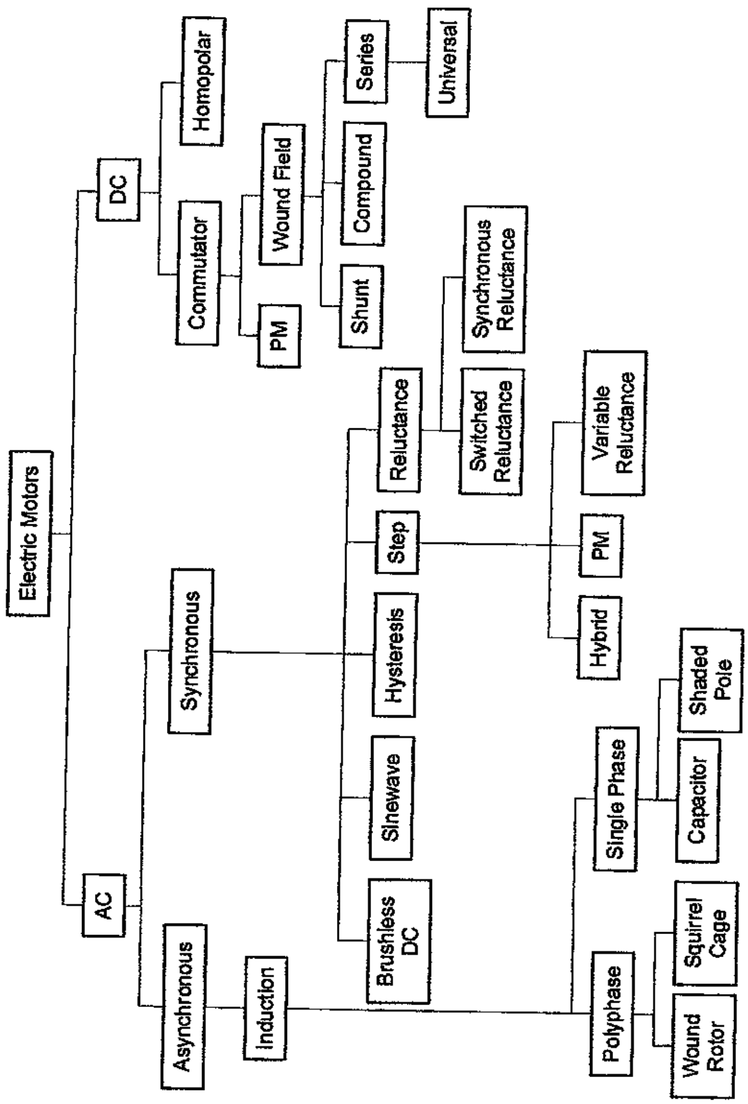
Vendors: Click here to view all available suppliers for this material.

Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	7.85 g/cc	0.284 lb/in³	
Mechanical Properties	**Metric**	**English**	**Comments**
Hardness, Brinell	321	321	
Hardness, Knoop	348	348	Converted from Brinell hardness.
Hardness, Rockwell B	99	99	Converted from Brinell hardness.
Hardness, Rockwell C	35	35	Converted from Brinell hardness.
Hardness, Vickers	339	339	Converted from Brinell hardness.
Tensile Strength, Ultimate	1110 MPa	161000 psi	
Tensile Strength, Yield	710 MPa	103000 psi	
Elongation at Break	13.2 %	13.2 %	
Reduction of Area	36.0 %	36.0 %	
Modulus of Elasticity	205 GPa	29700 ksi	Typical for steel
Bulk Modulus	140 GPa	20300 ksi	Typical for steel.
Poissons Ratio	0.290	0.290	Calculated
Machinability	50 %	50 %	annealed and cold drawn. Based on 100% machinability for AISI 1212 steel.
Shear Modulus	80.0 GPa	11600 ksi	Typical for steel.
Electrical Properties	**Metric**	**English**	**Comments**
Electrical Resistivity	0.0000248 ohm-cm	0.0000248 ohm-cm	20°C (68°F)
	0.0000298 ohm-cm	0.0000298 ohm-cm	
	0.0000552 ohm-cm	0.0000552 ohm-cm	
	0.0000797 ohm-cm	0.0000797 ohm-cm	
Thermal Properties	**Metric**	**English**	**Comments**
CTE, linear	12.3 µm/m-°C	6.83 µin/in-°F	specimen oil hardened, 600°C (1110°F) temper
	12.6 µm/m-°C	7.00 µin/in-°F	1.88% Ni, normalized and tempered
	12.7 µm/m-°C	7.06 µin/in-°F	specimen oil hardened, 600°C (1110°F) temper
	13.7 µm/m-°C	7.61 µin/in-°F	specimen oil hardened, 600°C (1110°F) temper
	13.7 µm/m-°C	7.61 µin/in-°F	1.88% Ni, normalized and tempered
	13.9 µm/m-°C	7.72 µin/in-°F	1.90% Ni, quenched, tempered
	14.5 µm/m-°C	8.06 µin/in-°F	specimen oil hardened, 600°C (1110°F) temper
Specific Heat Capacity	0.475 J/g-°C	0.114 BTU/lb-°F	Typical 4000 series steel
Thermal Conductivity	44.5 W/m-K	309 BTU-in/hr-ft²-°F	Typical steel
Component Elements Properties	**Metric**	**English**	**Comments**
Carbon, C	0.370 - 0.430 %	0.370 - 0.430 %	
Chromium, Cr	0.700 - 0.900 %	0.700 - 0.900 %	
Iron, Fe	95.195 - 96.33 %	95.195 - 96.33 %	As remainder
Manganese, Mn	0.600 - 0.800 %	0.600 - 0.800 %	
Molybdenum, Mo	0.200 - 0.300 %	0.200 - 0.300 %	
Nickel, Ni	1.65 - 2.00 %	1.65 - 2.00 %	
Phosphorous, P	<= 0.0350 %	<= 0.0350 %	
Silicon, Si	0.150 - 0.300 %	0.150 - 0.300 %	

APPENDECIES E:

Motor Family Tree [3]:



APPENDECIES F:

Cost of Project:

ITEM	PRICE	QTY	SHIPPING/ TAX /HANDLING	TOTAL
3.5", 4340 ALLOY BAR STOCK STEEL (1')	157.98	1	23.14	181.12
LABOR (EXTRA HELP)	10.00	10	0.00	100.00
ARC MOTOR MAGNETS (SET)	30.00	1	5.00	35.00
HALL EFFECT SENSORS	6.07	4	14.05	38.33
BLDC MOTOR CONTROLLER	210.58	1	18.58	229.16
5/18" THREADED BAR (2')	3.17	1	0.28	3.45
3/5" DIAM. STEEL BAR (2')	5.00	1	0.30	5.30
HALL EFFECT SENSOR MAGETS (3')	8.00	1	9.18	17.18
TIE DOWNS	2.98	2	0.33	6.29
MISC. SCREWS AND BOLTS	5.35	1	0.53	5.88
KAPTONS TAPE (50')	4.98	1	21.25	26.23
CNC CARBIDE BIT 1/4"	20.08	1	0	20.08
CNC CARBIDE BIT 1/8"	8.41	3	8.17	33.40
HIGH SPEED ELECTRIC MOTOR BEARINGS (SET)	18.77	1	0	18.77
24 AWG WIRE (Ft.)	0	1000	0	0.00
TOTAL				720.19