THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

DESIGN, SIMULATION AND PROTOTYPING OF A LOW-SPEED PERMANENT-MAGNET DIRECT-DRIVE ALTERNATOR

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ABSTRACT

Losses in electrical generators due to gearboxes can be costly in terms of efficiency. However, the high speed at which generators run most effectively prohibits the generator being run without gearing. Exploration of design choices which could most effectively lead to a direct-drive solution provides a solution for a small-scale alternator. COMSOL Multiphysics simulation is used to compare design choices. A working prototype is then used to provide a performance comparison against the commercially-available alternator. This research showed that effective design choices such as magnet grade, magnet size, the amount of magnetic shielding, and whether or not the magnets were arranged into a Halbach array; all are able to increase the output of a permanent-magnet alternator at the cost of additional materials and assembly. A physical prototype confirmed the validity of magnet grade, magnet size, and shield size as a means of output up to 193% of root mean square voltage and up to 372% of root mean square power with root mean square voltage increasing to 162% root mean square voltage on average and root mean square power increasing to 264% on average.

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ACKNOWLEDGEMENTS

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Chapter 1

Introduction and Literature Review

Renewable sources of energy which help minimize greenhouse emissions are increasing in demand. Among the sources of energy that fit these sustainability requirements is wind generation, in which large turbines harvest the energy of air currents and convert it to electrical energy. Electric wind generation has the largest growth of any electric energy source and is projected to encompass 1.2 million MW by 2020 (Mathew, 2006). However, many problems persist which inhibit the efficacy of wind energy. Wind energy is expensive to store, and geographic areas have differing energy capacities for wind power (Flarend, 2013). However, many losses occur within the mechanism, which must be addressed in order to fully realize the potential of wind power.

Wind Energy Mechanical Concerns

Within a wind turbine, there are many components and assemblies that reduce the efficiency of the turbine. In Wind Energy Conversion Systems (Tamura, 2012), seven specific losses are identified. Among these losses are losses due to the gearing which is required to convert the rotational velocity of an electric wind generator to a much faster rotational velocity required for efficient operation. Gearbox losses are primarily due to friction and become larger at lower operating powers. In a study published in Tribology International, a full-scale test rig encountered gearbox operating efficiencies between 89.3% and 98.7% (Fernandes, Blazquez, Sanesteban, Martins, & Seabra, 2016). While the upper range of efficiencies are acceptable for an engineering application, the higher efficiencies are only present in the best-case scenarios. Wind turbines will operate in a wide band of power inputs, which will result in lower efficiencies. Changing the type of lubricant used can have a large effect on the efficiency but will still have a reduced efficiency due to the presence of the gearbox. Gearboxes also present a problem due to the increased number of failures within the gearbox on wind generators (Mueller & McDonald, 2009).

Recommendations from Previous Research

A novel idea which eliminates the gearbox is the direct-drive generator. Direct-drive (DD) generators do not require a gearbox between the turbine and the generator, which increases the operating efficiency and reduces the need for maintenance. As a solution for the problems of a gear box, a DD generator shows potential and will be the focus of this research project.

Direct-drive permanent magnet generators have been in development, and therefore have some design optimizations prior to the research presented in this paper. An article from the Latvian Journal of Physical and Technical Science analyzes the performance of both distributed- and concentrated-winding direct drive generators. Mathematical analysis of both systems shows that a concentrated winding achieves seventeen percent greater torque for similar geometry of construction (Levin, Pugachov, & Orlova, 2012). However, the paper also notes that using concentrated windings also increases the starting torque, which can be problematic within wind applications.

Another concern specific to direct-drive generators is the stress generated in both the rotor and the stator. The considerable force generated in the mechanisms requires rigid structural components which can account for more than eighty percent of the mass of a PM generator (Mueller & McDonald, 2009). The article "A Lightweight Low-speed Permanent Magnet Generator for Direct-drive Wind Turbines" details the approach taken at the Institute of Energy Systems. The two main recommendations are 1) repositioning the components to reduce the amount of magnetic forces on the core, and 2) reducing the magnetic material. The model generator outlined in the article does not use iron cores. Rather, the stator is made of non-magnetic material and the coils are formed using non-magnetic epoxy, reducing the magnetic attraction between the permanent magnets and the core. Without the cores to provide a means to channel the magnetic field, non-magnetic material must be used structurally to avoid disrupting the necessary fields. The lack of magnetic forces reduces the strength required to support the core. To reduce the strength required to hold the coil, the core was constructed in a radial "C" configuration. The benefit of the radial "C" configuration is an increase in the flux path and a decrease in the required mass to ensure structural integrity. The use of crescent-shaped magnet systems in the rotor also reduces the amount of material the magnetic field must flow through to return to its point of origin. While these design changes are not applicable for the alternator design in this work, they provide a list of considerations. The styles listed above are shown in **Error! Reference source not found.**

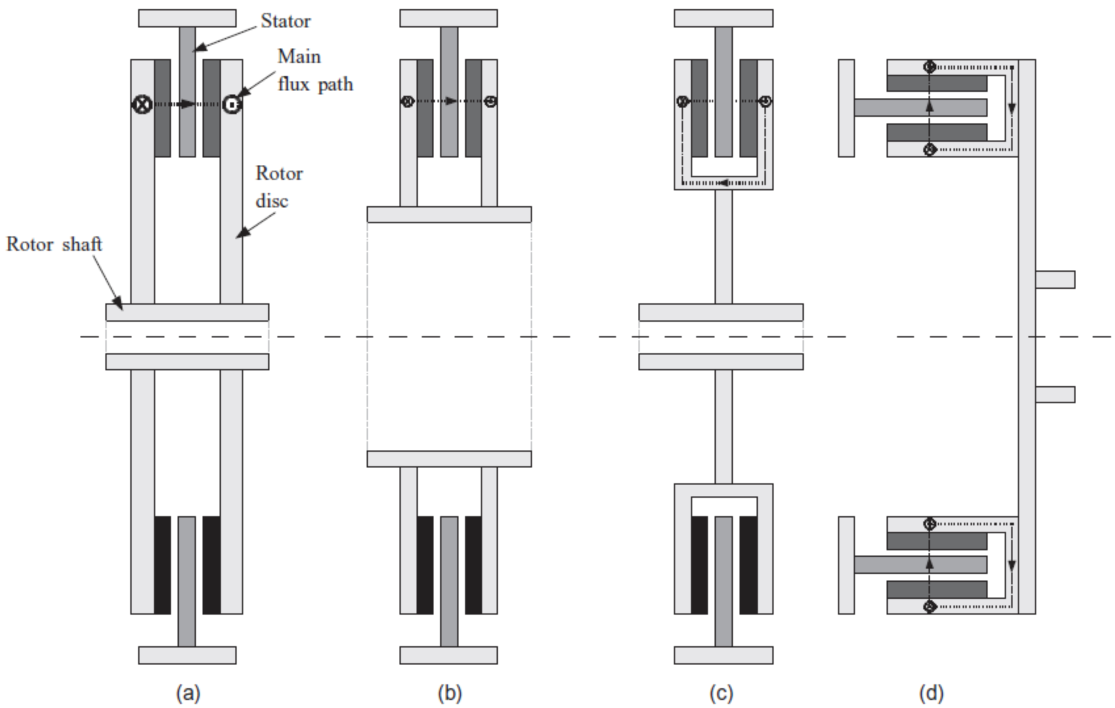


Figure 1: Cross section of double-sided axial-flux machine (Mueller & McDonald, 2009). (a) Baseline design (b) Increasing rotor shaft radius means the thickness of the rotor discs can be reduced (c) 'C' core machine with extra flux path (d) Radial-flux 'C' core

Another application in which permanent-magnet alternators are being considered is automotive applications, as noted by Caricchi, et al. (Caricchi, Crescimbini, Capponi, & Solero, 2001). Presented within the conference proceeding is another idea for a direct-drive generator which uses an axial-flux configuration, with two permanent-magnet layers laminated over the cores. An exploded view of an example alternator can be seen in figure 2.

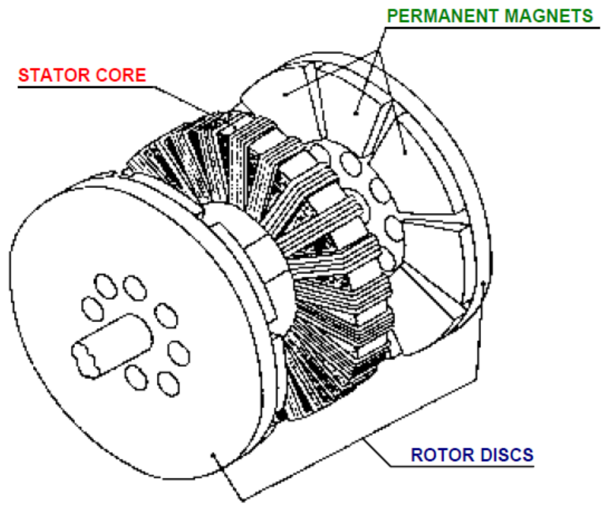


Figure 2: Axial-flux permanent-magnet alternator (Caricchi, Crescimbini, Capponi, & Solero, 2001).

The advantages of such a design include increased cooling and decreased losses and torque. Concepts from this design that are applicable for the scope of this project include the control of magnetic fields.

A novel idea for increased magnetic field strength in a permanent-magnet alternator is the Halbach array, a method of maximizing magnetic flux on one side of a set of specially-arranged magnets (Mallinson, 1973). A depiction of the arrangement and their respective magnetic field is shown in Figure 3: Standard magnetic array (left) compared to a Halbach array (right). Note the concentration of magnetic flux at the top surface..

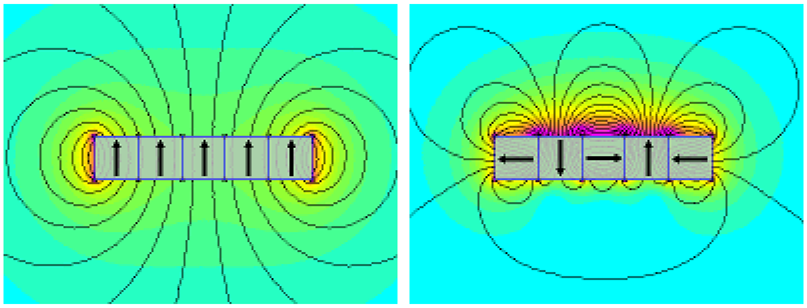


Figure 3: Standard magnetic array (left) compared to a Halbach array (right). Note the concentration of magnetic flux at the top surface. (K&J Magnetics, n.d.)

Such an array uses permanent magnets in an arrangement which directs the magnetic field away from a permanent magnet facing out of the array and re-directing it towards a magnet facing into the array. The primary advantage of such a system is the increase of magnetic field for the same amount of material. Given the large cost of permanent magnets, an improvement for which the cost is minimally raised presents great economic benefit.

Research Direction and Objective

Due to the time frame and scope of this research project, the scale of the project will be limited. Therefore, the alternator which will be designed and built will be small in scale (about 3 volts). A small alternator such as the one proposed will be allow for continuous refinement of design, minimal cost of resources, and quick assembly.

While direct-drive low-speed high-torque generators are an emerging field, some design points are consistent across designs. First, permanent magnets provide more magnetic flux through cores and coils than self-induction, providing more power for the same displacement. Disadvantages of not using self-induction include an increased complexity in normalizing output frequency, increased weight, and increased cost (Muljadi, C.P., Sallan, & Sanz, 1999). Within the realm of this project, the small scale will negate the increased cost and weight of the PM design. Because of the generator's design focusing primarily on increasing operational torque and reducing operating speed, the frequency of electric current generated will be monitored, but not accounted for in the design.

Levin et al. recommend the use of concentrated windings to increase power. For high-torque generators, any increase in power will increase the efficiency of operation. High starting torque associated with concentrated windings will not be a concern in this application. The small scale of the generator, as well as the experimental application, does not require a smooth transition to producing power. However, some recommendations may be experimented with to see if the performance of the generator is improved.

Chapter 2

Methods

Design Choices

Ensuring experimental validity required the establishment of baseline performance parameters and a standard envelope for modification. Wind generator scale and cost prohibited the modification of a full generator and prompted the selection of a smaller generator. Selecting a permanent-magnet generator for comparison provided the greatest ease of modification as well as a more direct comparison between the modified and stock generator. However, high-grade permanent magnets required for modification present the largest cost, and therefore especially necessitate the selection of a smaller generator. Only the permanent magnets and their surrounding encasement showed applicability for improvement, and therefore became the primary considerations in selecting a generator.

Considering the aforementioned criteria, the “CrocSee Micro 3 Phase AC Mini Hand Brushless Motor Generator Model Experiment Teaching Aid” from Amazon.com met all criteria for an explorative alternator. In addition to its applicability by merit of the established requirements, the generator provided several additional benefits. The alternator is pictured in Figure 4

Figure 4: CrocSee 3-phase alternator, image provided by CrocSee at www.amazon.com.

First, its availability on Amazon.com allowed for quick replacement, relatively low cost, and short delivery period. Second, its permanent magnet rotor surrounded its stator, providing larger physical envelope in which modifications can be made. Its stationary coils also simplified the wiring and preclude the need for intricate brushes or rectifiers. Third, the presence of screw holes in its case allowed for quick and simple installation on an experimental setup. Fourth, its usage of a common rotary shaft size and ease of disassembly allowed for the simplest modification.

Accurate simulation and modification necessitated measurements of the generator. See Appendix 1: Determined Dimensions of Generator for dimensioned drawings of the generator components.

Design Constants and Parameters

While many of the alternator parameters can be investigated, some parameters were kept constant to provide a basis for design. Design constants included:

- Generator configuration (magnets in rotor, coils in stator)
- Stator size
- Core material
- Winding material
- Number of windings per coil
- Depth of generator
- Dimensional tolerance
- Coil pitch
- Phase Number

Elimination of the constant parameters presented the parameters which could be varied. Variable parameters included:

- Magnet size
- Magnet arrangement (Standard vs. Halbach Array)
- Magnet grade
- Shielding thickness

Direct-drive generators for this application are typically run at low frequencies. As such, data for simulations began at 10 Hz, and move to 1000 Hz logarithmically. The prototype's frequency range ranged from 0.6 Hz to 70 Hz, which is a good low-frequency range.

Magnet Design

Because of the magnet-centric scope of my research, a list of ideas which could produce favorable results guided the investigation. Each of these magnets could be simulated using COMSOL to provide a comparison of performance. Table 1 lists the magnet shape and a description of the advantages of each.

Table 1: Selected magnet shapes

Magnet Shape	*Advantage*
Double-thickness direct replacement: 12 neodymium magnets which are twice the thickness of the ceramic magnet	Increases the performance of the generator, while maintaining the three-phase operation and
Halbach array: using a specified pattern of magnets to concentrate the magnetic field on one side of the pattern, with twelve poles	Described as a "magnetic curiosity" (Mallinson, 1973), a Halbach array has the capability to maximize magnetic output with minimal regard to shielding.

While testing each of the magnetic designs through physical prototyping was prohibitively expensive, simulation provided a means by which to compare each design's validity.

Magnet Grade

Different grades of strength, and by extension strengths of magnetic fields, produce varying voltages in alternators at otherwise similar conditions. Typically, the strength of the magnet is related to the cost of the magnet, and magnets of highest available grade are not appropriate for all applications. Some commercially available permanent magnets which may be used in a generator is shown in table 2.

Table 2: Remnant flux density of magnets used in simulations. Neodymium magnet properties from manufacturer used for prototype (Neodymium Magnet Physical Properties, 2018). Ferrite magnet properties from TDK Corporation reflective of typical magnets (Magnets | Catalogue | TDK Product Center, 2018).

Permanent Magnet Type	*RFD [Br], manufacturer spec.*	*RFD [Br], Used*
N52	14.5-14.8	14.65
N42	13.0-13.2	13.1
N35	11.7-12.1	11.9
Ferrite FB13B	4.65-4.85	4.75

High-grade magnets provided the most magnetic flux, which is essential for the generator to produce the most power per turn. The most powerful magnets commonly available are grade N52 neodymium magnets, which were available in custom shapes from K&J magnetics. Ring magnets with double the thickness of the existing magnets balanced the cost of materials, performance enhancement, and comparison applicability for high-grade magnets for the alternator.

Magnetic Shielding

The use of a magnetic "shield" can maximize magnetic output of the limited number of magnets with minimal cost and size envelope increase. Magnetic shields, contrary to the name, do not block magnetic fields. Rather, a magnetic shield redirects a magnetic field from travelling through free space (air) by providing a ferromagnetic conduit through which the field can travel. Using a circuit allegory, both free space and metal provide a connection from the positive to negative magnetic potential. Metal is far less resistive (more conductive) than air, which allows more of the magnetic field to travel through it. In the existing generator, the magnetic metal casing for the rotor provides some shielding. However, the casing consists of thin sheet metal which may not provide adequate shielding for a stronger magnet. By increasing the size of the casing, the conductivity of the casing increases to the point where the escaping field is nearly negligible. Shielding becomes important when preventing loss of magnetic field strength through the coils.

Magnet Thickness

Because of the magnetic field's dependence on volume, increasing the thickness of the magnet will increase the magnetic field, and therefore the magnetic flux through the coils of the generator. While increasing magnet size is a straightforward way to increase power production in a similar package, investigating the benefits against a benchmark generator and studying the decreasing returns of such an approach will provide a guide for magnet size improvement.

COMSOL Multiphysics Analysis

Analysis Setup

The nature of finite-element analysis in Multiphysics required the use of assumptions in order to balance accurate results with feasible computational power required. The reference book <u>COMSOL 5 for Engineers</u> provided a framework for these assumptions and analysis (Tabatabaian, 2016).

Two-dimensional analysis provided the largest assumption for simulation. Most magnetically-conductive material within the alternator resides in the stator, as opposed to the base or the rotor end. Placement of magnets within the generator further validated this assumption. Magnetic field propagating from the permanent magnets travels to the adjacent magnets and therefore either travel directly through the stator or loop through the shell of the rotor. Increasing the rotor shell thickness as a parameter increases the magnetic field containment. The simulations included the depth of the alternator as a constant for calculation of voltages. An example of a two-dimensional model is shown in figure 5.

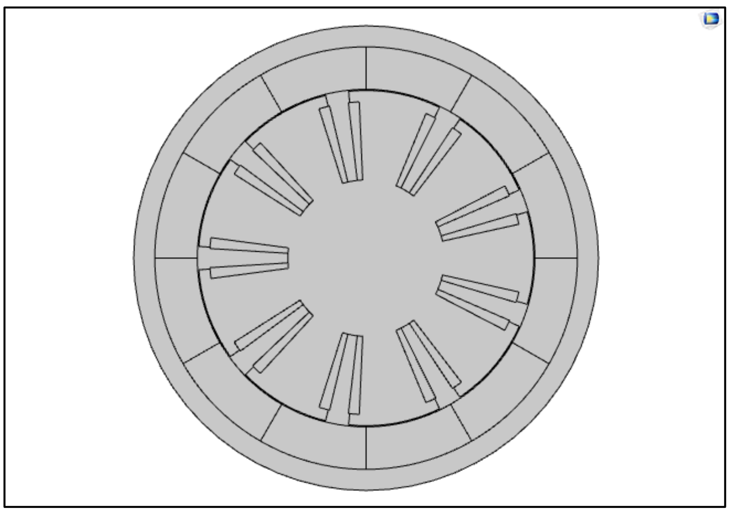


Figure 5: 2-D generator model for initial analysis. This model is based upon the commercially available generator with magnets of increased thickness

Radial symmetry provided a means to further streamline analysis. Simulating only one unique section of the generator reduced the necessary computing power by reducing the number of specific elements which must be analyzed. Sectional analysis indirectly allowed for more accurate results because a finer mesh could be used for each section while maintaining a reasonable computing time. Three-phase alternators have a unique symmetric section consisting of three cores corresponding to two north-facing and two south-facing magnets. In a Halbach array, two north- and two south-facing poles with corresponding magnets between them could then be used to achieve the same effect.

The common materials present in the alternator allow for a material-simplified simulation. COMSOL contains common materials for generators in its materials library, all of which are nearly fully defined. Soft iron could be used for the ferromagnetic stator and rotor shell to allow for easier simulation of magnetic field propagation in those components. Copper became the primary coil material to act as a conduit for the electric field. Remnant flux densities defined the magnets rather than materials. Remnant flux densities for different magnet types used are listed in Table 2. Open spaces consisted of air for simulation purposes.

Voltage being the primary result of simulation necessitated the accuracy of voltage simulation. COMSOL Multiphysics contains a preexisting method for calculating voltage in its AC/DC – Rotating Machinery package with the use of the Electric Circuitry package. However, initial simulations using the Electric Circuitry package extended the computation time beyond feasibility. COMSOL 5 for Engineers offered a simplified method using an electric field approximation. Integrating the electric field over the cross-section of a coil, dividing by the area, and multiplying by the length determines the voltage per winding in the coil. Voltage per winding could then be multiplied by the assumed number of windings in the coil and the number of analyzed sectors to give the total voltage produced by the alternator.

Result Analysis

Because the simulation analysis of the alternator covered both configuration changes (such as alignment and number of cores/magnets) and parameter changes (rotational velocity and strength of permanent magnets), analysis used both distinct simulations and parametric sweeps.

Parametric sweeps provide an advantage in comparing designs because results of simulations can be directly compared on the same graph. For example, when comparing the voltage within a three-phase generator winding at different speeds, the voltage pattern can be shown as a function of normalized time as in figure 6. Parametric sweeps could also be used to export data to one table for ease of use.

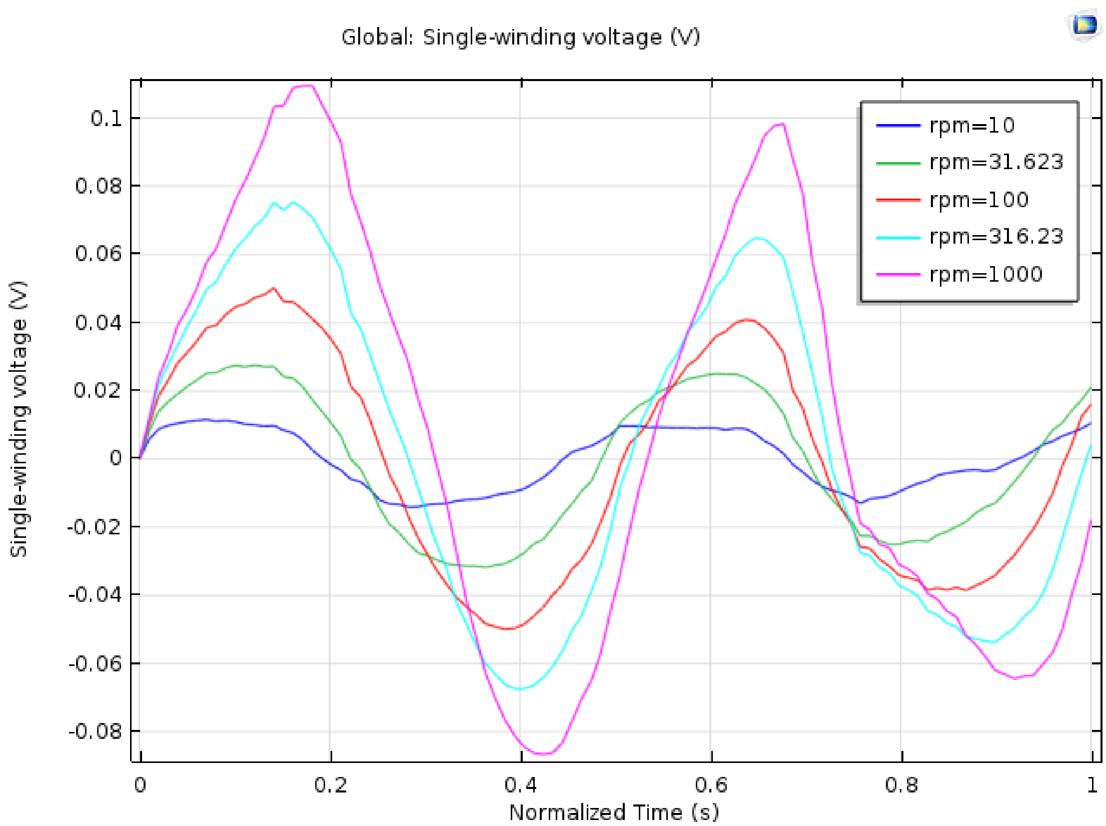


Figure 6: Example COMSOL output graph - Voltage over a single phase in a three-phase alternator winding for five distinct rotational velocities. Note that the amplitude of the semi sinusoidal eave increases with velocity, which is expected.

Physical Prototyping of the Generator

Due to the inherent limitations of simulations to provide accurate data (material inconsistencies, non-ideal relations, etc.), a prototype provided useful data that is otherwise unobtainable. Modifications to the same generator that provided the basis for the simulation model presented a worthwhile method for determining the validity of design choices. However, prototyping a generator requires significant monetary resources, especially with regard to high-grade neodymium permanent magnets. These limitations narrowed the investigation to a single prototype.

After receiving quotes from K&J Magnetics, the alternator employed a double-thickness magnet of grade N52 in order to balance the cost per magnet and the increase in alternator performance. A 1mm-thick shield was used to contain the increased magnetic field and provide the structural support needed for high-grade magnets. The physical dimensions of the prototype can be seen in Appendix A.

Comparison of the two alternators concerns the similarity of frequency at which the alternators are evaluated. In order to achieve the most direct comparison, the alternators must be simultaneously evaluated at the same frequency. To achieve synchronous operation, a single motor with two gears provided rotation to both generator simultaneously. The dual connection setup is shown in figure 7. The use of two motors, a high-torque/low-rpm motor and a large standard motor allowed for the high torque required to drive the mechanism while remaining capable of producing the necessary range of frequencies. A DC voltage source supplied the motor with power, while enabling me to vary the voltage, and therefore the frequency of the motor and generators. The entire setup is shown in figure 8.

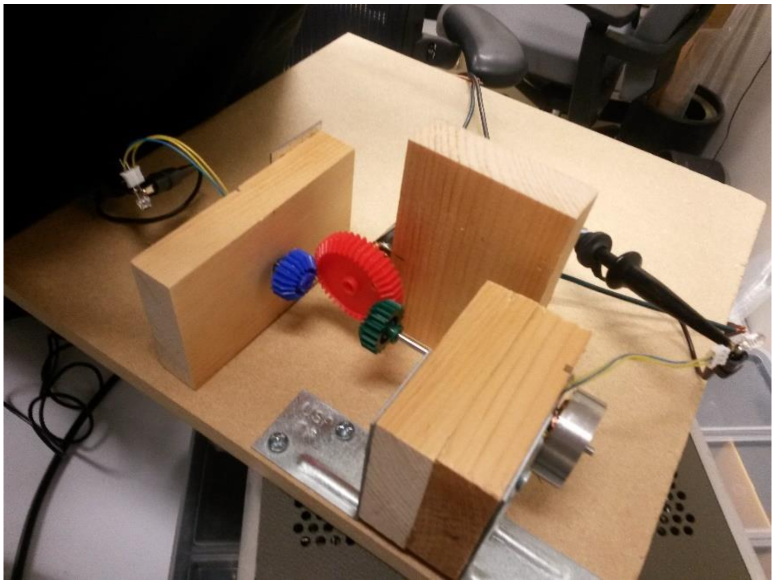


Figure 7: Alternator-motor connections. The large red gear is connected to the motor, and provides power to the alternators (the small green and blue gears).

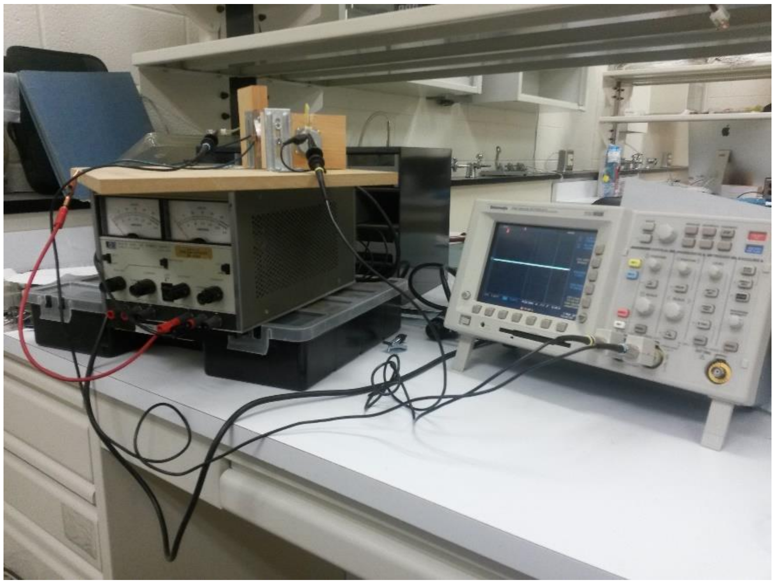


Figure 8: Example setup, including generator, DC power supply, and oscilloscope.

The smaller motor operated at lower frequency ranges with appropriate torques for the operation of the generator. The larger one required higher operational frequencies but could be used to achieve frequencies much higher than the geared motor. Through testing, an additional effect in the quality of the data appeared. The smaller motor could not maintain as steady rotation as the larger motor and produced more noise in the output. A typical output from the generators powered by the larger motor is shown in figure 9. A typical output from the generators powered by the smaller motor is shown in figure 10.

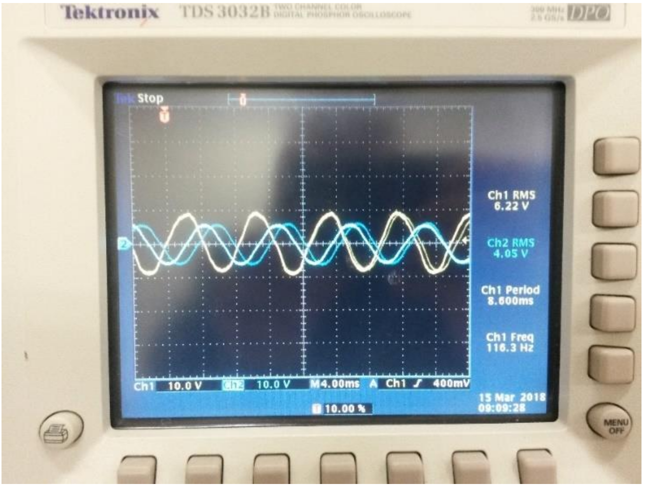


Figure 9: Typical output from the larger motor. The Channel 1 voltage, channel 2 voltage, and period are shown to the right of the voltage-time plot.

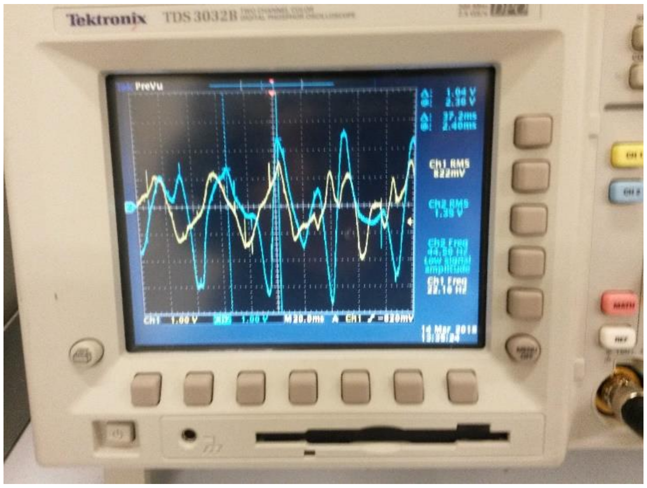


Figure 10: Typical output from the smaller of the two motors

An oscilloscope allowed measurement of alternating voltage over a time, and simplified data taking. Using an oscilloscope allows for root-mean-square voltage calculation, as well as frequency data. Both of these automatic measurements simplify the process of taking performance measurements. However, an oscilloscope requires a ground voltage to which to compare its input voltage. A “wye” connection facilities the common ground connection, as demonstrated in figure 11. A circuit diagram of the setup for a single generator is shown in Figure 12.

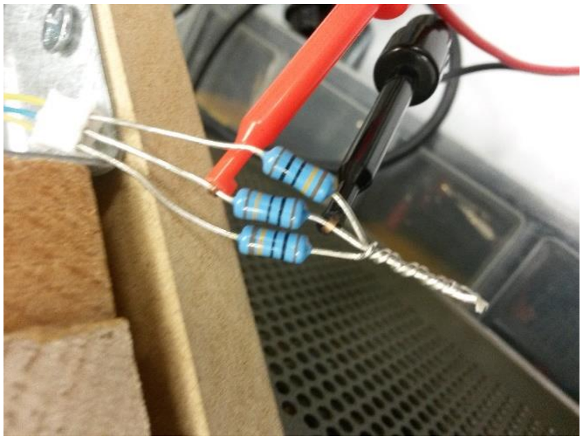


Figure 11: Resistor and probe wye configuration to measure voltage drop across resistor.

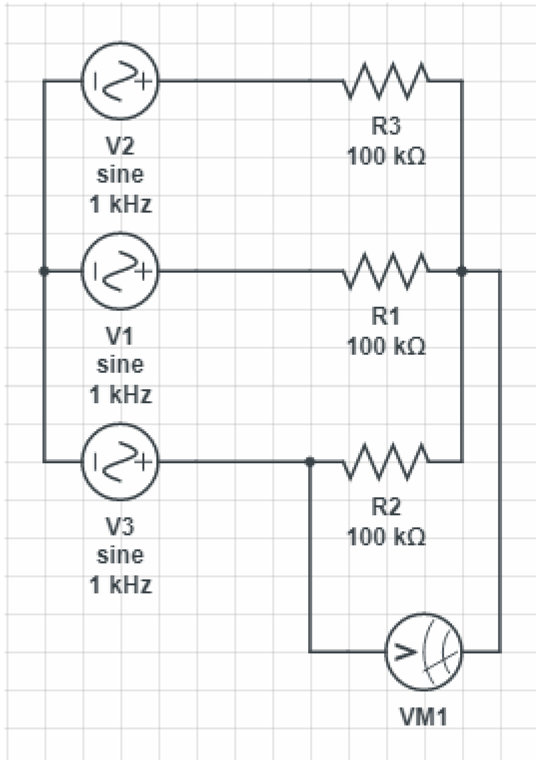


Figure 12: Circuit diagram of single alternator test setup. Note that the voltmeter represents the oscilloscope and has a built-in ground. Circuit designed using www.circuitlab.com.

Each phase of the alternator contains a high-value (100 kiloohm) resistor before the common ground. Because a three-phase alternator produces three phases which sum to a net zero voltage, all three can share a common ground after the resistor load. This single node simplified the ground connection and gives a point at which a constant zero potential does not affect the measurement. Using a resistor also allowed for implicit measurement of current, since both the resistance and voltage are known. Power could also be calculated using the voltage and resistance. Performance metrics, therefore, remain the same between models. Using high-value resistors also prevents coil and alternator-side connection resistance from interfering with the output measurements.

Chapter 3

Results

Simulation Results

Magnet Thickness

The voltage per winding of the alternator with varying permanent magnet thickness is shown in Figure 13. The magnet thickness ranges from half a millimeter to three millimeters. For comparison, the experimental prototype generator featured a magnet thickness of 2 mm and the stock generator featured a magnet thickness of 1 mm.

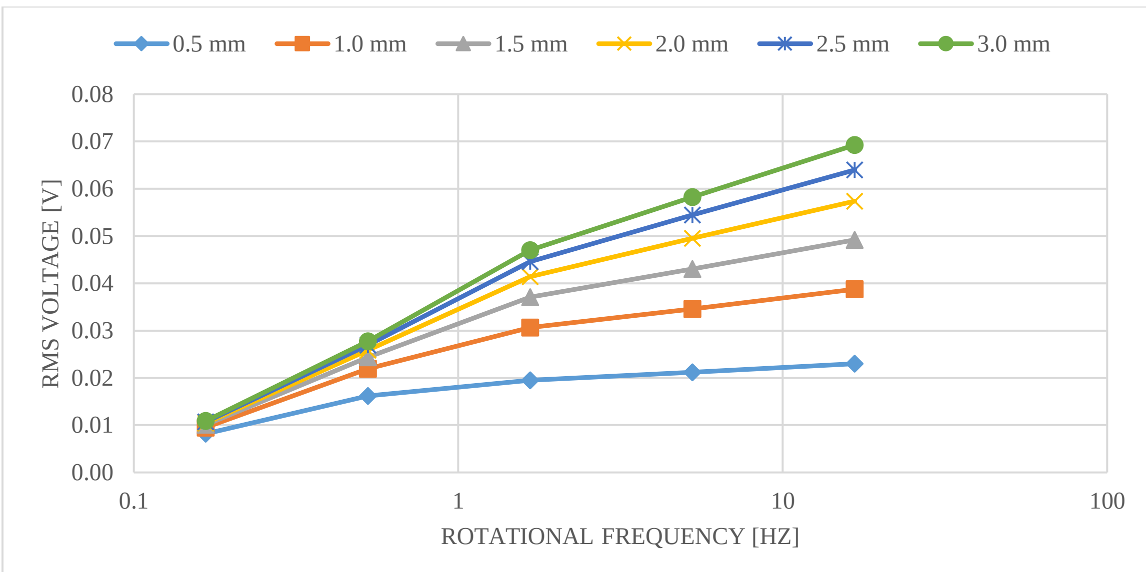


Figure 13: RMS voltage per winding at varying magnet thicknesses over a range of discrete rotational velocities. As the thickness of the magnet increases, the RMS voltage output increases.

Magnet Grade

The voltage per winding of the alternator with varying magnet grade is shown in Figure 14. Magnet grades included all from Table 2. For comparison, the prototype generator featured an N-52 magnet with a residual flux density of about 1.465 T and the stock generator featured a ferrite magnet with a PRD of about 0.475.

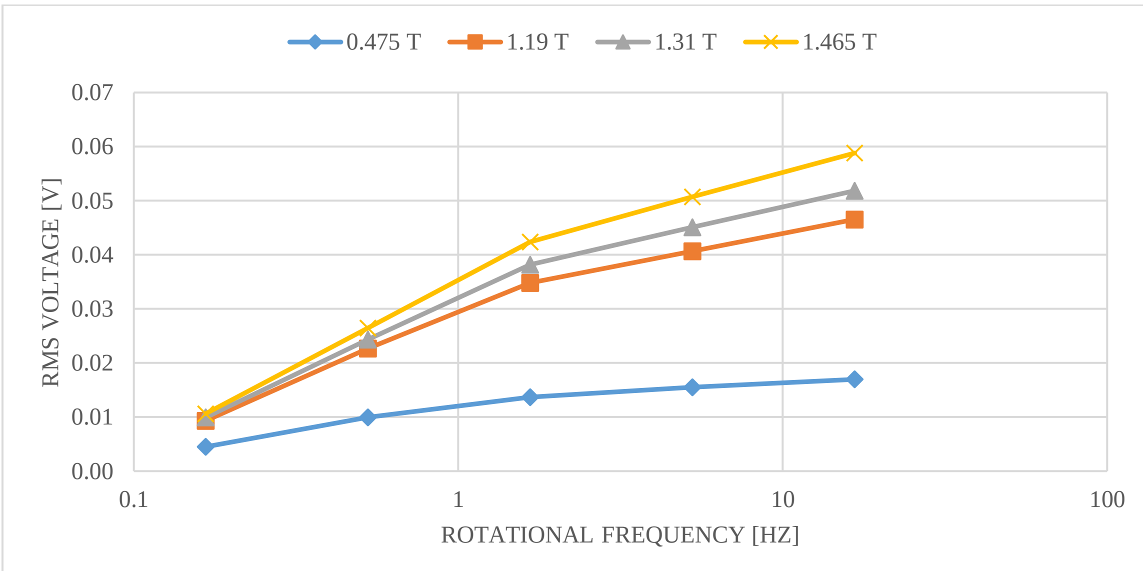


Figure 14: RMS voltage per winding at varying magnet grade over a range of discrete rotational velocities. As the thickness of the magnet increases, the RMS voltage output increases. As the grade of the magnet increases, the RMS voltage output increases.

Halbach Array Grade

The voltage per winding of the alternator with varying magnet grade is shown in Figure 15. Magnet grades included all from Table 2. For comparison, the prototype generator featured an N-52 magnet with a residual flux density of about 1.465 T and the stock generator featured a ferrite magnet with a PRD of about 0.475.

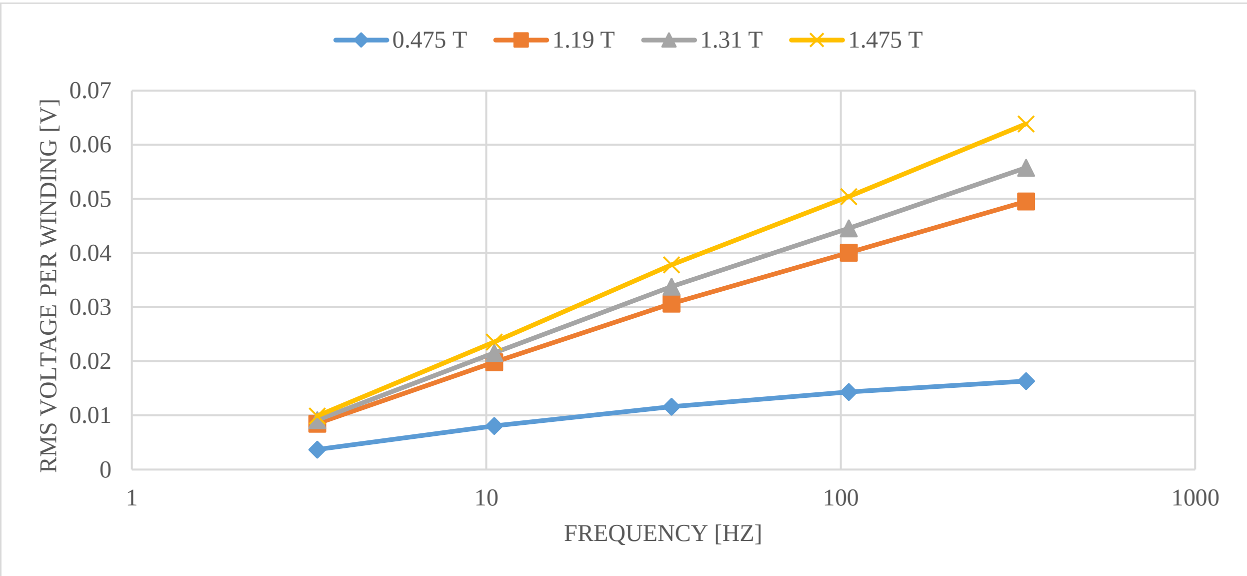


Figure 15: RMS voltage per winding at varying Halbach array grade over a range of discrete rotational velocities. As the thickness of the magnet increases, the RMS voltage output increases. As the grade of the Halbach array increases, the RMS voltage output increases.

Magnet Thickness in a Halbach Array

The voltage per winding of the alternator with varying magnet thickness in a Halbach array grade is shown in Figure 16. While the prototype generator acted as a comparable magnet thickness, the Halbach array produced a different output.

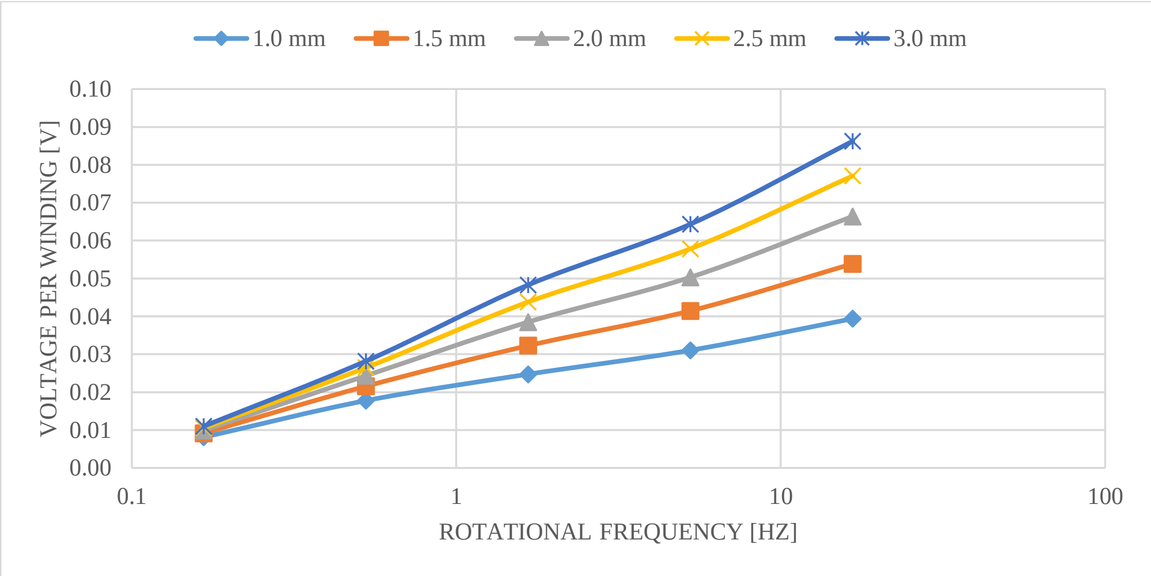


Figure 16: RMS voltage per winding at varying Halbach array thickness over a range of discrete rotational velocities. As the thickness of the Halbach array increases, the RMS voltage output increases.

Shield Thickness of Standard Magnets

The voltage per winding of the alternator with varying magnetic shield thickness is shown in Figure 17: For comparison, the prototype generator featured a shield thickness of around 1 mm, and the stock generator featured a shield thickness of around 0.5 mm.

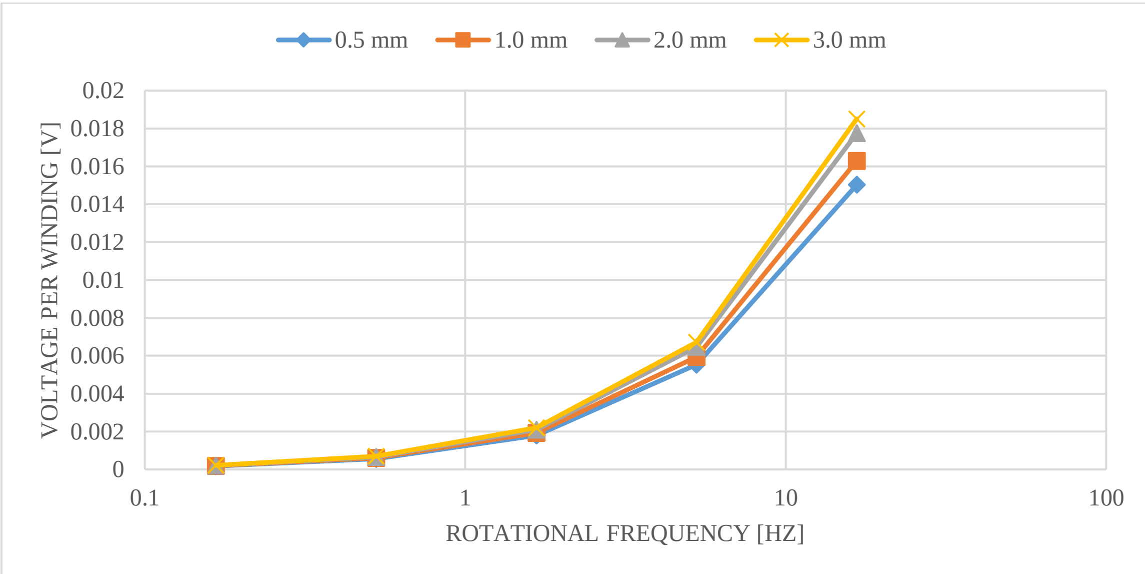


Figure 17: RMS voltage per winding at varying shield thickness over a range of discrete rotational velocities. As the grade of the shield thickness increases, the RMS voltage output increases.

Experimental Alternator

The root mean squared voltage difference between phases in the experimental alternator is shown in Figure 18. While not a direct measurement of the output of a three-phase generator, the voltage difference provides a means to compare the output of the two alternators. A notable gap in the data occurred from about 3 to 7 revolutions per minute, due to the different motor speeds previously mentioned.

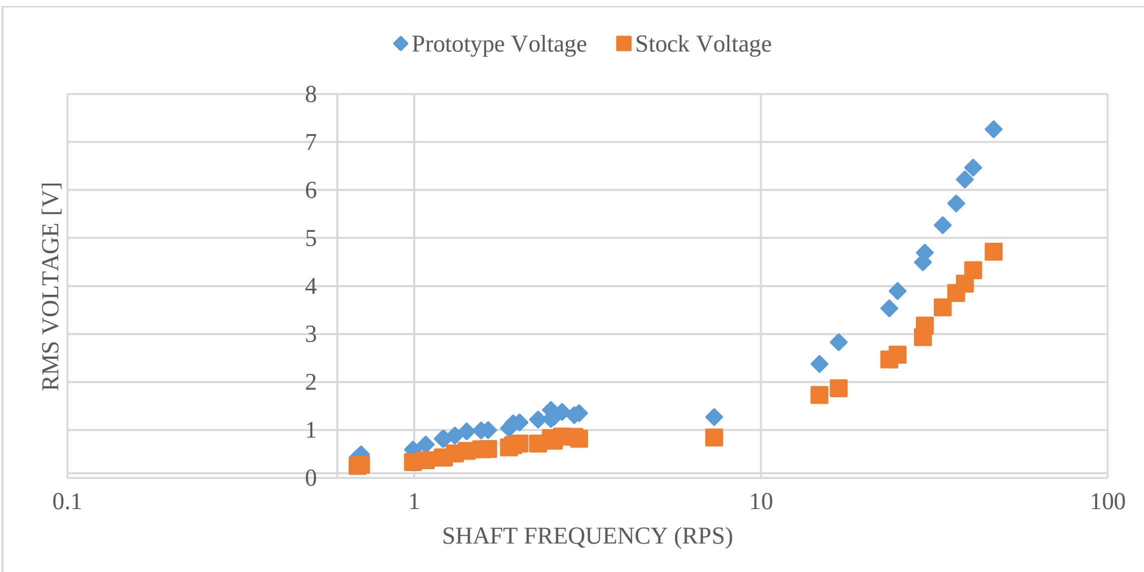


Figure 18: Experimental output of modified vs. stock alternator. Specific data points are shown in each data series. The gap between 3 and 7 revolutions per minute is due to the velocity range differences between motors.

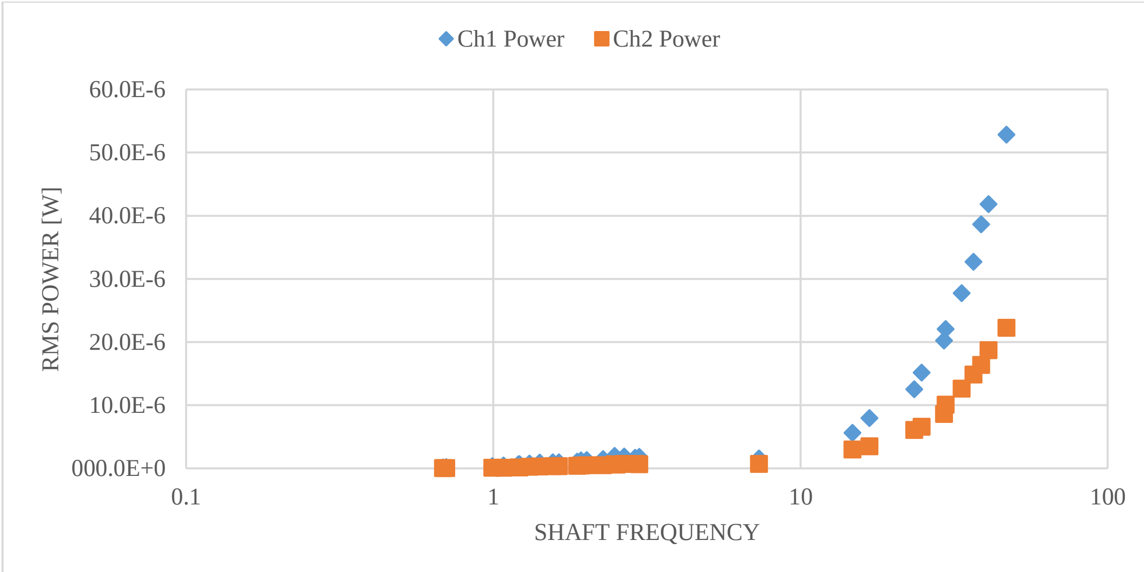


Figure 19: RMS power output of stock alternator and prototype. The power values within the graph are calculated from the voltage data.

Chapter 4

Discussion

Simulations

All simulations behaved in the expected manner. Increasing the grade, thickness of magnet, and thickness of the shield increased the relative voltage output of the generator in each case. Each parameter increases the construction cost of the generator as performance increases, to varying degree. Every parameter encounters a limiting factor, each of which is explained.

Magnet Thickness: Standard Magnets

The total magnetic flux increased with the volume of the magnet and therefore increased the output potential of the alternator. Because of the exterior rotor of the design, the magnet thickness could potentially theoretically increase to no limit. However, each 0.5mm increase of the magnet thickness confers less of a voltage increase than the previous increase. Therefore, magnets must be individually evaluated for each generator design. Especially given the expensive nature of high-grade permanent magnets, increasing the magnet thickness should not be used as the primary means of increasing a low-speed generator’s output.

Magnet Thickness: Halbach Array

Similar to the case of the standard magnets, increasing the thickness of the magnets in a Halbach array produced a higher output voltage for the same magnet grade. However, the simulations of a Halbach array showed a more direct correlation between speed and voltage output. Unlike the standard magnets, the rate at which the change in output voltage per change in speed remains relatively steady. The change in voltage per change in thickness was also greater and does not have the same degree of diminishing returns as the standard case. Less loss from the magnetic field entering the adjacent magnets may have caused this effect. For a given magnet size and grade, the output of a generator can be increased if a Halbach array configuration can be used in place of a standard magnet array.

Magnet Grade

When the thickness of the magnet and shield is kept constant, the grade of the magnet used in a generator has a direct relation to voltage output. At the simulated thickness, the output of the generator was nearly proportional to the remnant flux density of the permanent magnets. Unlike other parameters examined, a definite limit exists in the form of available grades. The N-52 neodymium magnets used in the prototype represent the highest grade that is commonly commercially available. While other magnets that exist produce more magnetic potential, other materials may be prohibitively expensive or rare. Even among neodymium magnets, magnets with greater remnant flux density cost more than lower grades. However, the cost for more powerful magnets are worthwhile for applications in which obtaining the highest output for a given package size and configuration. Low-grade magnets, such as ferrite, should not be used in such applications due to the low output for a given size envelope.

Shield Thickness

Plotting the output of the alternator over a range of speeds gave a shape not previously exhibited by other simulations. As the speed increased, the output voltage increases in what appears to be an exponential pattern. Magnetic field effects in the 'air space' surrounding the simulation not present in other models may have caused this effect. Due to the comparative/qualitative nature of the design recommendations of this document, only the difference between the data series in the simulations shall be considered.

As the thickness of the shield increased, the output voltage increased at a decreasing rate. While shielding can re-route magnetic fields and prevent losses, the amount of magnetic field re-routed is limited by the residual flux density of the permanent magnet. A subsequent simulation demonstrated the effect of different shield thicknesses for different magnet grades on voltage. The results of the simulation are shown in figure 20.

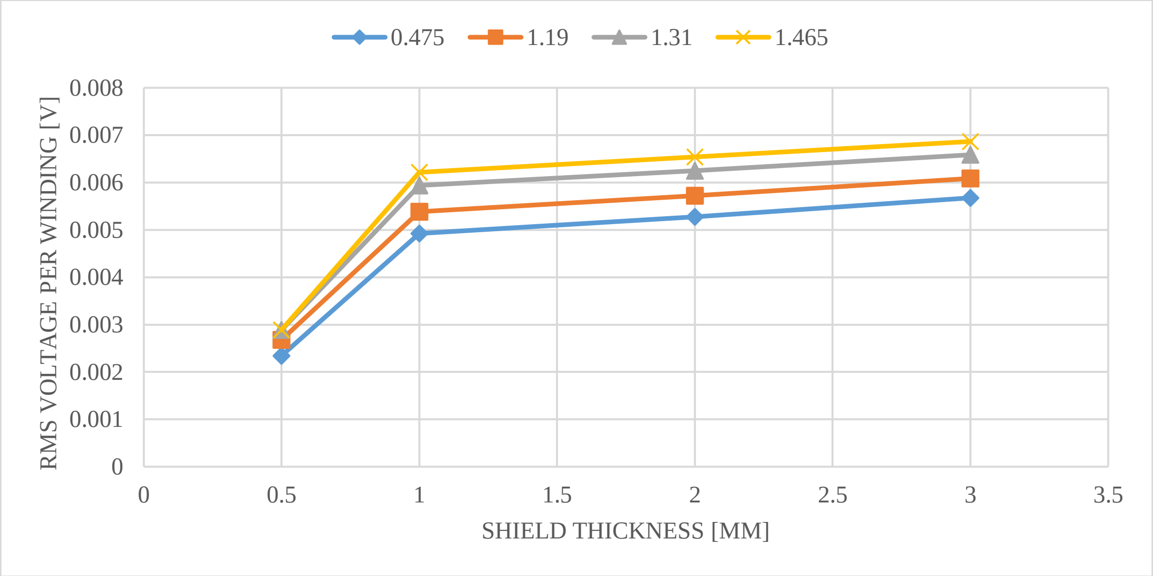


Figure 20: RMS voltage of an alternator at 10 Hz for varying shield thickness and permanent magnet grade

The most apparent feature of Figure 20 is the cut-off point at which the shield thickness begins to deliver diminishing returns, which exists between 0.5mm and 1.0mm. In addition, the grade of magnet determines the efficacy of the shield. Between a shield thickness of 0.5mm and 1.0 mm, the highest grade of magnet (N-52) exhibited an increased rate of RMS potential per change in shield thickness than the next-highest grade. Increased need for shielding of more powerful magnets explains the increasing returns for the same thickness increase.

Having an appropriate amount of shielding within a generator can increase the output of the generator. However, the returns of shielding decrease as the thickness of the shield increases. Because structural ferromagnetic materials are generally more affordable than high-grade magnets, increasing shield thickness should be used to increase the output before increasing magnet thickness, especially with high-grade magnets. Because neither magnet or shield thickness is limited in the configuration explored in this paper, similar configurations should attempt to increase both in conjunction to ensure the most performance for a given outer size envelope.

Physical Evaluation of Prototype

Increasing the thickness, grade, and shielding of the magnets produced a larger output voltage from the alternator. While the increase was not as large as simulations predicted, the voltage did increase. The limited increase could be due to several noted factors in the modified alternator:

- Increased gap between inner magnet face and iron cores
- Gap in modified magnet pattern
- Errors in measurement due to noise in output data

As observed in Figure 10, the data from the smaller motor was not as regular as the larger motor. While data did have a semi-sinusoidal form, much more noise was present. Comparing the two groups of data in Figure 18 demonstrates the similarity of the two rotation source's results. Because of the same general shape of the frequency-voltage plot, both series show legitimacy.

Despite the increase in simulations being larger than the experimental data, the fact that improvements were seen despite the errors mentioned above implies the efficacy of the improvements. Most notable in the errors is the increased gap between the magnets and the core faces. The amount of magnetic field which may escape directly into the magnets from the gap increases greatly with small differences in gap. Unfortunately, the manufacturing tolerances required for both magnet and rotor shell prohibit a finer tolerance than existing.

A simulation of tolerance's effect on output is shown in figure 18, in which the gap size and frequency vary and produce different output voltages. The results of this simulation are shown in figure 21.

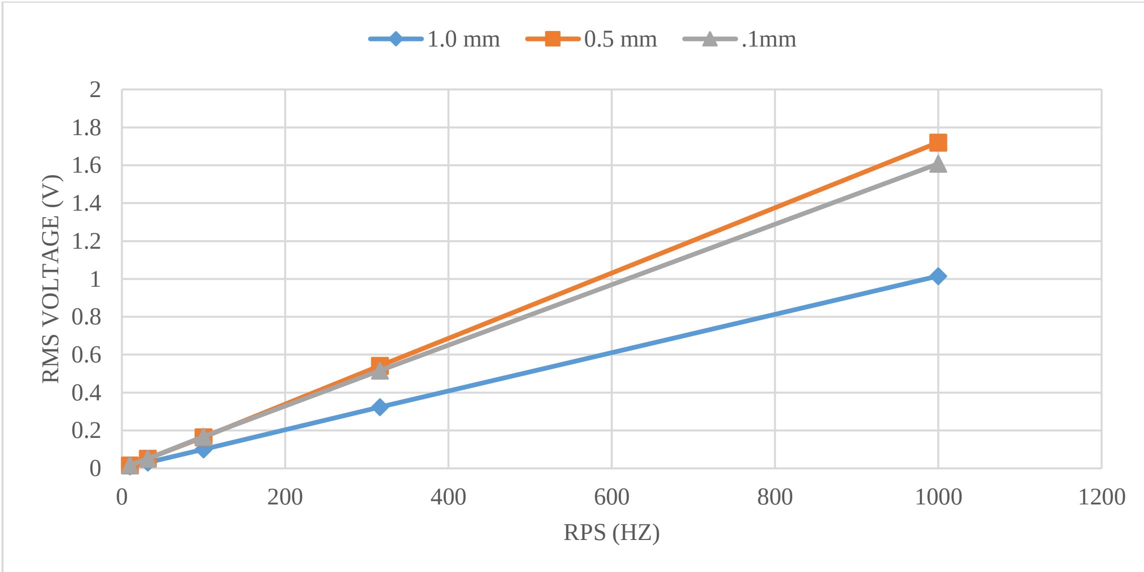


Figure 21: RMS voltage versus shaft frequencies for various magnet-core gap widths. The two smallest gap sizes present little change, but the largest gap shows a great decrease in voltage output.

The voltage of a large gap is lower than that of either of the smaller gaps, as expected. However, the smallest gap did not provide the most output voltage as expected. Despite these irregularities in simulation explain the unexpected results, the largest gap producing a fraction of the voltage of either ‘small’ gap size still verify results.

Chapter 5

Conclusions

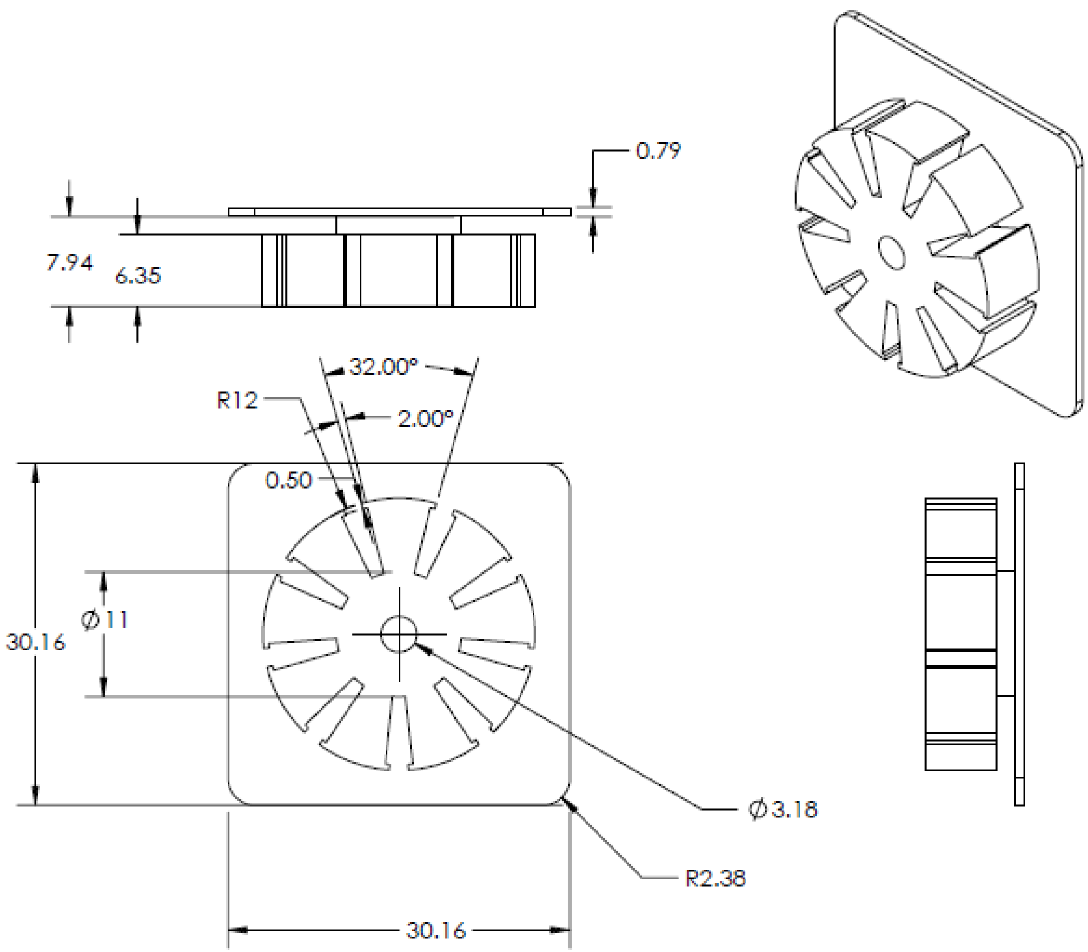
A direct-drive permanent-magnet alternator intended for wind applications presents many opportunities for design optimizations, all of which provide improvements of varying amount. The largest single improvement is the inclusion of a Halbach array, because it provides large benefits without significantly increasing cost.

Using thicker magnets of a higher grade with a thicker shield on the same body as a stock generator showed marked improvements in performance. However, due to the lower tolerance of design, power losses occurred. Therefore, improvements in design must be paired with consistency of manufacture.

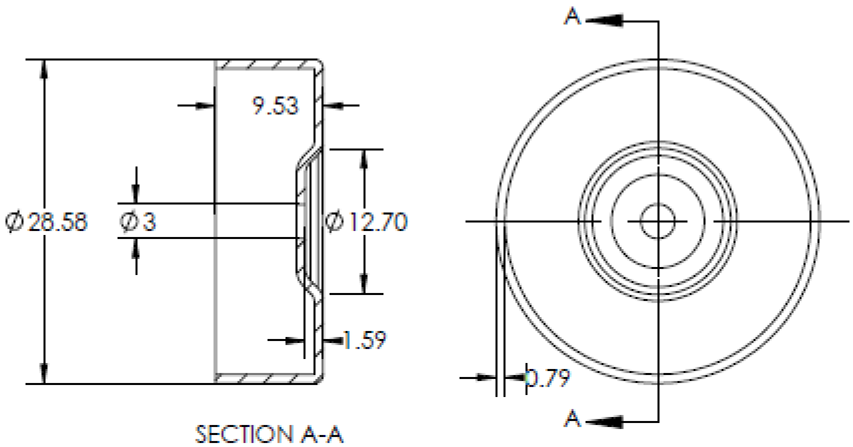
Further design possibilities may include changes in the stator and configurations, such as noted in the literature review. Scale may also present difficulties in design and manufacture and should also be considered in further research. Simulation also presents concerns with accuracy of outputs, and a physical prototype is exclusive in giving reliably tangible output data.

Appendix

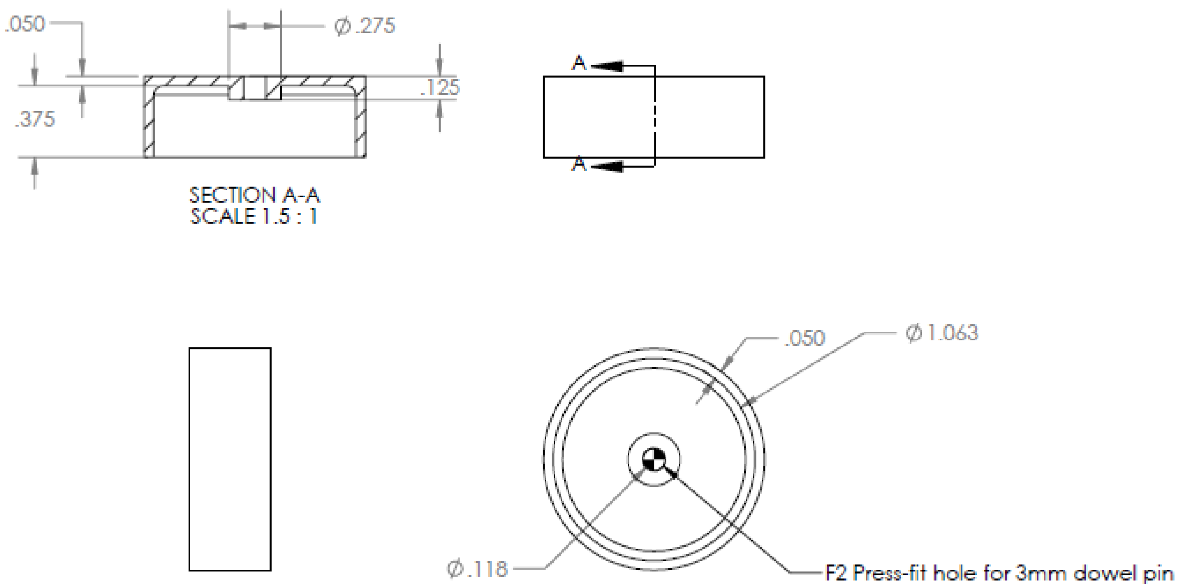
Determined Dimensions of Generator



Stator and core dimensions



Stock rotor dimensions



Modified rotor dimensions

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EDUCATION

The Pennsylvania State University, Schreyer Honors College — *University Park, PA*
Bachelor of Science in Mechanical Engineering — *Class of May 2018*

- Minor: Engineering Mechanics
- Dean's List (7/7 semesters)
- Publications: "Design, Simulation, and Prototyping of a Low-Speed Permanent-Magnet Alternator", "The water recovery x-ray rocket", "Elastic-thermal Stresses in Open-Heart Refractory Furnace Brick"

ENGINEERING EXPERIENCE

PSU Department of Engineering Science and Mechanics — *University Park, PA*
Research Assistant – Refractory Brick Heat Transfer — *December 2017-Present*

- Use inverse finite-element analysis to find unknown heat flux through a brick of known temperature
- Troubleshoot problems while running code cards for proprietary program
- Analyze heat transfer computations for validity

PSU Department of Astronomy & Astrophysics — *University Park, PA*
Engineering Assistant – Water Recovery X-Ray Rocket — *August 2016-Present*

- Create and assemble 3D CAD models in SolidWorks for a high-atmosphere rocket
- Design and revise structural assemblies, restraints, and vacuum components within the rocket
- Create dimensioned drawings for fabrication of components by NASA machine shops
- Design and build a test setup for ion vacuum pump for the rocket using a $5,000 budget
- Locate vendors for manufacturing quotes and purchase custom components
- Build, assemble, and disassemble rocket and experimental components in a laboratory/cleanroom

Schreyer Honors College Capstone Project — *University Park, PA*
Honors Student – Schreyer Thesis — *June 2016-Present*

- Research, design, and build generator which can generate electric power from low-speed sources
- Collaborate with faculty and coworkers to generate power requirements and design parameters
- Experiment with physical prototypes to ensure product utility using modified existing components
- Report conclusion and summarize work by authoring thesis for review by Honors College faculty

LEADERSHIP EXPERIENCE

Lion Tech Rocket Labs – NASA Model Rocket Competition — *University Park, PA*
Co-lead – Payload Subsystem — *August 2015-April 2017*

- Designed, tested, and built payloads for NASA's University Student Launch Initiative competition
- Co-led the Payload subsystem by arranging and overseeing meetings and collaborating with other leads
- Projects include:
  - Fragile Object Protection System: Protects a specimen from damage through launch and landing
  - Kiwi: Autonomous gyrocopter that guides itself to a specified landing point
  - Terrain Analysis Package: Camera system which analyzes the landing zone for potential hazards
- Authored proposal and status reports for review by NASA for project completion
- Operated, recovered, and analyzed payload performance at launches

WORK EXPERIENCE

- **HUB Retail Dining**: Student work, Fall 2015
- **Taco Bell, LLC**: Summer work 2014-2016
- **Giant Food Stores**: Summer work 2013

SKILLS

- MATLAB
- SolidWorks 3D
- Microsoft Excel
- ISO Class 7 Cleanroom operations