CWC 3D Printed Generator
(21Spr07-CWC3DGen)

Final Report

Luis Castaneda

Skyler Penny

Lucas Sottile

Simon Stoner

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NORTHERN ARIZONA UNIVERSITY | College of Engineering, Informatics, and Applied Sciences

Sponsor Mentor: Dr. David Willy, ANSYS

DISCLAIMER

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EXECUTIVE SUMMARY

Team CWC 3D Generator is tasked with designing and building a 3D printed generator that will be used on future CWC micro wind turbines from NAU. The purpose of this project is to encourage future CWC teams to design their motor which can integrate more seamlessly with the turbine design as well as have tuned performance characteristics that the future team desires. The team must teach themselves further in electrical engineering and how electric motors operate. This will be aided by the teams benchmarking through the first semester of this project as well a thorough literature review throughout the semester. The team decided to try different styles of motors to obtain the strengths and limitations of each. After the motors are built, the team will use a dynamometer or electric drill to measure power outputs with and without a load applied. The team then received sponsorship from ANSYS who provided the team members access to their software program called Motor-CAD which the team used to further analyze current and future motor designs that the team is pursuing. The team has taken what is learned through the past semester and this semester to develop the best solution to the problem with calculation-based decisions.

The team has decided on an outer-rotor design for the motor due to selection criteria from the decision matrix as well as the comparison from the analysis conducted in Motor-CAD. The outer rotor design was chosen due to how flat the motor can be if desired or needed by the customer requirements. The team iterated through a few designs during the semester to improve upon customer and engineering requirements. This includes performance characteristics of the motor as well as safety and 3D printability. Through testing the team was able to confirm more requirements have been met based on size, weight, and KV rating. The final configuration of the motor is as follows. The motor is a brushless permanent magnet outer rotor motor with 24 neodymium magnets, a stator with 18 slots, and 75 turns per slot, the motor is in a 3-phase wye configuration. The motor was made with a polycarbonate/ABS plastic blend to improve strength and temperature resistance and an iron-filled PLA plastic to improve motor performance and improve the KV rating of the motor. The team achieved a safe 3D-printed motor with high factors of safety, a KV rating of 110 which exceeds the team's expectations, and minimal cogging torque per the customer and engineering requirements.

ACKNOWLEDGEMENTS

Our team would like to acknowledge the instruction and support provided by Dr. David Willy throughout this year-long project. His assistance as a mentor and client sponsor was invaluable to the team project development. The NAU machine shop faculty, Wyatt, Paul, and Dr. Wood, all gave both advice as well as time towards helping with project component manufacturing which is greatly appreciated. Our team would also like to acknowledge ANSYS for allowing our team to run simulations to aid in the development of the project as well as offer a case study showing off the team's hard work and dedication through this project.

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1 BACKGROUND

1.1 Introduction

This project is to use 3D-printing technology to create a motor that is to be used as a generator on micro wind turbines for the Collegiate Wind Competition. The team is using their first semester to benchmark and test pre-existing 3D-printed motor designs as well as learn as much about motors as possible. This project has two sponsors, the first sponsor is David Willy who is our client and mentor through this project. David Willy is sponsoring this project as he is also the client and sponsor of the CWC team and wants the future teams to be able to design their motor instead of buying a commercial one. Upon completion of this project, the CWC will be benefitted by being able to have the motor become a part of the design process instead of having to design around the selected commercial motor. The second sponsor of this project is Motor Design Limited, which is a software company who is powered by Ansys. This sponsor does not have a stake in this project and was kind to provide a free license to one of the team members to aid the team with their project. Being able to have the CWC team in the future design their motor can help improve the design around the motor which has been done by the NAU CWC team. Being able to design and make a motor purpose-built can also give the CWC team an advantage by being able to design for minimum cogging torque or maximum power output.

1.2 Project Description

Following is the original project description provided by the sponsor.

> "For the DOE Collegiate Wind Competition, teams usually buy a motor to use as their generator within their design space or they design their generator specific to their needs. NAU has never designed their generator (due to student resources/interest) and has historically just purchased 3-phase permanent magnet synchronous motors that are found in drones to use as their generator. This leads to teams designing around (or forgetting to design around) the motor that they purchased. This design decision will dictate everything from torque-speed characteristics, voltage-current characteristics, and even when the turbine can overcome the total resistive torques of the drivetrain to begin turbine "startup". It is the classic "design around the commercially available parts" instead of "designing from the aerodynamics to the ground and the grid" that gives wind turbine startup companies problems in their design. The other added complication that this project would solve is the ability to not have long lead times and availability of commercially available. You would not redesign a bearing or even a bolt, but designing the generator to match the aerodynamics is a prudent decision in wind turbine design."
>
> This project will explore manufacturing techniques in 3D printing to solve some of the resistive torque issues seen in small wind turbines (more theory can be provided upon request) as well as the generator voltage constant. The team will be expected to build a few existing designs in 3D printed motors to learn the pros and cons as well as to gauge the performance of the resulting product. The team will then be required to come up with their design, after referencing the physics of the problem, that could be used as a testbed for future generator design. This final design will be able to modify things like voltage, current, torque, speed, and resistive torques (including cogging torque) as easily changed design parameters."

Timeline:
First Semester

1. Build 1-3 existing 3D printed designs that can easily be found online
2. Test at least one (ideally two) built design(s) using the CWC dynamometers
3. Design their mechanical design in full based on their favorite motor

Second Semester

1. Tweak the electrical design of their favorite motor to show that the above parameters can be controlled

2. Build their complete design
3. Test their design using the CWC dynamometers
4. Report on manufacturing techniques and best practices to control design parameters

2 REQUIREMENTS

The following three subsections will explain the customer requirements, the engineering requirements, and the house of quality that the team has created over the semester. Each of these requirements and criteria is tailored to the scope of this project and aided in the decisions that the team has made so far and for the future decisions moving forward with the project. The requirements remained unchanged from the first to the second semester of the project.

2.1 Customer Requirements (CRs)

Customer requirements have not changed ever since they were stated in the preliminary report from ME 476C. There are thirteen customer requirements. In descending order of weight (w): 3D printed components (w = 5), must be safe to operate (w = 5), robust design (w = 5), brushless motor (w = 4), compact size (w = 4), cost within budget (w = 4), CWC mounting pattern (w = 4), optimal power range (w = 4), reliable (w = 4), withstand speed (w = 4), minimal cogging torque (w = 3), reasonable power output (w = 3), integrable with CWC wind turbine (w = 2). However, one customer requirement has been adjusted for the final design. The customer requirement that called for a compact size design has been given a new meaning in which the size will be much larger than expected, yet it will still be compact enough to be mounted on a CWC wind turbine without compromising power output. This was done with the approval of our client. The reason behind this is to fulfill the electrical aspect of engineering requirements as more space for windings and magnets was required.

2.2 Engineering Requirements (ERs)

The following sections outline the nine engineering requirements and their respective target and tolerance values. The engineering requirements include voltage, power, price, power rating, weight, current, resistance, reliability, and durability. Each target was set by our client with room to adjust these values as needed through further design iterations.

2.2.1ER #1: Voltage

2.2.1.1 ER #1: Voltage Target </= 48 Volts

Professor Willy set the target voltage at approximately 48 Volts to produce a KV rating of 125. This value was chosen as 48 is a modest output voltage produced by commercial motors. The CWC team uses several commercial motors namely the MAD 5010 and the 5012 and operate anywhere from 24-48 Volts.

2.2.1.2 ER #1: Voltage Tolerance = +/- 10 volts

The voltage tolerance is dependent on the KV rating. If the voltage is too low but the speed of the shaft remains constant, then the KV will increase, and similarly, if the voltage is too high then the KV rating will decrease and the KV may be off our target rating of 125-240.

2.2.2 ER #2: Power

2.2.2.1 ER #2: Power Target = 300-400 Watts

The power was set by Professor Willy at 300-400 watts. Based on the commercial MAD motors used for the CWC team, they produce a power output of 340 W at continuous speed and a max of 720 W for the MAD 5010 and 5012. The implemented power output was based on the commercial motors used by the CWC team and is subject to fluctuate with the next iteration of the 3D printed motor design.

2.2.2.2 ER #2: Power Tolerance = + 500 Watts, -100 Watts

Based on an FEA simulated motor, the peak wattage is nearly 800 W and was used to make the unilateral tolerance for the power in the motor. The tolerance sways high in the positive range as more power output is ideal but less power produced by the target range is less than. The motor may fluctuate in power based on the manufacturing process. Not using a specific wire or too few or too many magnets can affect the overall power output.

2.2.3 ER #3 Price

2.2.3.1 ER #3: Cost under $500 - Target = $300

Our team was given an overall budget of $500 to spend no more than $300 on materials for 3D printing and manufacturing. So far, our team has put in 4 purchase request orders between this semester and last with an accumulated total of $247.86. Our team made sure to order all materials for our final iterations in the fourth purchase request meeting our target value under $300. If our team decides to purchase more items, we'll have just under $60 left before we run over our target mark.

2.2.3.2 ER #3: Cost under $500 - Tolerance = +/- $100

An additional $100 could be used to help manufacture multiple iterations and help mitigate any last-minute design choices that depend on more material purchases. By purchasing final materials ahead of time, our team can also reduce the overall budget and save money. Due to time and the purchases made for our last order, our team is well within our targeted budget and will likely never spend more than our overall budget of $500.

2.2.4 ER #4 Power Rating

2.2.4.1 ER #4: Power Rating Target = 125-240 KV

A motor rating of 125 KV was determined by the set voltage and speed of the device by Professor Willy. The ratio between RPM and voltage is the KV rating and with a set value of 48 Volts with a speed of 6,000 RPM, the motor rating starts at 125KV. The speed was suggested at 6,000 RPM to start but has room to increase to 8,000 making the KV nearly 170 using the voltage at 48 Volts. Voltage is also subject to change based on its tolerance and the interactions of motors if the voltage is less than the required maximum of 48 the KV rating will increase thus making the range of ratings set between 125-240KV.

2.2.4.2 ER #4: Power Rating Tolerance = +/- 100 KV

It is important to stay within the range suggested by our target rating as the higher the KV rating the higher the idle current of the motor which increases the heat from the core of the motor. Having a tolerance of 100 above or below the midrange for our targeted ratings won't affect the performance of the motor and less heat will be produced.

2.2.5 ER #5 Weight

2.2.5.1 ER #5: Weight Target = <1000 grams

The weight of the motor was determined by the commercial MAD motors weight which usually runs between 200-300 grams. The target is any weight less than 1000 to accommodate larger 3D printed motor designs than the commercial MAD motors. The appropriate limit of 1000 grams also increases the integrability with a small-scale turbine as the weight of the motor will not be too heavy to mate with the turbine.

2.2.5.2 ER #5: Weight Tolerance = +/- 100g

A lower tolerance is specified to reduce the weight of the motor and mate it with a small-scale turbine. If the motor weighs more than the specified tolerance amount, it runs the risk of failure and adds too much weight to micro wind turbines that utilize it. The tolerance is set to ensure functionality and integrability of the motor

2.2.6 ER #6 Current

2.2.6.1 ER #6: Current Target = 2.89 Amps

Current for the motor was found using Ohm's law with the constraint max voltage of 48 volts and a suggested resistance by Professor Willy to be under 200 Ohm's in resistance. The amperage is lower than the commercial motors but is necessary to ensure that less heat is dissipated from the core or copper wires as the 3D filament is not as heat resistant as the material used in the commercial MAD motors.

2.2.6.2 ER #6: Current Tolerance = +/- 0.5 A

The tolerance is set low to ensure the motor does not produce too much waste heat. Waste heat will affect the performance of the motor if components are melted or damaged due to too much current through the gauge of wire used for winding.

2.2.7 ER #7 Resistance

2.2.7.1 ER #7: Resistance Target = 166 Ohm's

The targeted resistance was found using Ohm's law with a set max voltage of 48 Volts and a suggested resistance of under 200 ohms. 166 Ohms ensures that the device will produce 48 using a low current.

2.2.7.2 ER #7: Resistance Tolerance = +/- 50 Ohm's

The resistance has a low tolerance to accommodate the KV rating and the max voltage of 48 volts. If the resistance is outside the specified tolerance range, the KV rating or voltage output may not reach our desired target values.

2.2.8 ER #8 Reliability

2.2.8.1 ER #8: Reliability Target = 10^6 revolutions

Multiple ball bearings are used to help actuate the rotation of the rotor. A life of 10 million cycles was designed so that the motor could theoretically last for over 10 years. Heat and other components may affect this life in revolutions and the target reliability is subject to change in further iterations. This is important to ensure the design works for a lengthy amount of time for the client.

2.2.8.2 ER #8: Reliability Tolerance = +/- 500,000 revolutions

The tolerance for the life of the bearings is low but does not have to be fixed to the specified tolerance as the life just needs to allow for over a year of performance to meet the requirements necessary to test.

2.2.9 ER #9 Durability

2.2.9.1 ER #9: Durability Target = 6,000 RPM

Professor Willy set the rotor speed at 6,000 RPM and was acquired to produce a relative KV rating of 125. Our max target KV is 240 which allows for an increase in RPM for future iterations. The speed is also set to allow the generator to handle the rotational velocity it must endure in a micro wind turbine experiencing high winds.

2.2.9.2 ER #9: Durability Tolerance = +/- 2,000 RPM

A tolerance of 2,000 RPM was implemented to reach a larger RPM of 8,000 or 4,000 RPM which are both within reason and support the KV rating and the voltage output.

2.3 Functional Decomposition

The functional decomposition section covers the Black Box and Decomposition models created and utilized by the team to ascertain and pinpoint the workings of a typical wind turbine outer rotor generator. These models are shown and described in detail below. Breaking down the function of a generator allows the team to achieve a better understanding of the internal workings of generators going into the generation phases of the project in which design ideas rely heavily on the basic principles of function. Both models were referenced throughout the first and second semesters.

2.3.1 Black Box Model

For a generalized breakdown of a wind turbine generator design, a Black Box Model was created to identify the primary function and types of materials, energies, and signals necessary. The model was broken down based on the primary function of power generation achieved by wind power generators. Figure 1 below shows the model created based on the inputs and outputs defined by the energy signal arrows. Material and signal input and output are not present due to the nature of the generator model. The only input is rotational energy transmitted from the wind turbine which in turn outputs an electrical current to convert kinetic energy to electrical power. There is not necessarily material inputted or outputted by these systems, neither is there any present signal such as audio or visual to indicate performance incorporated with the generator itself.

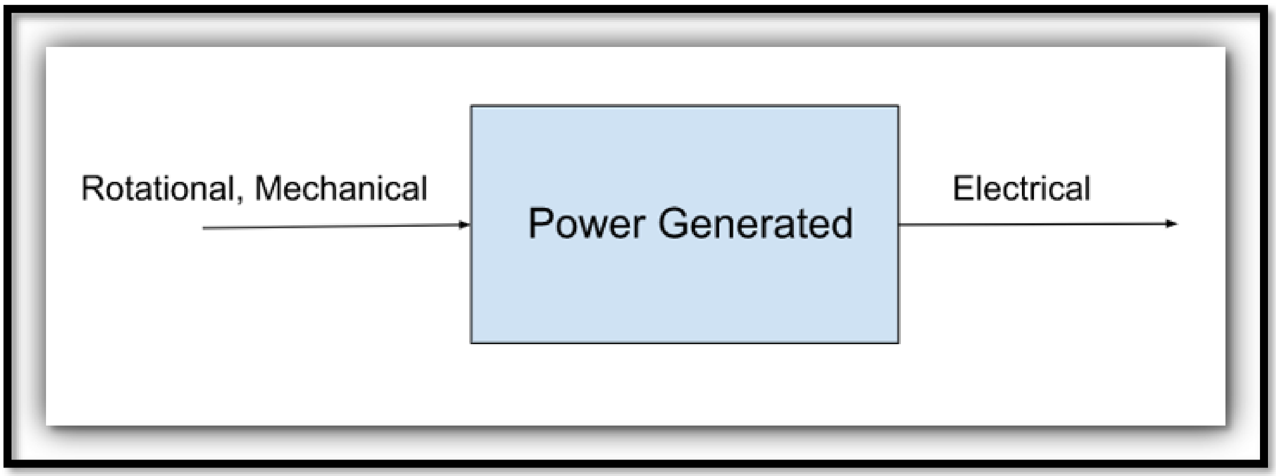

Figure 1: Black Box Generator Model

This model, although simple in appearance is important to the team's understanding of the generator's primary function and what is necessary to achieve this function. Furthermore, this model is important to relate to in times of confusion or clarity of purpose. In effect, the Black Box Model is the primitive measure necessary to ascertain a proper idea of the result to be achieved. It helped allow the team to break down the clarifying types of inputs and outputs involved with creating a generator. This model remains the same in the second semester of the project, still showing the platform for the outer rotor generator final design.

2.3.2 Functional Decomposition Model

The breakdown of a standard generator model using a decomposition model provided support behind all the functions occurring to meet the primary application of generating power. This model is an expansion of the black box model shown in figure 1. Using the input to output approach the design team broke down every step in the conversion of rotational kinetic energy to the outputted electrical energy. The following figure 2 shows the decomposition functional model for a magnetic flux generator that is brushless to adhere to the design goal. The arrows indicate the direction of energy flow through the system breakdown. This model continues to directly emulate the final product design, of an outer rotor breakdown of functionality.

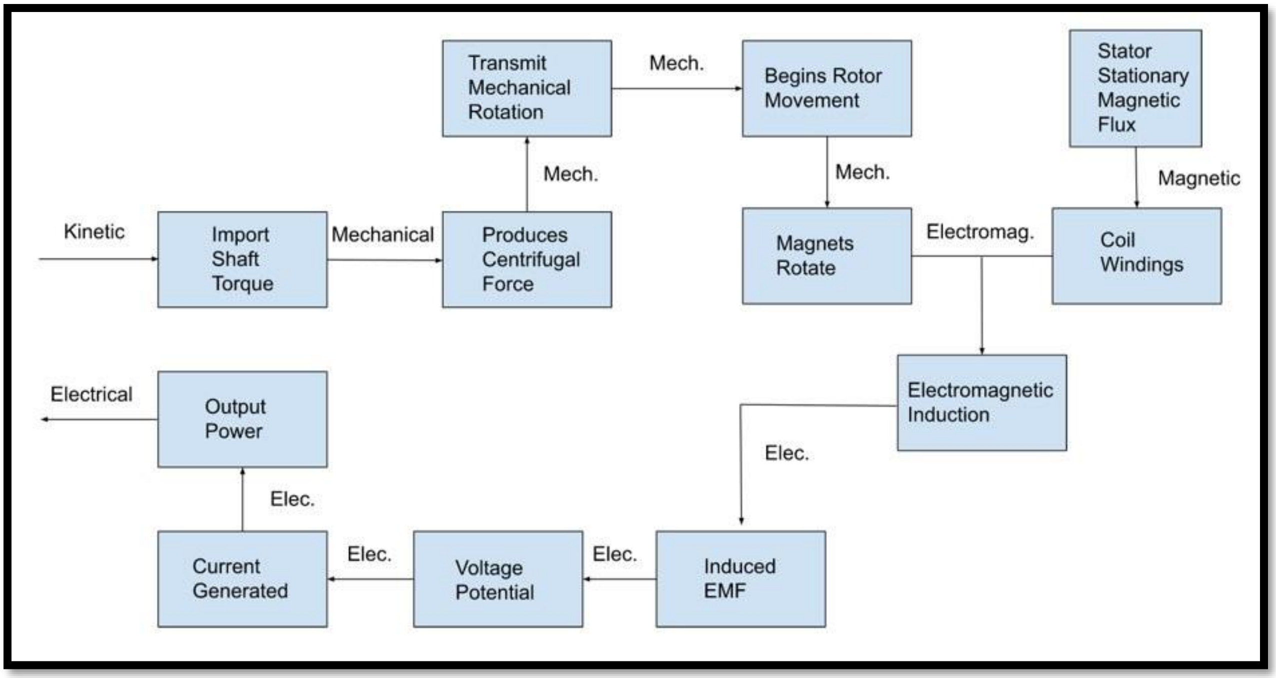

Figure 2: Functional Decomposition

The functional model shows all the elements that comprise the generator design, starting with the kinetic energy supplied which is converted to mechanical, electromagnetic, and finally electrical energy throughout the process shown. The major subsystems included are the rotor and stator which in turn produce the magnetic flux necessary to induce EMF creating a voltage potential to the current generated through rotation. The two subsystems are combined by the energy transfer elements that are included in the model. This model enabled the team to pinpoint the underlying functions occurring in a generator to achieve the output power from the inputted wind turbine-supplied rotational shaft torque. Confusion arose and was settled by the model process, primarily as to the stator and rotor relationship. After several iterations this final model allowed the team to develop an idea of the final generator design functional process. The decomposition model reflects the breakdown of an outer rotor generator design and thus remains unchanged in the second semester. This model was utilized multiple times throughout the second semester to help all team members grasp the inner workings of design decisions made for the final prototype.

2.4 House of Quality (HoQ)

A house of quality was created based on the already mentioned customer needs (CN) and engineering requirements (ER). Both, customer needs and engineering requirements, were compared and results were weighted to understand which ERs require the most attention in design. Results can be seen in Appendix A in figure 40. It was concluded that durability is our number one priority and resistance is our least priority. For durability, it would be measuring how fast can each design go without failing in rpm. Must be more than 6000 rpm. It is followed by the price in dollars for each prototype to be built, and it is expected for the cost to be less than $300. In the third place, there is weight, which refers to the weight of the overall design that has to be less than 1kg. Reliability is in fourth place and refers to the fatigue life of the design. It is important to point out that this was based on the minimum fatigue life of each member in a generator for which the bearings came out to be the shortest with 10^6 revolutions. The fifth place has output voltage measured in volts. Our goal is to reach 48 volts. The sixth place is followed by power produced by the generator to produce 300-400 watts. The seventh-place has a power rating KV with the goal of keeping it between 125-240 rpm/v. For the eighth place in importance, there is current production to have around 2.89 A. The least important is electrical resistant, the desirable resistance is 166Ω.

2.4.1 ER Testing Procedure

ER#: Voltage – Voltage was determined through open circuit testing in which our designed motor was driven by a dynamometer at varying speeds. For no-load AC, the motor is attached to the dynamometer and the voltage differential is determined via a multimeter. For DC, the motor is attached to a rectifier where loaded resistance can be applied, and the voltage is read through a current/voltage modulator.

ER#2: Power – The power is determined by loaded circuit testing where the designed motor is connected to a dynamometer and a rectifier to convert AC to DC. Resistance is applied to the load and the product of the applied resistance and current yields the power at a specified speed.

ER#3: Price – Each component of the motor was estimated in terms of cost based on the amount of material used for each part. The cost for the total amount of PLA and ABS used from their respective spools was determined by approximating how much polymer was used from each and multiplied by the total cost of the spools which was roughly $30.00. Dividing the approximated cost of material from each spool by the masses of the 3D components yielded the estimated cost for each part. The shaft, bearings, magnets, and wire costs were specified by the seller and were used in conjunction with the approximated cost for the 3D printed components.

ER#4: Rating – The KV rating was determined during no-load open circuit testing in which the motor was driven by a dynamometer and produced an output voltage at varying input speeds. The ratio of the speed to the output voltage was used to calculate the rating.

ER#5: Weight – The weight for each of the comments was measured by summing the masses for each of the parts.

ER#6: Current – The current was tested through loaded circuit testing where a resistive load connected to the rectifier affected the amount of output current. The current was measured via a current/voltage modulator at varying speeds from the dynamometer.

ER#7: Resistance- Resistance was tested by applying a load to the rectifier during loaded circuit testing. The input resistance was measured alongside the voltage and current.

ER#8: Reliability – The speed of the motor was analyzed through loaded and non-loaded open circuit testing. Our team opted to keep the speed relatively lower than the required speed running the motor at 3,000-4250RPM for roughly 5 minutes at a time. Our team did run our motor at 6,000 RPM but only for 10-second intervals.

ER#9: Durability- Durability was not tested but inferred based on the MR128ZZ ball bearings used and the Timken catalog. The Timken catalog rates deep groove ball bearings at 10^6 (1 million cycles). Our team used this rating for the durability of the designed motor.

2.5 Standards, Codes, and Regulations

To choose properly outsourced bearings for the final generator model, the use of the American Bearing Manufacturers Association (ABMA) will uphold the conventional standard of industry-selected bearings. This standard will come into play when the proposed forces, cycles, and heat of the generator model influence the type of bearings necessary to accommodate the target performance of the design. Using ABMA will make the selection process easier and uphold to currently used engineering standards applied for the use of bearings in most products in the energy production industry. Furthermore, this will allow this portion of our proposed design to comply with the American National Standards Institute (ANSI) [1]. Our final selected bearings adhere to ABMA as high-speed ball bearings that can perform at the speeds and forces of the generator model.

ASTM tests the magnetic flux of soft magnetic material [2]. Using standard ASTM practices, the soft material MnZn (Manganese-zinc) ferrite is used to measure the flux at varying core sizes. The test sample sizes are determined by the producer of the magnets, but the magnets must have a uniform cross-sectional area. ASTM tests the flux of each sample, measuring the core losses (diamagnetism) at 100kHz at 25 degrees celsius. To test the magnetic flux of the magnet, the flux calculated by the core losses is divided by the areas of the sample. To test the inductance permeability of the magnets the inductance of the magnet is divided by the air core inductance. The inductance is measured using a digital LCR meter. Although we did not have access to an LCR meter, the magnets chosen were up to par with the ASTM standard as presented by the manufacture. Furthermore, the part drawings all used ASTM standards to adhere to proper engineering layout.

IEEE 112 is a US standard created by IEEE for motor testing methods. This standard presents five motor testing methods for electrical motors. These methods include brake, dynamometer, duplicate machines, input measurement, and equivalent circuits. It is recommended to use the first three methods since input measurement should be used if a dynamometer is not available and an equivalent circuit is the least accurate test [3]. Our team primarily utilized the dynamometer testing method to evaluate the final design.

The National Electrical Manufacturers Association (NEMA) gives standards for multiple different size motors from service factors to maximum temperature rises in the motor. This information can act as a guide for the team when designing the motor with a certain factor of safety as well as when running thermal simulation through MotorCAD. There is a multitude of different standards for a small AC motor in this standards document which can aid the team in most aspects of the design and testing process [4]. The standard helped devise a proper factor of safety for the angular speeds of operating the generator in testing. There was very little heat rise in the final motor design which adhered to the standard outlined by NEMA.

Table 1: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ABMA	American Bearing Manufacturers Association	Allows for proper selection of outsourced bearings for the proposed final design. Our final selected bearings meet this standard through Timken.
ASTM	American Society for Testing and Materials Standard Specification for Soft Magnetic MnZn Ferrite Core Materials for Transformer and Inductor Applications	Analyzes magnetic flux for soft magnetic material such as MnZn (Manganese-zinc) ferrite at various temperatures. Helps in choosing what magnets produce the optimum amount of magnetic flux for the motor Used for the final N-52 grade magnet selection. Further utilized in component drawings.
IEEE 112	Institute of Electric and Electronic Engineers	The standard used for testing motors in the US. Gives five testing methods totals.
NEMA MG1	Standards for Motors and Generators	This standard document gives information about small AC motors service factors as well as temperature rises etc. The team can use this for designing factors of safety for the motor.

3 DESIGN SPACE RESEARCH

3.1 Literature Review

Each team member researched influential topics related to the progress of the project. Team member Luis Casteneda's research included papers about a dual stator motor, 3D printed motors, analysis of dual stator motors, and computational computer software for analysis of motors. His research aided the team with the decision process of which motor to use. His research also aided in his knowledge of testing the motor physically and theoretically. Team member Skyler Penny's research included a college report about an axial flux motor that was 3D printed, a developmental process and analysis of using a 3D printed generator for power harvesting, analytical analysis of integrating a generator into a wind turbine, and a book about different developments between multiple types of motors. His research helped the team with design decisions and considerations through the project and integration considerations. Team member Lucas Sottile's research included tutorials for the analysis software Motor-CAD, a book about electric machines focusing on how to develop an efficient electric machine, an article comparing FEA results to 3D printed parts, efficiency requirements for specific motors what their standards, and an article about how different variables affect torque of motors. Lucas' research helped the team with analysis of the motor mechanically and electrical performance. Team member Simon Stoner's research included learning about KV ratings, copper and iron losses, and magnetic flux. Simon's research helped the team understand what inefficiencies that might be present and possible methods to avoid some. Overall, the team's research has aided in the development and analysis of the motor to develop the final product.

3.2 Benchmarking

To capture a slew of designs to be used in analyzing for creating generator concepts, the benchmarking phase consisted of research into existing projects with a similar approach to the project description and current on-the-market motors. Multiple existing 3D printed designs were investigated and are thoroughly identified in this chapter section. Contacting a current CWC wind turbine team, the investigation of the currently used and outsourced generators purchased was also found to be of interest. The ability to use these currently outsourced motors as benchmarking factors further pushes the scope of the project mentioned in the project description. With very few constricting requirements the ability to use benchmarking generator designs as a guide enables the 3D generator team to narrow down the scope of the project and make concrete decisions that will guide the performance standards to uphold in the final design. The findings from the benchmarking process are further detailed in the remaining sections of this chapter.

3.2.1 System-Level Benchmarking

The systems selected of importance to meeting the project requirements to an extent that produces viable informative study are listed in the next sections. The first selection made for the benchmarking systems is an existing axial flux generator model [5]. This particular model conforms to some of our design criteria specified by the project parameters, including being brushless. The reason behind choosing this generator model for design number one is due to its simple construction and 3D printable parts. The second choice of study is an existing BPMIR motor [6]. This design was chosen for benchmarking due to its similar project approach and ability to generate power using low-speed rotation. Because the project specifies a generator that produces power based on wind turbines at higher speeds, yet if this design can produce power at lower speed ranges it may be useful to improving high-speed efficiency and a good comparison tool for manufacturing. Lastly, design number three the MAD motor was chosen as a benchmarking tool, selected purely based on its current use in the CWC wind turbines [7]. The ability to analyze the workings of this generator will greatly improve the team's ability to understand how it performs and either match or inevitably try to surpass its performance in the final team prototype design. Specifications on these chosen design details are given in the flowing sub-sections for chapter 3.

3.2.1.1 Existing Design #1: Axial Flux Generator

The first existing design that the team reviewed is an axial flux generator. This type of generator is where the rotors and stators are on the same plane, parallel to each other. Figure 3 shows a blown-up image of this type of generator.

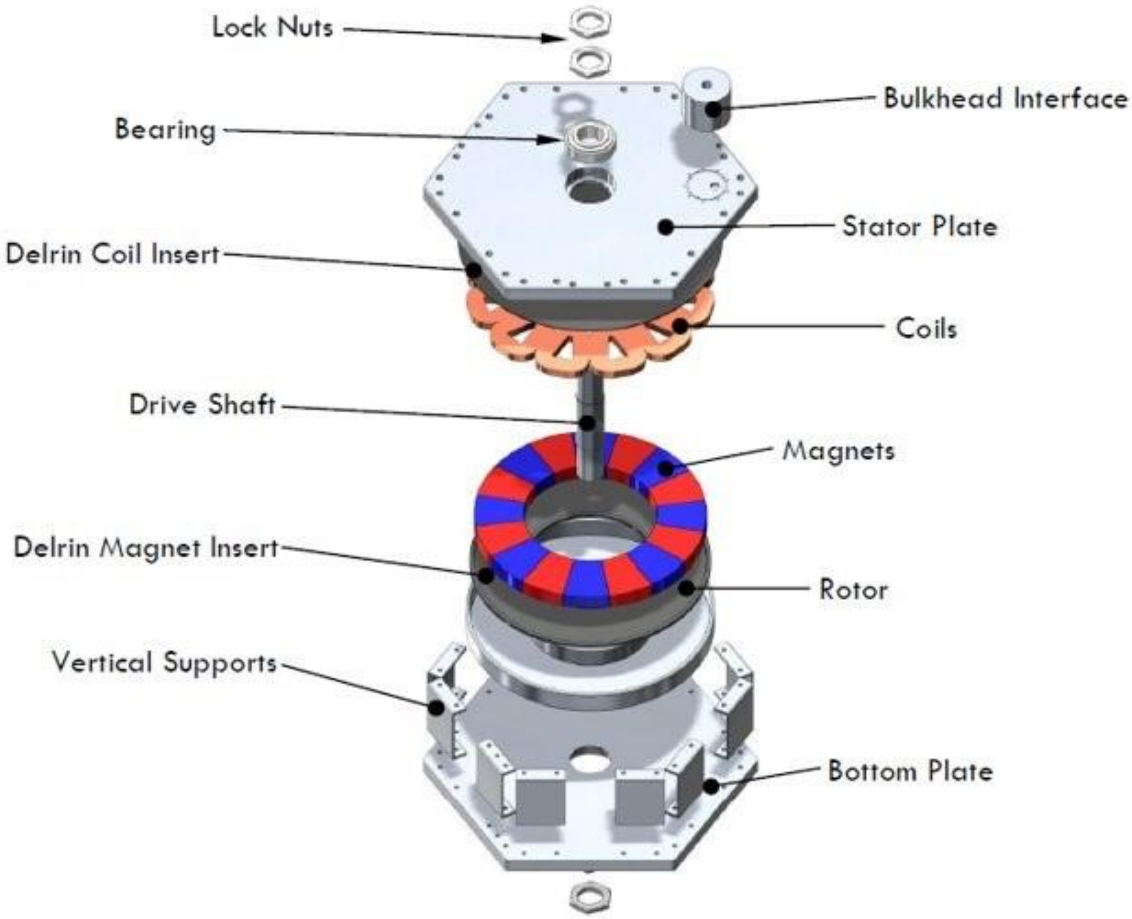

Figure 3: Axial Flux Generator [5]

This generator can perform compactly with an efficiency that is up to standards when it comes to electric motors. The specifications and performance of this motor under certain conditions are listed below.

- @ 92.3 rpm 803.57 watts and 85.56% efficiency
- Maximum Voltage of 71.86V
- Halbach Array magnet positioning for highest efficiency (neodymium magnets)
- 'Wye' configuration for coiling (Higher voltage, lower current than Delta)
- (TSR) Tip Speed Ratio at 1.4
- 7mm air gap

This motor meets most of the requirements that the team listed and exceeded performance. The team's motor must be able to perform at those requirements while at a 6000rpm speed, with this motor, the voltage is too high for such a low rpm, but is a very compact and simple design.

3.2.1.2 Existing Design #2: BPMIR

The second motor that the team benchmarked was a brushless permanent magnet motor with the rotor on the inside. This motor type is one of the most common motor types. These motors have high torque to size ratio, however, this is not what the team is looking for in a motor.

Figure 4: BPMIR Motor [6]

This type of motor can be used as a generator as well, but to get the power output desired in the engineering and customer requirements, the size of this type of motor would be too large to fit on a micro wind turbine. These motors are also efficient and can handle the rpm's that will be seen in this scenario.

3.2.1.3 Existing Design #3: BPMOR

The motor pictured below is a MAD 5010 EEE motor which is a brushless permanent magnet motor that has its rotor on the outside. This is one of the commercially available motors that is a multi-purpose motor that can be used for a variety of applications.

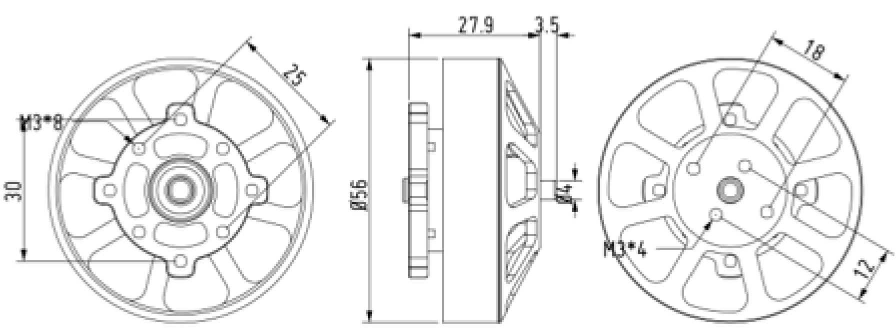

Figure 5: MAD 5010

The motor pictured above met the most customer and engineering requirements out of the three. This motor can produce 720 watts of power [8], this motor can also withstand the high RPMs seen in micro wind turbines. With this style of motor, the size can be relatively small by just increasing the diameter of the motor. This style of motor can also have minimal cogging torque when designed to have that characteristic.

3.2.2 Subsystem Level Benchmarking

There are three subsystems for all the generator models being analyzed for benchmarking and current exiting systems, the following three subsections will describe each different one and which part of the generator that they correspond to. The subsystems relate directly to the decomposition model in which their various functions are outlined and broken down. The generator design is quite simple in structure and is only composed of these three subsystems in total.

3.2.2.1 Subsystem #1: Stator

The first subsystem of any generator is the stator. The stator is one of the stationary parts of any motor. The stator is where the coils or copper windings are and therefore are not able to rotate, which is true for every type of motor. The eddy currents are formed on the stator and in the wire windings where the electricity will flow out. Figure 6 below is one example of a common generator stator design.

Figure 6: Generator Stator Example [7]

3.2.2.2 Subsystem #2: Rotor

This next subsystem is called the rotor. This is where the magnets are placed on the motor which will rotate around or next to the stator to generate eddy currents which in turn creates electricity. The rotor rotates due to direct transmission of torque to the rotor shaft connection supplied by either a dynameter or wind turbine in which it is installed. The magnets will also always be on the rotor for any type of wind power generator. Figure 7 below shows a simple rotor design in which the magnets on the outside can be observed.

Figure 7: Generator Rotor Example [9]

3.2.2.3 Subsystem #3: Shaft

The last subsystem that every motor has is the shaft. The shaft can be of any length or size and is usually a non-ferrous material. The shaft is what transmits the work put into the system or transmits the work out of the system. The shaft will always be attached to the rotor for any type of motor. It is the primary component in transmitting the rotational torque to the generator system from a micro wind turbine, usually through a gear box. Figure 8 below shows a metal shaft example that could be used in a generator model.

Figure 8: Generator Shaft Example [10]

4 CONCEPT GENERATION

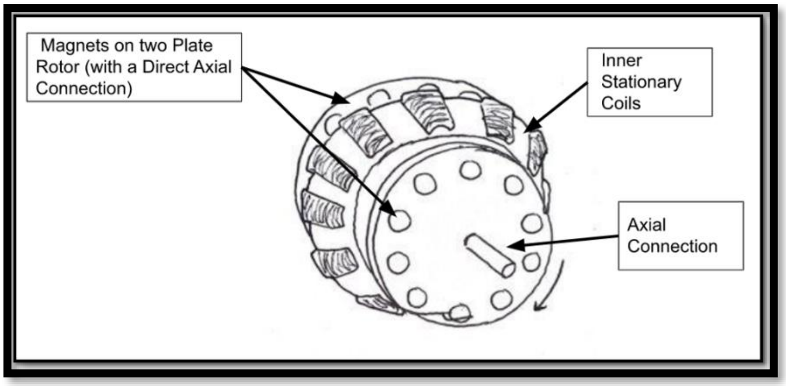

Figure 9: Axial Flux Illustration

Figure 10: First Design Prototype

The axial flux generator was designed first and can be seen in figure 9. This design has a housing for the rotor and stator with two functioning rotors in front and back of the stator. The stator has bearings from a circular pattern along with the rotor plate with each bearing wound with copper wire to help produce an EMF relationship with the rotor plates. The circular rotor plates have 16 magnets along the edges that help the design create an induced EMF relationship with the copper coils around each of the bearings. The axial flow is the preferred design for heat dissipation as the flow can pass through either side (front or back) of the design and the air can be circulated from the two rotor plates. The design is limited on functionality as the integration with wind propellers is seemingly more difficult than an outer rotor design. [5] A wind propeller must be attached to the central cylindrical brass rod which can cause a wobbling torque effect due to the load of the propeller blades onto the shaft. Direct mounting between the propeller blades and the rotor was considered after the design of the prototype.

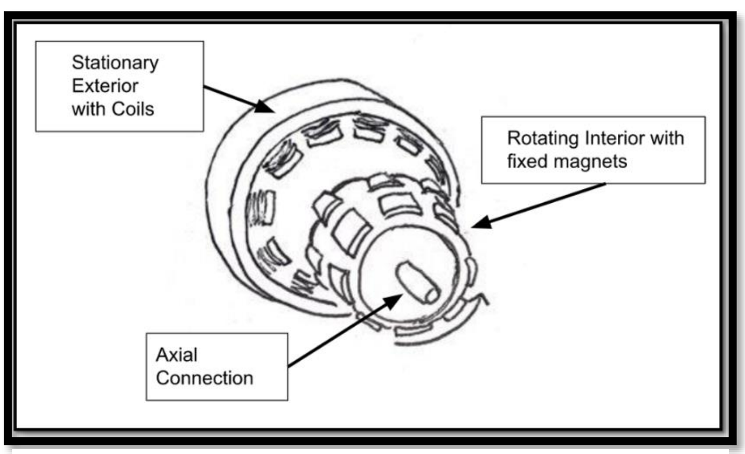

Figure 11: Inner Rotor Illustration

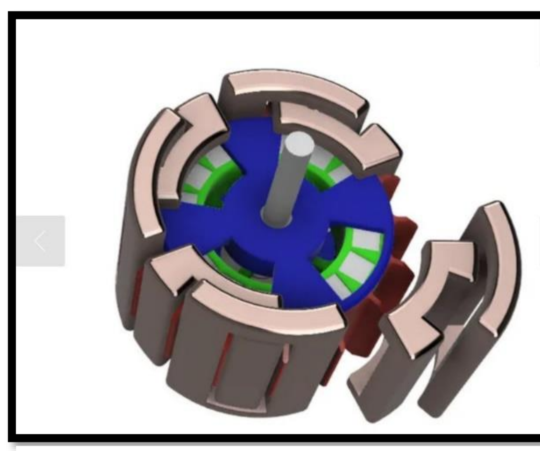

Figure 12: Second Design Choice

The inner rotor generator is the next design our team will analyze and design. Figure 11 showcases the design for the inner rotor design. As shown, the rotor is in the center of the stator with 2 support casings (shown in blue) in the front and rear of the design. The stator has 16 slots for copper winding which are in 2 phase y-configuration. Similarly, to the axial flow design, the integration of the wind propeller is not as strong as in an outer rotor design. This also will affect the torque of the design as the propeller load might cause wobbling. The benefit to this design is it could cost less to produce as fewer parts such as the additional rotor and bearings are not necessary. The rotor on the interior is also less vulnerable to outside elements such as rain, wind, or dirt that can cause rotor misalignment and cogging torque. [5] The inner rotor design is the most common dc motor type which means that there is more data involving this design which can help our team create a better model by comparing data.

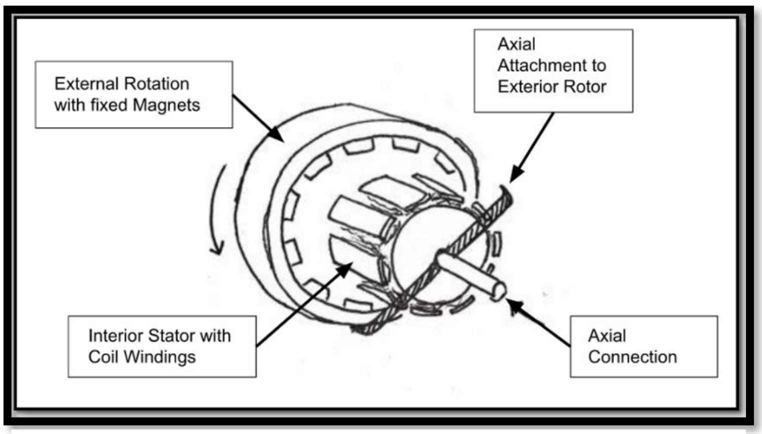

Figure 13: Outer Rotor Illustration

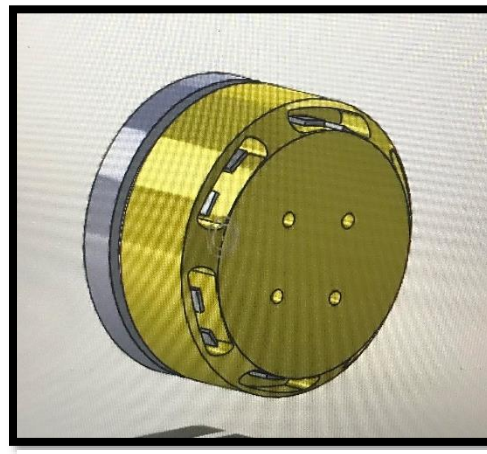

Figure 14: Final Design CAD

The final concept generated was the outer rotor design. This particular design is used in many of the outsourced motor models used by the CWC teams. Figure 13 above shows the concept sketch. The outer rotor design contains a rotor with magnets and a stator with coils. A single axial connection travels through the entire design as shown. The shaft rotates through the center of the stator and is attached to the rotor part. This design seems the most promising for the functions of the project parameters, the initial CAD design is shown in figure 14 above. The gold portion represents the rotor and the grey the stator/mounting portion.

5 DESIGN SELECTED – First Semester

This section will detail the processes leading to the eventual final generator design. Highlighted in the subsequent sections are the basic calculations for the final design based on the customer requirements and the three design types analyzed throughout the first semester. Elements from each design were considered before deciding upon the final generator and each of the following generators will be discussed to better understand the decision for the final design. Lastly, the approach to innovating and constructing our final design will be discussed along with the layout for individual tasks in the next semester. All materials for the final design will be listed in the bill of materials. The bill of materials is an active document and is likely to change before semester 2. Our team has several resources to aid our design. Some resources include the CWC 2021 team, NAU machine shop, and MAD motor design for 5010 and 5012 models for reference.

5.1 Design Description

5.1.1 Basic Design Calculations for Final Design

Table 2: ERs and Associated Equations

Given Parameters	Formula	Result
Power = 300Watts	KV = RPM/V	110 [RPM/Volt]
Max Voltage = 48Volts	Current = P/V	Unkown [A]
Approximate Speed = 6000RPM	Resistance = V^2/P	7.68 [ohm]

Rotor Moment of Inertia:

$$J = \frac{1}{8} mD^2 = 0.48(N * m) \quad 1$$

Torque Constant:

$$k_t = \frac{T}{I} = 0.0768 \left(\frac{Nm}{Amp}\right) \quad 2$$

Back EMF Constant:

$$k_e = \frac{v}{Rpm} = 763.9 \times 10^{-6} \left(\frac{V}{RPM}\right) \quad 3$$

Mechanical Time Constant:

$$\tau_m = \frac{\Omega \times J}{k_e \times K_t} = 62.8(\text{sec}) \qquad 4$$

The calculations above are based on the requirements for power, voltage, and speed. The power must be at least 300 Watts, have a maximum voltage of 48 Volts, and a speed of approximately 6,000 RPM. Together, from the constraints, the formulas for the KV rating, current, and resistance can be applied and determined. The team chose a final design of an outer rotor generator which will be discussed further in the following sections. For this design, integration with turbine blades and other RC elements is most used and is affected by the machine time constant which is calculated below the basic calculations for the final design. The rotor inertia, resistance, back emf constant, and torque constant were considered to generate the formula for the machine time constant in seconds. The mass of the entire final design was approximated using the MAD 5012 motor as a reference with a mass of approximately 0.11kg. This was also factored into the rotor inertia formula. The back emf constant is the ratio of voltage to the speed of the design in rad/s. The requirement of 6,000 RPM was converted into rad/s and was divided by the max voltage constraint of 48 volts. The Torque constant is the ratio of the torque of the design to the current in amps. The torque was back solved using the relationship of power and speed from the customer requirements. The resistance also plays a role in the machine time constant and was back solved using the relationship of voltage and power. [5] Together, these parameters produce the machine time constant which is the amount of time for the generator to reach roughly 63% of the max speed at the max voltage. The time constant is 62.8 seconds taking the generator over a minute to reach maximum speed at the required voltage.

5.1.2 Outer Rotor Generator

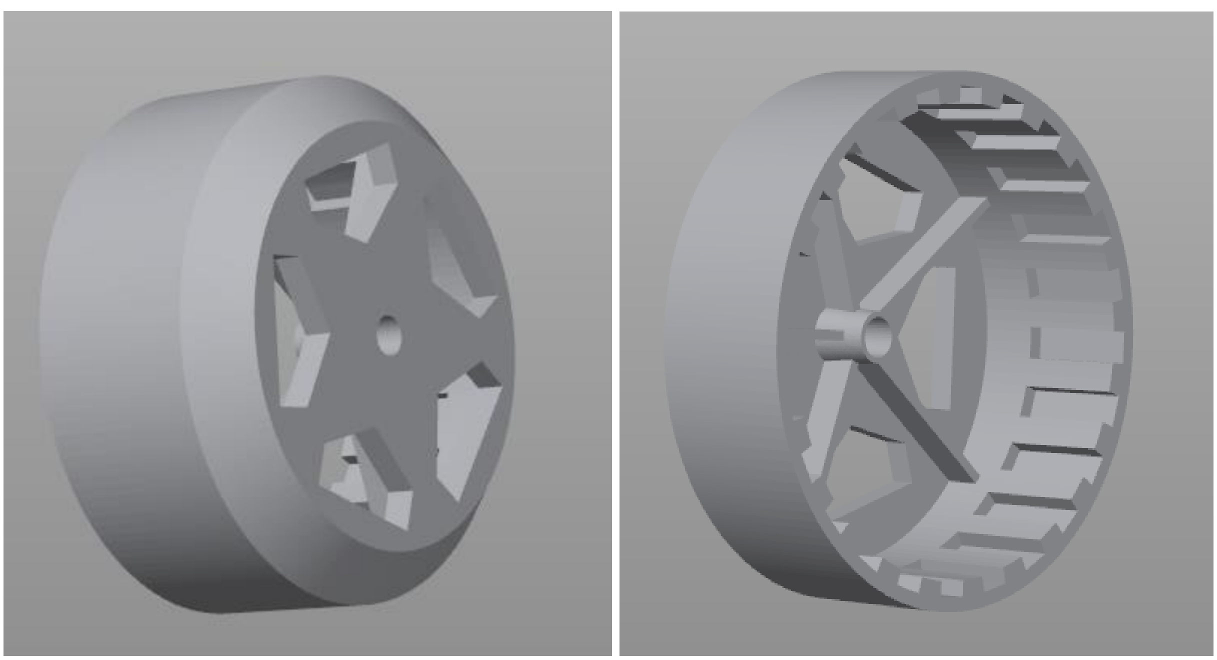

Figure 15: Final Rotor Design

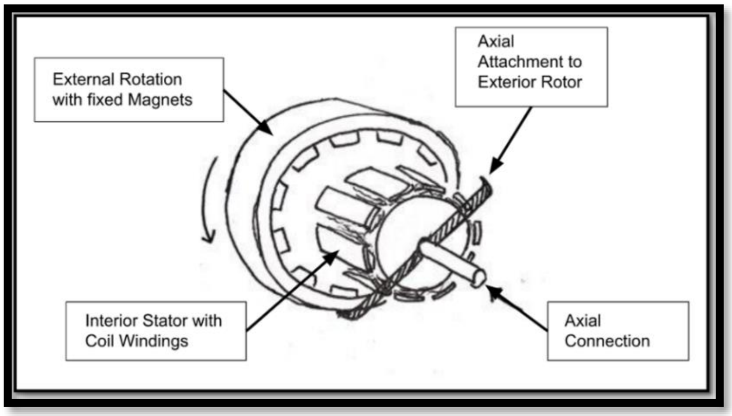

Figure 16: Outer Rotor Illustration

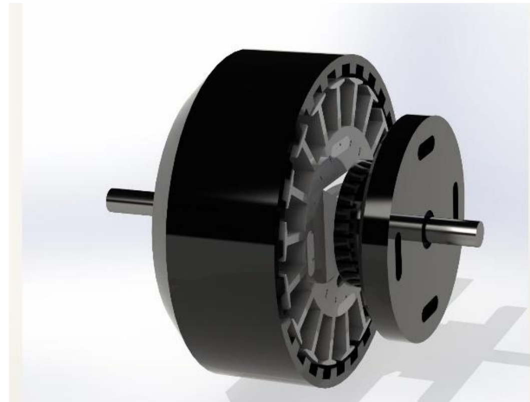

Figure 17: Final Design CAD

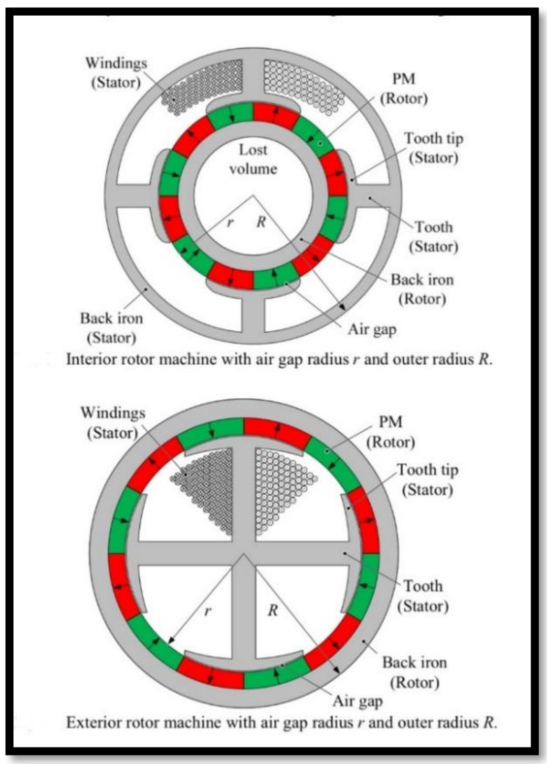

Figure 18: Outer Rotor Section View [5]

The outer rotor design was chosen based on our decision matrix and integrability with a small-scale wind turbine. Figure 17 showcases the final CAD model for the outer rotor design. The rotor is shown in black and has 24 magnets and is made with PC/ABS plastic for strength and heat resistance. This motor design is commonly used with small propellers and RC electric events due to the ease of integration with propeller blades with direct mounting onto the rotor itself. This reduces the wobbling torque when compared to the axial and inner rotor designs. [5] By adding propeller blades to the rotor, the design will act as an impeller which helps dissipate heat from the core of the design and allows for added air circulation via the propeller blades. The impeller will reduce the machine time constant as seen above as the speed of the rotor may be reduced if wind propellers are mounted to the motor. Figure 15 illustrates the sectional view of an outer rotor design which is used to help calculate the torque. [5] The torque is a measure of the force times the radius of the air gap and since the outer rotor has the largest air gap between a standard dc motor (i.e., inner rotor) the outer rotor produces the most torque. Outer rotors are generally smaller, axially than the inner and axial flow generators. This means that this design is more compact than the previous two.

5.2 Implementation Plan

5.2.1 Proof of Concept

Decision Factors		Concept 1		Concept 2		Concept 3	
		R.S.	W.S.	R.S.	W.S.	R.S.	W.S.
Criteria:	Weight						
1) Optimal Power	0.1	100	10	50	5	95	9.5
2) Voltage Output	0.1	90	9	70	7	90	9
3) Withstand Max RPM	0.1	100	10	75	7.5	100	10
4) Brushless	0.12	100	12	100	12	100	12
5) Integration	0.05	90	4.5	45	2.25	35	1.75
6) 3D Printed Elements	0.2	100	20	100	20	95	19
7) Minimal Cogging	0.1	90	9	90	9	85	8.5
8) Standard Mounting	0.11	100	11	40	4.4	25	2.75
9) Compact Size	0.12	85	10.2	80	9.6	30	3.6
	Totals		95.7		76.75		76.1
	Relative Rank		1		2		3

Figure 19: Decision Matrix

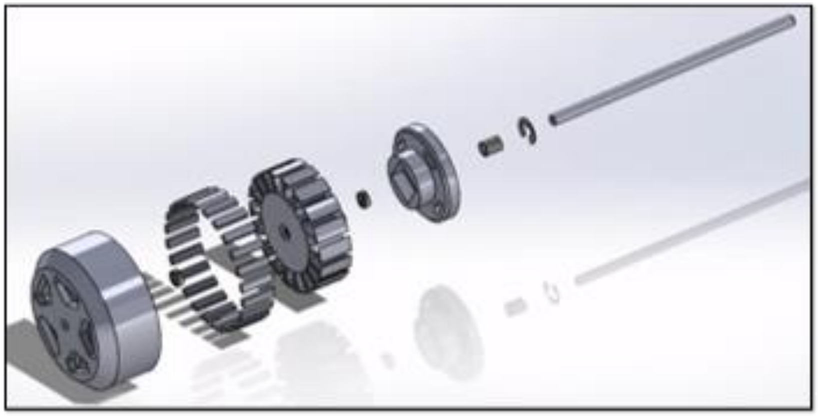

Figure 20: Final Design Exploded View

An exploded view of our final design can be seen above along with the decision matrix. Based on our customer requirements, optimal power, standard mounting, compact size, and low cogging torque were weighted the highest. The outer rotor design was ranked first based on these requirements compared to the inner and axial flow generator. A final CAD design was built in SolidWorks to be used as proof of concept and allow further analysis of this design. The design has 24 block magnets that slot into the rotor which will be actuated by the stator shown as part 6 in the exploded view. The steel shaft will be permanently fixed to the rotor and will pass axially through the design. The bearing will allow the rotor to spin clockwise or counterclockwise depending on the induced EMF from the copper windings. The stator will be permanently fixed to the housing of the design, but further analysis is required to implement that at this time.

The following two figures below are analyses of our two-top designs from the decision matrix. The analyses were done using Motor-CAD's generator feature for the two motors in as
similar configurations as possible to further compare the two. The first motor is the BPMOR motor with a power versus rpm graph.

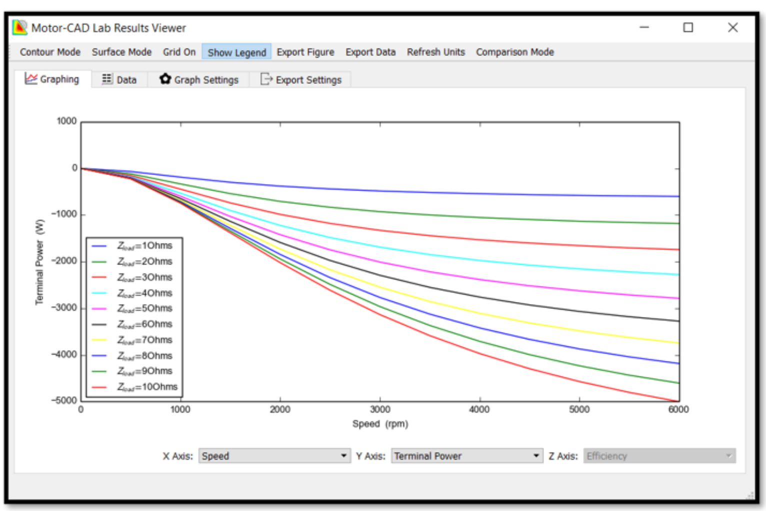

Figure 21: Power VS RPM BPMOR [6]

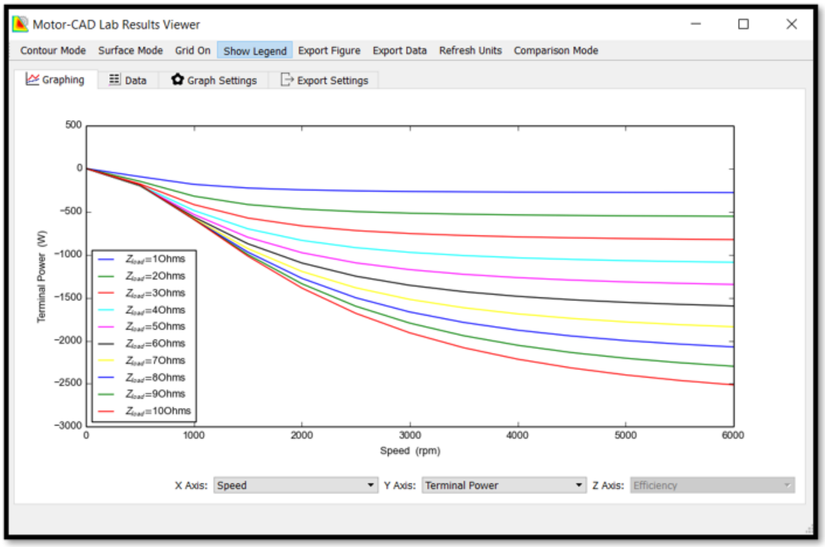

Figure 22: Power VS RPM BPMIR [6]

Comparing the data from the two graphs shown above, it can be seen that the BPMOR motor has a higher output power than the BPMIR motor which further confirms the correct outcome of the decision matrix in the previous section.

The last figure shown below shows the current CAD model of our team's design based on all the data previously mentioned throughout this report.

6 IMPLEMENTATION – Second Semester

6.1 Design Changes in Second Semester

6.1.1 Design Iteration 1: Change in [Rotor] discussion

Our team redesigned the rotor as seen in Figures 23 and 24 to include 4 trapezoidal vents to allow waste heat to dissipate from the copper windings and the iron-PLA stator. The first iteration was nearly 65mm in depth with 20mm designated towards making the arches for aesthetic purposes. The first iteration had no ribs that connected to the shaft port which made the rotor wobble at high speeds. The total number of poles was 24 for magnets to allow for minimal cogging torque. PLA was the material used for the first iteration rotor to minimize printing time and cost.

Figure 23: First Iteration Rotor Back View

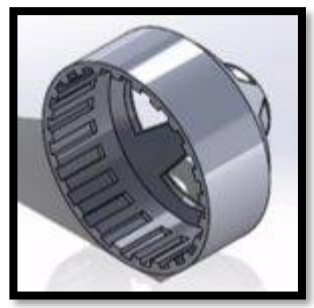

Figure 24: First iteration Rotor Isometric View

Figures 25 and 26 showcase the second iteration rotor with the inclusion of 5 pentagonal vents to allow even more heat dissipation. The depth of the rotor was reduced by 20mm to decrease printing time and allow for the moment arm of the shaft to create less wobble in the rotor at high speeds. 5 supporting ribs were added to the base of the rotor that connects to the shaft port to decrease the moment due to the shaft even more. We kept a magnet pole of 24 as it minimized the cogging torque more than when our team printed the same rotor iteration with 26 poles. The included 45° chamfer around the perimeter of the rotor was used for aesthetic purposes. ABS was the material choice of the second iteration rotor to make it stronger and allow the smaller detailed ribs to remain intact and functional without worry that they could break.

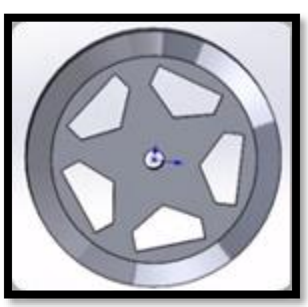

Figure 25: Second Iteration Rotor Front View

Figure 26: Second Iteration Rotor Isometric View

6.1.2 Design Iteration 2: Change in [Stator] discussion

The first iteration stator for the second semester can be seen below in figure 27. ABS plastic was our first material choice as it was stronger than most other commercial polymers most namely, PLA. The first iteration stator had 18 teeth to hold magnetic copper windings and had a 45° angle from tooth base to tip. The tooth width was approximately 2mm in depth allowing for a coil using AWG 24-gauge wire to have a turn count of 65 for each tooth. The first iteration includes a square-patterned mounting location to allow the backplate component to integrate with the stator.

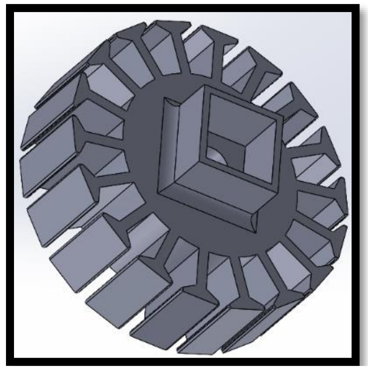

Figure 27: First Iteration Stator

The second iteration stator reduced the tooth thickness to nearly 1.5mm and decrease the tip angle to 30° compared to 120 degrees to allow a coil turn count of 75 using the same AWG 24-gauge wire (see figure 28). The inclusion of dot-like markings was etched along the perimeter of the stator base to mark where each of the three-wire phases would wind. An ovular-shaped bore was placed center to the start of the first phase marker and is used to hold the soldered phase endings of the copper wire. The square-mounting location was kept allowing mounting capabilities. The second iteration stator is made from a magnetic iron-filled PLA to minimize cogging torque and help increase the induced EMF.

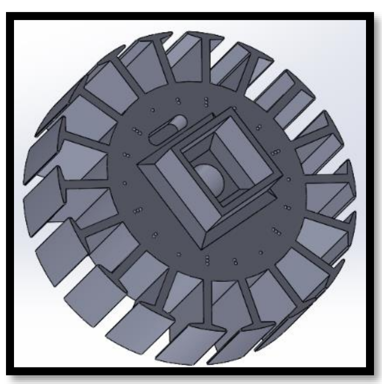

Figure 28: Second Iteration Stator

6.1.3 Design Iteration 3: Change in [Mounting] discussion

The first iteration backplate seen in Figure 29 has 4 ovular mounting ports designed to hold M4 bolts that can mount to a surface. The front of the backplate has a square cutout to allow it to mate to the stator. The backplate also includes a hole in the center to allow a pressure fit for a 5mm ball bearing. PLA was also the chosen material for the first iteration backplate as it reduced printing time and cost for the component.

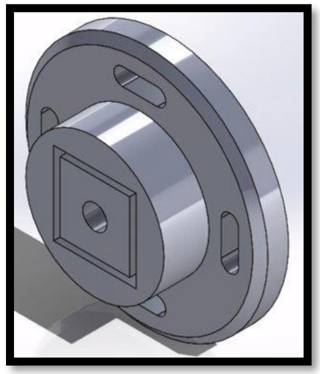

Figure 29: First Iteration Backplate

The second iteration backplate can be seen in figure 30 below and has a larger square cutout to allow more ease of fit between the backplate and the stator. The hole center to the backplate is a couple of millimeters larger than previously to allow an MR128ZZ 8mm bearing to pressure fit inside. The basic mounting pattern was kept and the backplate still uses M4 bolts to mount to a surface. ABS was the material choice used for the second iteration backplate as the material was stronger and more durable than the PLA used in iteration 1.

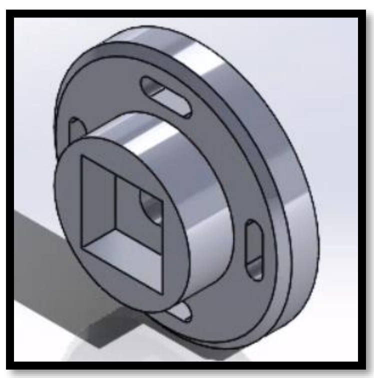

Figure 30: Second Iteration Backplate

6.1.4 Design Iteration 4 Change in [Shaft] discussion

The first iteration shaft seen in Figure 31 is made from standard brass at a length of 150mm and a diameter of 5mm. The brass shaft was sanded to allow a pressure fit with 5mm bearings. The shaft was machined to include a step to ensure the rotor would not slide away from the shaft during operation.

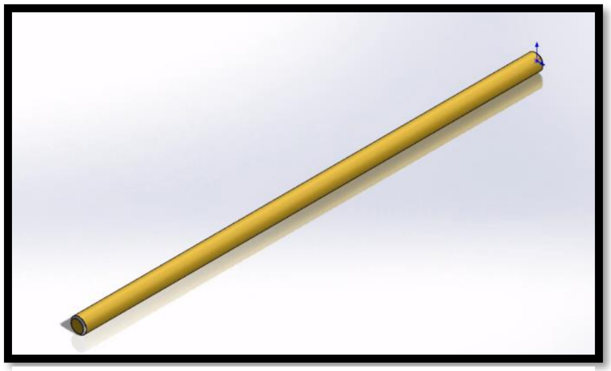

Figure 31: First Iteration Shaft

The second iteration shaft seen in Figure 32 was made from 1055 Cold-Drawn steel and has a diameter of 8mm. The second iteration shaft was much stiffer than the brass shaft and helped decrease the moment due to the rotor on the shaft during operation. The shaft did not need to be sanded to allow a pressure fit with the 8mm MR128ZZ bearings and was 50mm longer than the previous shaft to allow even distribution of components along the shaft.

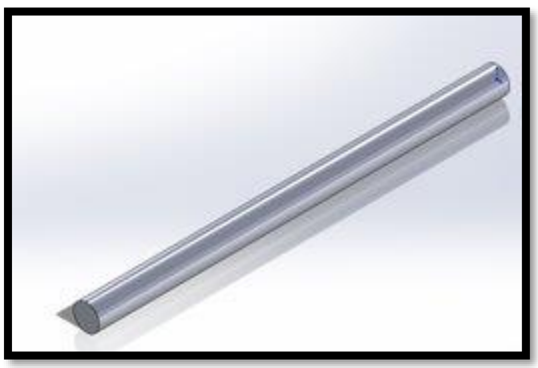

Figure 32: Second Iteration Shaft

7 RISK ANALYSIS AND MITIGATION

The following section reflects all the possible modes of failure that the team may encounter with the final product generator. The possible failures are organized within an FMEA chart for both the first semester and second-semester final product development. Any additional failure modes are highlighted and described the operation of the final outer generator design prototype. The design decisions made to mitigate such failures are detailed. The process includes the trade-off decisions made to mitigate possible failures that appear pressing for the final model operation. A comprehensive understanding of the failures associated with the 3D printed generator is explored using simulative software results, structural properties, and material choices. Lastly, the possibility of new risks appearing due to the design changes made is touched upon to wrap up this section.

7.1 Potential Failures Identified First Semester

Tables 3 and 4 show the two sections of the shortened FMEA created during the first semester of the capstone project. The shortened FMEA has been broken up into the two tables shown due to its large format. These tables allow the team to break down all the potential failures of each generator model subsystem. The table is arranged by subsystem components and all the preconceived possible failures that could occur. This is followed by columns that list the potential foreseen effects that the failures could have on the design and the causes.

Table 3: Shortened FMEA Part 1

Subsystem #, Functions, and Parts	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure
Subsystem #1: Rotor			
Shaft (Transmits Rotor Rotation)	High Cycle Fatigue	Shaft Bend/Break and Flying Debris	Poor Material Construction
	Corrosion Fatigue	Shaft Weakened-Break, Loss of Function, Debris	Exposure to Elements, No Protective Coating
	Surface Fatigue	Propogation of Cracking, Sheering, Hindering Rotation	Material too Soft, Tolerancing
	Brittle Fracture	Shaft Fracture at Speeds, Complete Loss of Power, Debris	Weakened Segment of Shaft Part
Rotor Body (3D Printed Structure of Rotor)	Temperature Induced Deformatio	Friction with other Components, Loss of Rotation	PLA Overheating During Run Time
	Temperature Fatigue	Break in Component, Possible Debris Emitted	Heating and Cooling During Cycles, Part Structure Compromised
	Brittle Fracture	Flying Magnet Debris	Weak Part Construction
Bearings (Allow Rotational Capacity of Rotor)	High Cycle Fatigue	Frictional Buildup and Rotational Efficiency Compromised	Life of the Bearings Exceeded
	Thermal Fatigue	Loss of Rotation, Possible Debris Omitted	Max Lubricaiton Temp. Exceeded
	Fretting Fatigue	Loss of Rotational Ability, Power Loss of Generator	Too much Radial and Tansverse Loading on Shaft to Bearings
Subsystem #2: Windings			
Coil Wire (Transmit Current/Induced EMF)	Ductile Rupture	Loss of Current, System Instability	Inproper Winding/Damaged Wire
	Pitting Corrosion	Instablilty in Maximum Current Transmission	Age of Wire, Exposure to Elements
	Corrosion Fatigue	Possible Break in Wire, Inability to Generate Power	Age of Wire, Exposure to Elements
	Thermal Fatigue	Inability to Run Effectively, Current Obstructed, Fire	Wire Diameter Not High Enough for Polonged Current
Teflon Tape (Hold Windings Together)	Surface Fatigue	Unwrapping, Coils Could Become Loose, Potential Stoppage of Device	Teflon Tape Becomes Brittle, Not Suitable for Condtions of Generator
	Thermal Fatigue	Serverance in Tape, Coils Could Become Loose	Age of Tape, Repeated Heating and Cooling During Cycles
	Corrosion Fatigue	Tape would Disintegrate, Possible Movment of Coils During Operation, Friciton	Exposure of Tape to Outside Compounds During Testing
Solder (Connections Between Coils)	Tensile Rupture	Disconnection of Generated Power to Exterior Application	Inproper Soldering, Attachment Wire of Insignificant Length
	Galvanic Corrosion	Weakened Solder Connection due to Elements and Electrical Current	Extended Age of Solder and Generator Use Cycles
Subsystem #3: Magnets			
Neodymium Magnets (Produce Magnetic Field)	Corrosion Fatigue	Loss of Full Magntitude of Magnetic Field Produced, Less Efficient Power	Magnets Exposure to Elements and Formation of Rust
	Brittle Fracture	Inability to Run Effectively, Magnetic Field Inturrupted, Possible Debris Emmitted at Spe	Handling Magets, Any Force Applied During Construction
	Pitting Corrosion	Magnetic Poles Affected, Power Produced Affected	Prolonged Esposure of Magnets to Elements
	Selective Leeching	Magetic Field Hindered, Power Produced Affected	Reaction in Magetic to Zinc Surface Coating
Glue Adhesive (Hold the Magnets to the Rotor)	High Cycle Fatigue	Loss of Magnets from Stator Over Time, Possibe Debris at High RPM	Adhension Lost Over Time, Not Enough Applied
	Thermal Fatigue	Glue Compromised, Indiviual Magnet Loss While Running	Heat Causes Improper Adhesion while Running
	Ductile Rupture	Break in Cured Adhesive, Causes Loss of Magnet, System Compromised	Weak Point in Adhesion, Not Spread Uniformly
	Interfacial Bond Loss	Weakened Adhesion, Causes Magnet to Separate from Rotor, Loss of motor Function	Expansion and Shrink of Adhesive, Improper Surface Application
	Adhesion Failure	At High Speed - Potentially Harmful Debris	Attachment/Adherance
	Brittle Fracture	Cause the Loss of the Magnets Held into Rotor Part, Cause them to Loosen	Hard Setted Adherance causes Fracture due to Forces of Motion and Weakened Application of Are
Subsystem #4: Stator			
Stator Body (Outisde of Generator, Holds Windings)	Brittle Fracture	Cause Friciton, Loss of Function	Weak Part Construction
	Temperature Induced Deformatio	May Cause in Balance During Operation, Possible Stoppage of Device	PLA Material Heating Beyond Capacity Due to Spinning Outer Rotor/Current
	Ductile Rupture	Outside of Generator Could Collapse, Possible Debris Emitted, Loss of Function if Strutu	Heat Leading to Crack Propagation of the Thin Exterior Wall
	Corrosion Fatigue	Weakened Stator, Possible Breakage of Part During Operation	Exposure to Various Compounds to see Results of Corrosion on Part
	Degradation	Weakened Part, Dongerous at High Speeds, Possible Breakage	Exposure to Sunlight/Elements that Cause Plastic Structure to become Comprimised
Mounting Plate (Sets Stator to the Wind Turbine)	Stress Cracking	Generator May Break from Base, Cause Damage to Wind Turbine	Too Thin of a Plate, Insufficient Tolerancing of Holes
	Ductile Rupture	High Speeds, Loss of Generator Control and Debris	Not Enough Materail in 3D Printed Part to Handle Forces
	Brittle Fracture	Cause the Generator to be Inoperable without Secure Mounting	Tightened Beyond Specifications Leading to Mounting Plate Break
	Deformation Yeilding	Generator Moves a bit and Imbalance is Created in Shaft Rotation	Strain of the Generator Function Leads to Yeilding of Mount
Screws (Hold Device Together)	Corrosion Fatigue	Generator to Break Apart, Possible Debris if Running	Deteriation Due to Age and Enviormental Factors

The second table 4 section 2 shows the outcome RPN value indicating the importance to address these potential failure modes. The higher the RPN the higher the perceived possibility of failure and importance for design mitigation to reduce concerns. The last column of table 4 section 2 gives a list of recommended actions that could help mitigate the failure mechanism of the generator design. Many of the failure concerns presented in these two tables were valid throughout the second-semester final generator design process. Highlighted RPM values in yellow indicate the highest-ranked failure modes, proving to be the main failures to be inspected.

Table 4: Shortened FMEA Part 2

RPN	Recommended Action
28	Revised Material Specification and Geometry
14	Find an Effective Less Corrosive Material, Protective Coating
24	Find a Material for Shaft with Higher Modulus of Elasticity
42	Redesign Exterior Attachment Mechanism, Material Selection Change
54	Determine better Geometry to Manage Heat Transfer, Other Material than PLA
42	Figure out Better Material for the 3D Parts Undergoing Heating and Cooling Process
112	3D Part Infill, Geometry, Material Combination Revisited
60	Select Bearings of Similar Geometry from Catalog for Higher Life Cycles
48	Bearing Selection Revisited
42	Stronger Bearing Needed for the Forces Involved
25	Investigate Winding Method, Additonal Attachment Mechanism, Wire Diameter Adjustment
24	Ensure the Caoting on Next Wire Choice is Stronger/Better Against Copper Corrosion
30	Wrapping of Coils, Better Slection of Coated Coil Choice
28	Choose a New Wire Guage that is Lower in Value to Meet Current Production
24	Move from Typical Teflon Tape to another Option
36	Create more Layers of the Tape, Select Another Option
24	Based on Test Results, Determine if Different Selection for Tape Material is Necessary
42	Use Solder Combined with Shrink Wrap or Combine Wire to Enable Stronger Connection
24	Posssibly Try Different Solder Compound, Enusure Wire is Low Enough Gauge
10	If Magnets do Corrode, Finding Neodymium Magnets with Better Properties for Rust Prevention
48	Change the Stator Part Geometry to Allow for Easier Magnet Insertion, Upscale Magnet Size
30	Apply Surface Resin Coat to Magnets Used to Help Stop this Process
20	Faulty Magnets if this Occurs so New Outsourced Magnets to be Selected
42	Revise the Magnet Holding Geometry of the Rotor Component
28	Choose a Adhesive that is able to Withstand Found Temperature Requirements of Generator Operation
36	If Glue does not Accommodate Enough Stregth, Prep Surfaces Better/Choose a Stronger Glue
105	Revise the Rotor Magnet Placement to Depend Less on Adhesion
63	New Methods of Attachment to Stator
20	Find Methods that set the Glue with the Least Likely Failure Based on Tests
50	3D Part Infill, Geometry, Material Combination Revisited
10	Choose a Material other than PLA that can more Effectively Transfer Heat
36	If Test Prove to Create Cracking, Revise Infill Properties and Material Selection
36	Revisit the Material Selection for Printing if Necessary
63	None, Age will Affect all Materials, UV Resistant Coat or Specify that Generator is for Covered Conditions
63	Redesign the choosen Base Plate Mount
28	May Call for Redisign of Mounting Geometry
21	Revisit the Torque Specs that the Plate Geometry can Handle
10	If Yeilding, Geometry of Plate Needs to be Revisited
12	Choose New Screw Material Properties

The highlighted most critical failures are identified in the subsystems for the rotor, magnets, and stator portions of the final design. All of the critical failures are found to range from an RPN value of 48 to 112. This range puts these potential failures at a low to moderate level of importance, with RPN values of over 200 at a high-risk category. For the rotor assembly, the primary failure modes are temperature-induced deformation of the rotor body, high cycle fatigue, and thermal fatigue. The highest-ranked failure of this subsystem is the potential for a brittle fracture to occur during operation. All three of these failures are directly tied to the geometry and material properties of the rotor part. This part will be rotating at high speeds and thus is subject to failure. I run too high or print quality is low a brittle fracture in the component could occur. Running the generator over long intervals could induce high cycle fatigue and the possibility of thermal fatigue if coils heat up with the small air gap between the stator and the rotor. These modes of failure are most important to address further for the rotor assembly.

In the magnet subsystem, the highest-ranked failures were determined to be a brittle fracture, inference bond loss, and adhesion failure. The magnets are neodymium with a nickel-plated outer layer, the material combination is quite brittle in any form of bending load. The fitment of the magnets into the rotor slots could cause a hairline fracture that could result in rupture during generator operation. The magnets themselves are attached to the rotor using a super glue adhesive and this bond between the magnets and the inner surface of the rotor part could separate or become weak over time, turning a magnet into a projectile while the generator is in use.

For the stator subsystem, critical issues include brittle fracture of the stator body, degradation of the stator part, and stress cracking of the mounting plate. The stator holds the bearings and all components of the generator model stable when in use. Fracture of this part or a print with weakened structure infill could cause critical failure of the design. The backplate holds the generator assembly horizontal, thus any breaks in this part could cause the entire system to fail.

7.2 Potential Failures Identified This Semester

Appendix B, tables 5 and 6 show the full FMEA with the included updates for this semester highlighted in light purple. The updates made to the FMEA chart include a fifth subsystem for the e-clip and nylon bushing that holds the generator together by the shaft component. This subsystem includes possible failures that could happen with this newer design update. All other previously found FMEA material is still relevant to the final prototype generator. The original FMEA material is broken into subsystems for an outer rotor generator design, which was further pursued in the second semester of the project. Therefore, the only necessary additional failure modes to mention are in coherence with the only missing design element used to keep the shaft secure during operation. The investigation of the most critical, high RPN value, failures will be further investigated in the risk mitigation section.

As for the newest failures found this semester, the e-clip and bushing component possible issues were split into two separate sections. The e-clip could experience corrosion fatigue, ductile rupture, and high cycle deformation. The e-clip is made from 1060-1090 black phosphate spring steel material which can rust when exposed to elements over time. Due to this, the e-clip could experience corrosion, such as surface rust, over time. Corrosion can lead to a weaker component and could cause the failure of the part during operation which would result in the generator needing repair immediately. Furthermore, the e-clip could break or deform due to the forces when the generator runs at high speeds.

The bushing is made of nylon material and sits between the e-clip and the rear bearing. The bushing was found to possibly fail from thermal fatigue, compressive rupture, or high cycle fatigue. The bushing experiences some compressive force when the generator model is running, which could lead to rupture of the part. A bearing sits against the bushing which could over a prolonged period cause thermal fatigue, distorting the part and causing an increase in torque to run the generator. High cycle fatigue is another concern because of the tendency for nylon to wrap and become more brittle over time and repeated cycle use. None of the newly found failure modes were deemed critical and all remained under a value of 40 for the RPN values, shown in table 5 of appendix B.

7.3 Risk Mitigation

The critical failures, highlighted in yellow above, were mitigated using a series of design processes. The first potential failure modes mitigated were the high cycle fatigue and brittle fracture of the rotor component. Knowing that this sub-system would be rotating at high angular velocity values, the use of SolidWorks centrifugal stress simulation software was utilized. To mitigate these possibly critical design failure modes, the material of the rotor was changed to an ABS polycarbonate blend and the design was simulated at various speeds to find a factor of safety. Figure 33 below shows the simulated probed maximum stress of the rotor with magnets at a speed of 11,000 RPM. This process was completed for the rotor assembly at incremental RPM values to find the stresses that the part will endure. All material and density properties were included in the simulation to find the possibility of these critical failures occurring.

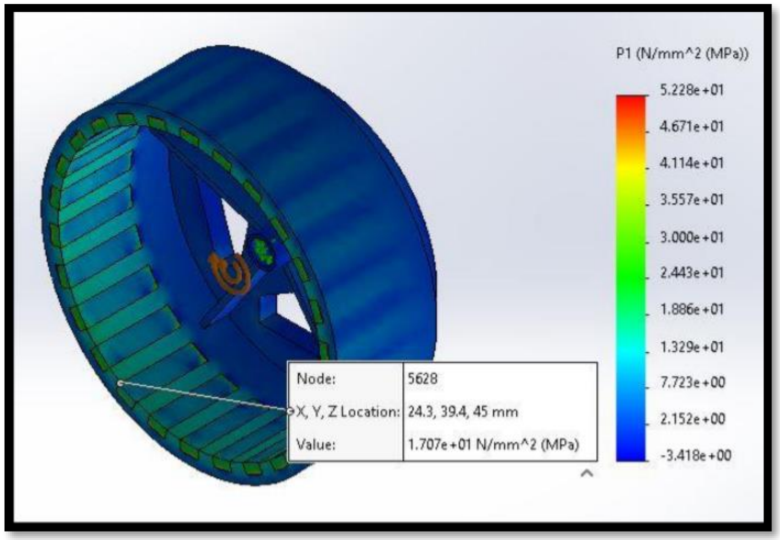

Figure 33: Simulated Centrifugal Force at 11,000 RPM

The results were plotted for the calculated and simulated principal stresses on the rotor design. Figure 34 below shows the resulting factor of safety values for the operating speeds. The plot shows that the testing indicated that operating the rotor assembly up to 10,000 RPM is safe with a factor of the safety rating of roughly 3.2 (between calculated and simulated). This allowed our team to figure out what testing operation speeds would mitigate the possible fracture of the rotor part, decreasing the likelihood of fracture.

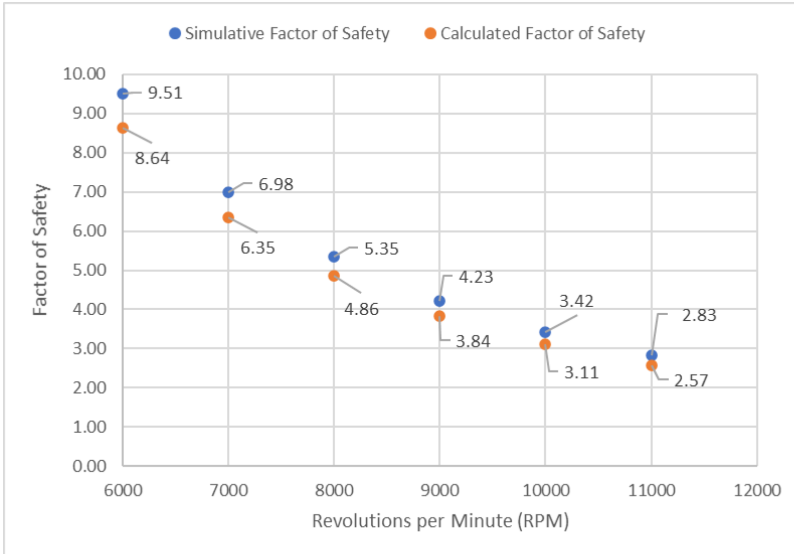

Figure 34: Final Design F.S. vs. RPM for Rotor

The temperature fatigue was mitigated by the decision to change from standard PLA printing material to the ABS polycarbonate blend, which has a much higher melting point. PLA for 3D printing was a melting range of 170-180°C where the ABS blend is 240-280°C [11]. During operational testing, the generator never even rose above room temperature of more than 5°C, making this design decision mitigate the issue altogether. Furthermore, the strength of the ABS was far superior to the PLA lessening the worry for high cycle fatigue at a full infill print setting. Changing the material only raised the overall cost and weight of the device by a remedial amount. Because the ABS blend has such a high melting point, the only introduction involves the slight warp in the print of the rotor shape. This occurs during cooling of the part and is very hard to stop with a home-use printer. This could potentially increase the risk of breakage due to an imbalance in the assembly, but testing proved that at the max speeds for operation this was not found to be an issue.

The possible critical failures associated with the magnets becoming thrown from the rotor due to a loss of adhesion were addressed by printing the rotor at 101.5% original CAD rendering size to allow for up to 2% shrinkage of the ABS blend material. This gave a very tight fitment for the neodymium magnetic bars which were pressed fit into the rotor assembly with the addition of super glue adhesive. The combination of this process strength and the eventually realized centrifugal force holding the magnets in the rotor diminished the potential failure. Pushing the neodymium magnetic bars into the rotor from the back stopped any possible fractures from occurring during assembly that could lead to brittle fracture concerns. The testing process of the final generator model further proved that the magnets were held in place securely with no sign of coming loose.

Another critical failure found due to a higher RPN value was the possibility of fracture on the stator component. This could happen due to the complex shape of the winding slots and possible weak part construction. Because the stator does not move, the only way a facture would occur is if the rotor was to hit the stator during operation. The final design did have a 1mm airgap but this was increased to 2mm to stop any such contact from occurring. Figure 35 below shows that the infill solid on the outer portion of the stator and center, both potential areas of weakness in the design. Implementing this design change increased the structural strength of the part to minimize the chance of fracture. The trade for this procedure was the increase in weight of the part, not considered an issue of increased risk in the design.

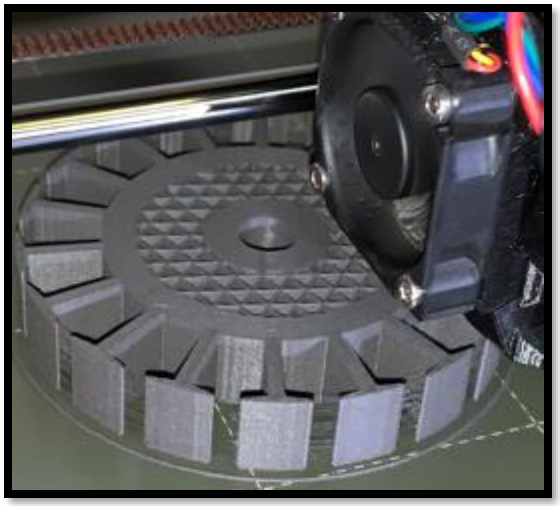

Figure 35: 3D Printed Stator Process

The last critical failure concerns are connected to possible breakage in the backplate component. This component, as mentioned, does hold the entire generator horizontal during operation. To avoid this component fracturing during use, the entire plate thickness was increased 3mm to a total of 10mm. The backplate was also printed with ABS blend over the original PLA design choice to increase the strength of the structure. Also, SolidWorks simulative study of torsion was completed on the part to predict the characteristics of the part. If the generator was to stop suddenly or start up suddenly, torque would be applied to the backplate fixture. Figure # below shows the simulative study on the final backplate design for a 3N-m torque, found to be higher than what would be applied.

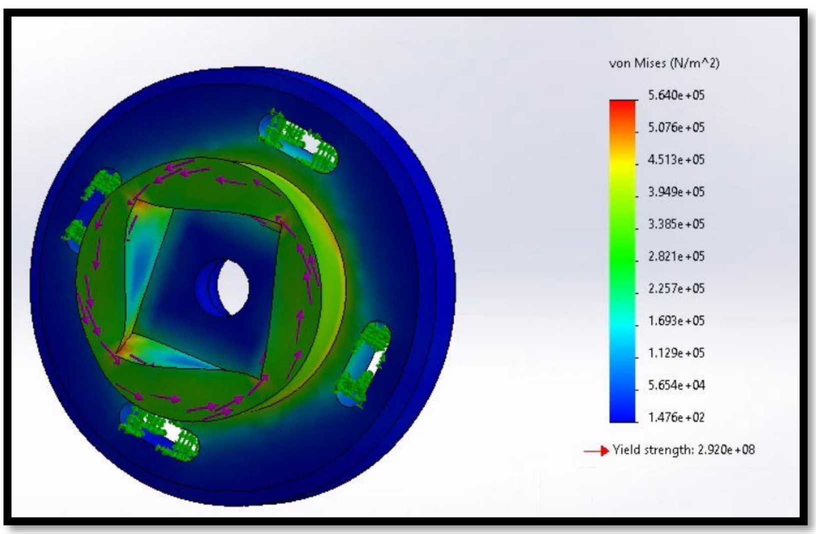

Figure 36: Backplate Torque Simulation

The resulting study shows that at a higher than predicted torque, the component is experiencing far below the yield strength. The material choice and thicker design helped mitigate the critical issue and did not cause any further risks in the trade-off of the changes made. These changes only improved the performance of the design overall.

8 ER Proofs

The ER proof section develops the specific project parameters that were used to work towards a final generator model goal. Most of the ERs presented within this section, seven out of nine, are geared towards the generator output performance following outsourced CWC generator industry models. The following project requirements are described in section 2 of the report but investigated in this section material. Each engineering requirement is proven to be met either by physical testing, modeling, or calculation for the final design generator. All reference material used to develop the proofs is supplied as background. The goal of the section is to show that the generator does exhibit the correct functionality to meet the fundamental project requirements.

8.1 ER Proof #1 – Voltage

The voltage engineering requirement was tested using an open circuit setup with the final generator iteration. To conduct this test, a dynamometer powered by a DC power regulator bank was used. The dynamometer is connected to the generator model using a coupling. The generator model itself is positioned horizontally using the stand built for displaying the device. Figure 37 below shows the front of the dynamometer connected with the coupling to the generator. The generator stand is duct-taped to the table to stop any vibration or movement from occurring during the testing operation.

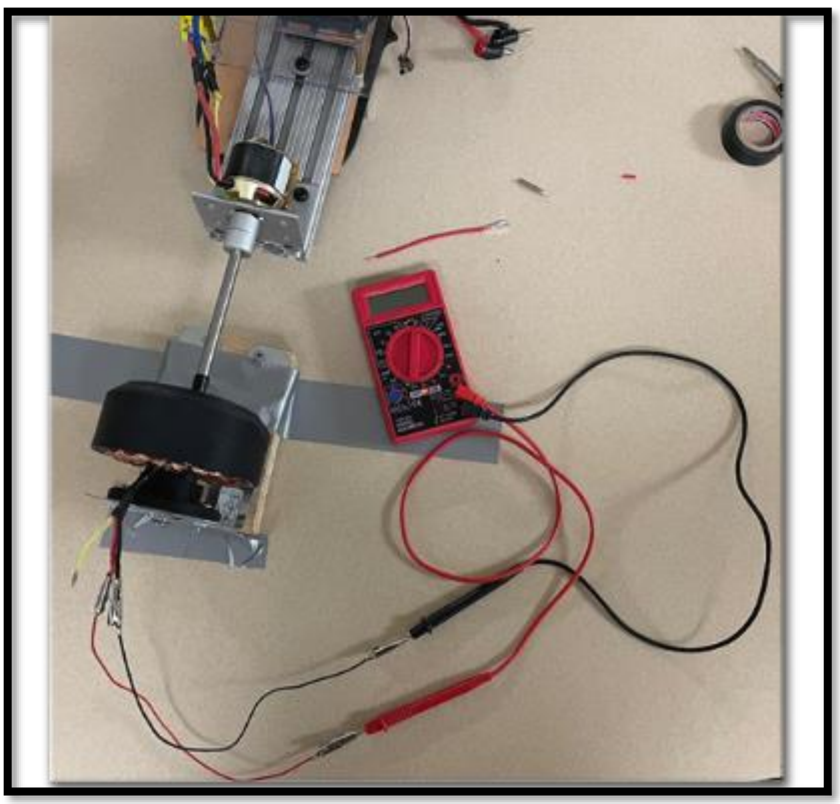

Figure 37: Open Circuit Testing

A multimeter is shown in figure 37 which was used to measure the phase voltage with two connectors with alligator clips. The multimeter was used to test and record the voltage of each phase while the dynamometer rotated the rotor at four increasing RPM values. During open circuit testing, a polycarbonate shield covered the generator to reduce the chances of injury if a failure occurred. Table 5 below contains the data collected during the open circuit testing. The first column shows each RPM that the dynamometer was set to when the voltage was measured from each phase. The total voltage average across the three phases for each speed is calculated.

Table 5: Open Circuit Phase Voltage Data

RPM	Phase A (V)	Phase B (V)	Phase C (V)	Total (V)
960	4.6	4.4	4.5	7.79
2160	11.1	10.6	10.9	18.87
3072	19.3	18.3	18.3	31.69
4060	22.8	21.5	22.1	38.27

During the open circuit testing operation, the generator was held at the RPM values shown in table 2 for 30-60 seconds. This allowed enough time for the multimeter to read the phase-to-phase AC voltage across all three banana plugs shown in figure 1. The phase A voltage was found by measuring from A to B. The second phase B voltage is found by measuring from B to C and the third C voltage from A to C. The notation for each phase is only to allow the team to keep track during testing, the color of the plugs distinguishes between the three phases of the generator. The total voltage is calculated using the wye connection phase to phase vector diagram in figure 2 below.

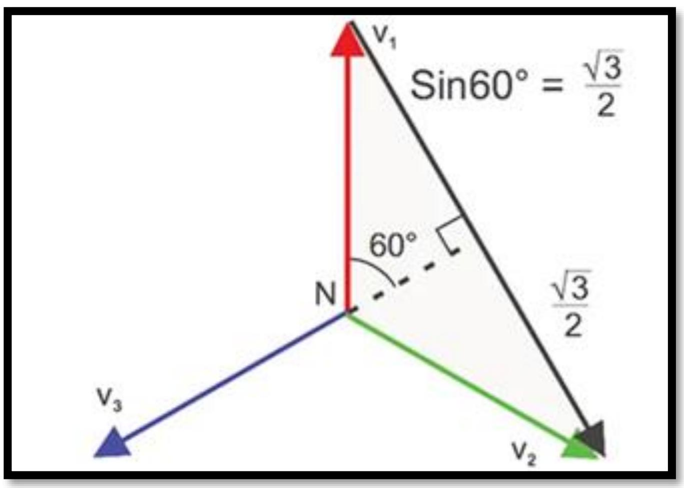

Figure 38:: Wye Three Phase Voltage Vector Diagram [12]

Utilizing the principles of the three-phase wye configuration voltage diagram of figure 2, the total voltage across each of the 120° phases is found using equation 1 below [12].

$$V_{Total} = \sqrt{3} * V_{Phase} \quad (1)$$

The resulting AC voltage across all three phases at each RPM value is shown in the right-most column of Table 2 above. The found voltage measurements meet the engineering requirement of less than or equal to 48 volts, with the maximum AC voltage output of 38.3 volts. The voltage dropped after the 4060 RPM was tested, explaining the table of data stopping at this peak value.

8.2 ER Proof #2 – Power

The goal of this engineering requirement was for the generator to reach a power value in the range of 200-400 W. Unfortunately, the generator underperformed during the last testing session as it was only capable of generating up to 8.9mW. Output power is calculated by multiplying DC voltage output by DC output as, as shown in equation 2.

$$P = VI \ (2)$$

The variables of voltage and current were measured during the load test. More about this test can be seen in section 8.7 below.

8.3 ER Proof #3 – Price

The estimated cost for each component of the final iteration generator can be seen below in Table 4. The cost for the final iteration generator is approximately $95.06 with the stator and magnets contributing to most of the cost at $12.43 and $42.86 respectively. The $500 engineering requirement is the total budget for all generator iterations and includes the 3 previous generator iterations from semester 1 and early semester 2. Accounting for all purchases, $320.01 has been spent leaving our final budget at $179.99 which is well under the overall budget. Judging the engineering requirement solely on the components and material used for the final iteration, the cost accounts for roughly 19% of the overall required budget of $500, and the total cost for all iterations based on the purchases made accounts for 64% of the overall budget.

8.4 ER Proof #4 – Power Rating

The open-circuit test described in section 8.1 above was utilized to measure the KV rating of the generator model. Using the data collected for the AC voltage output from table 5 above, a visualized plot was created. Figure 39 below shows the plotted voltage vs. RPM for the final generator model.

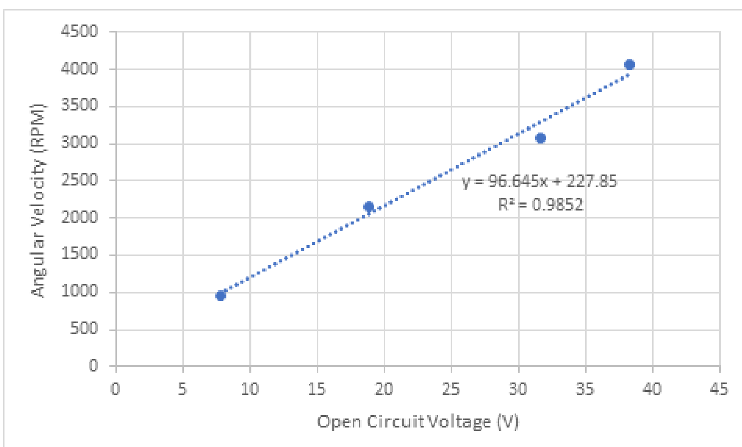

Figure 39: Voltage Output vs. Angular Velocity

The plotted data shows the increasing trend that remains linear between the RPM of operation and the voltage output. Using this data, table 6 below shows the calculated KV rating (RPM/V) for each measured step speed. The average KV power rating is found using the collected data from all 4 trials.

Table 6: KV Rating Data

RPM	KV Rating (RPM/V)
960	123.2
2160	114.4
3072	96.9
4060	106.1
Average KV	110.1

The KV rating of 110 is just below the range of 125-240 (RPM/V) in the engineering requirements outlined in section 2. This result could still be deemed acceptable as it lies just outside of the initial requirements and is on the lower end of the range. Achieving a lower KV is more desirable than a higher one because it proves the generator does create enough voltage output at lower operating speeds.

8.5 ER Proof #5 – Weight

The Weight of the motor was calculated by summing the mass of each component of the motor. The rotor has a mass of 111g, the magnets weigh 3.4g*24 magnets, the stator has a mass of 177g, and 55g for the backplate. The shaft weighs 79g, around 159g for the windings, and finally the bearings, E-clip, and nylon washer about 10g. This leads to a total mass of 672.6 grams which meets the team's requirement of having a mass under 1000 grams or 1 Kilogram.

8.6 ER Proof #6 – Current

The current goal value set for this project is approximately 2.8 amp. Unfortunately, the generator underperformed during the last testing session as it was only capable of generating up to 65.5mA. Such value was measured during the load test in DC.

8.7 ER Proof #7 – Resistance

The goal of this engineering requirement is for the generator to be able to sustain at least 166 ohms resistance without overheating. This was measured and tested during the load test. The load test consists in applying a load to the main generator to measure electrical factors such as DC voltage, DC, and angular velocity. The results can be seen in appendix D. The results show that it can handle more than 7.65 kohms without overheating. A schematic can be seen in figure

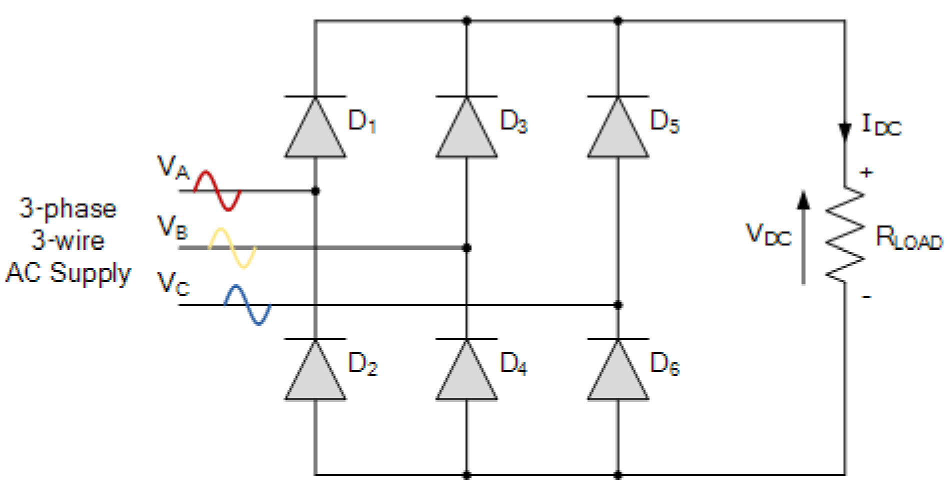

Figure 40: AC Supply Connected to the Rectifier Schematic[15]

8.8 ER Proof #8 – Reliability

Based on the MISUMI catalog for ball bearings, the MR128ZZ bearings can withstand a max speed of 40,000 RPM using grease as the main lubricant [13]. The max speed is well over the engineering requirement of 6,000 RPM, however, our team thought it best not to run the generator no more than 10 seconds at the required speed to prevent other components (i.e., magnets, backplate) from coming loose. Our generator will perform at lower speeds at around 3,000-4250RPM for nearly 5 mins before a loss in voltage, indicating more heat-driven through the copper coils from the generator core.

8.9 ER Proof #9 – Durability

Two MR128ZZ deep groove ball bearings were used in the assembly of the final iteration generator. Our team felt it best to approximate the bearing life in revolutions based on the Timken Deep-Groove Ball Bearing catalog which gives a rated life of 1million cycles for ball bearings [14]. The life in hours is dependent on the radial force applied to the bearing via the shaft. Since the radial force to the shaft is minimal, it is expected that the bearings will have an expected life in hours past 100 hours which gave our team optimal time to test and perform the necessary applications. Based on the type of bearing used for assembly, our generator meets the engineering requirement of 10^6 (1million cycles).

9 LOOKING FORWARD

9.1 Future Testing Procedures

Using Ansys' Motor-CAD is essential in preliminary testing as the general power output, current, voltage, and resistance can be determined for a motor of similar dimensions. Motor-CAD has options to change the material relative to the motor's design which can lead to more accurate simulations. Once a motor is simulated in Motor-CAD, future teams can determine the output power and how many poles/slots for the stator and rotor are appropriate. The team can then perform open circuit testing by connecting the designed motor to a dynamometer and determining the approximated KV rating for the motor using a multimeter to find the output voltage at varying speeds. The final procedure that future teams should tackle is loaded testing to determine the power output of the designed motor. The designed motor is once again connected to a dynamometer but with the addition of a rectifier that converts alternating current to direct current for the motor. The rectifier is attached directly to the motor via the phase ends and connected to a current/voltage modulator that shows the current and voltage of the motor. Resistance is applied to the rectifier during testing to induce a resistive load on the motor at varying speeds. Using a higher resistive value will increase the voltage but decrease the current and vice versa. The resistive loads are used to determine the output power by taking the averages of the current and applying loads at varying speeds.

9.2 Future Work

It's recommended that the CWC3D-Gen project should be interdisciplinary for both electrical engineering and mechanical engineering majors. Mastery over Maxwell's equations can help determine how electric and magnetic fields are created through current. This ties directly into this project as the generator creates EMFs (electromagnetic fields) through the change in polarity of magnets with an induced current. Tutorials in Ansys Motor-CAD are recommended to help with any preliminary testing to determine an appropriate number of poles and slots for the motor. Changing materials in Motor-CAD is vital in preliminary testing as the material choice can impact the measured outputs. Future teams should also focus on the wiring of the motor core as wye configuration is primarily used for slower motors and produces less heat than delta configured windings which can ultimately increase the motor's efficiency.

10 CONCLUSIONS

In accordance with the customer requirements and engineering requirements established from the beginning of the project, the team's final generator design has met all non-electrical requirements. The material selection and construction meet the criteria and performed as expected. However, the power output, voltage, and current does not reach the necessary values to be implemented by the CWC team in the competition. TBC

10.1 Reflection

The 3D printed generator team applied the use of design principles to primarily produce a solution to economic factors. These CWC student teams have limited budgets as part of a college institutional challenge, our generator aims to help them financially. The project design was made to bring down the cost of the outsourced generator models usually outsourced through existing market designs. The idea of building our model brings forth a hands on experience and a lower overall price for these teams to consider when designing their wind turbines. This factor was kept in mind throughout the design process, with decisions affecting material infill on parts and use of readily available componenets for ease of access. Furthermore, the environmental aspects of our design are both concentrated on the use of renewable energy sources and sustainable material practice. Although plastic was used, the team designed the generator building process to have very minimal material waste. 3D printing use of additive manufacturing process allows us to produce a product that does not have much production waste. The purpose of the generator keeps the renewable wind energy allocation goal as a end target for the device. This device and the team's progress works towards better public health in the development of wind power systems that reduce the amount of carbon emissions of alternate power sources. The generator is a great example of a design that helps take one small step towards the push for sustainable energy production sources. Saftey of the product was paid the upmost attention, both tested in our experimental durability and reliability trials accompanied by simulative testing of the design. Using these processes outlined in this report our team can confidentally say that the final design is found safe at the proposed operating speeds.

10.2 Post Mortem Analysis of Capstone

10.2.1 Contributors to Project Success

The team's purpose, outlined in the charter, expresses the demand for a non-commercial, small-scale wind turbine generator that integrates seamlessly with the design of the Collegiate Wind Competition model. The project takes on designing and 3D printing elements of a generator capable of meeting the output of current outsourced generator models used by the CWC teams. The goal is to render a design that not only performs at the necessary standard but also cuts down on costs and time associated with outsourcing. All the mechanical engineering requirements were met by the team's final design. It is easily integrable into the CWC model, resistant, reliable, and lightweight. However, the generator underperformed in its electrical aspect. Voltage, current, and power generated is below the goal imposed by the client. In other words, the team was successful in creating an additive manufacturing process for a mechanical and material-effective generator. However, the design cannot be a reliable source of energy.

A tool that contributed positively to the development of the project was an application called MotorCAD which is a modeling and analysis tool powered by ANSYS. This tool was able to contribute positively to the project due to the near-infinite designs that can be created and analyzed to help develop through simulations a motor that meets our customer requirements. A method that the team took to accomplish this was creating changing multiple variables of our motor and analyzing them. Once the team determined which parameter values worked well, a new iteration was printed and assembled.

Considering the performance of the team, using Microsoft teams to share documents and conduct meetings was the most essential tool that contributed positively to the team's performance. Another tool that the team used to stay on track was a Gantt chart which outlined the teams' milestones and gave a visual representation of the semester. Although the team was not always following the exact preplanned track, this tool was useful to the success of the team's first and second parts of the capstone. A method that the team used to keep up to date with these tools was to meet during capstone class as well as special scheduled days whenever it was required. This allowed for efficient communication between the team members as well as a collaboration that allowed staying on track with scheduling and the timeline for the team stayed true.

10.2.2 Opportunities/areas for improvement

Throughout the project, our team faced many challenges, some of which negatively impacted performance. Unfortunately, the generator constructed performed far below the necessary operating standard needed to comply with the customer requirements for the project outcome. This outcome was not very promising and needs further revision as well as better simulations. Although the final design was built up to the specifications listed by each design, the product output was below average, proving that the final design needs further development on the electrical aspect of the design. This includes the wire gauge, turns, and overall structural design. Furthermore, due to issues with material selection during MotorCAD simulations being truncated due to its material properties, the team was unable to provide accurate simulations using the last materials selected. Even though all project deliverables were met, more advanced prototypes would have set the generator capable of generating a sustainable amount of energy. Another area of project performance that proved to be difficult was broken components for testing such as a burned rectifier and broken variable load that did not let the team move forward as fast as expected.

Meeting times were discussed in the team charter and were followed on the times mentioned in the document. The meetings were used to present the main agenda of every week with each group member assigned to one or more individual and group tasks. A few barriers encountered involve broken apparatus, broken components, and miscommunication. The coping strategy for miscommunication was to allow 24 hours or more notice if a group member was unable to attend a meeting or complete a group assignment. This strategy was used effectively and helped keep every member up to date. Another strategy implemented involves having all the team attend tests done on the generators to keep all teammates on the same page of what is right or wrong. This also helped in time management since attending every meeting to understand what was happening with the motor, follow up by discussion allowed the team members to organize on what are the next steps to be done for the following iteration.

One problem that the team encountered was simulations done from MotorCAD. As the design progressed, becoming more unique and complex, creating simulations also proved to be a handful. Another problem that the team encountered was 3D printer issues where the printer being used was not able to print consistently, and some special measures were taken in order to prevent defective parts and printer deterioration. Thanks to previous experience, the team was able to endure the difficulties and find solutions in a timely manner. When building the motors values for certain parameters proved more difficult as the design evolved, with simulation becoming harder to properly make. Another problem encounter was the parts that could not be 3D printed such as shaft, clips, etc. The reason for this is the fact that these parts had to be machined. As other capstone teams required the use of the machine shop, and material needed were not available right away, it took time for the team to be able to machine or order the parts required for the proper function of the generator.

Team performance can be improved in two fundamental areas. These two areas are simulation work, and proper documentation. To improve the simulation efficacy, it is imperative that the team is ready to implement different software to complement the areas that certain software could not complete successfully. The team implemented Solidworks to complement the mechanical aspect of the design while MotorCAD was implemented for the electrical aspect of the design. However, the team could as well take advantage of other simulation software such as the big catalog of programs offered by Ansys, Matlab, and NI Multisim. Finally, the team's performance could be improved by implementing proper documentation.

So far, all work done has been uploaded to MS teams. However, certain documentation was handwritten or done by an old or latest version of software. Thus, making it hard and sometimes impossible for a teammate to access the document. To decrease waiting time on such documents, the teammate could capture the written documentation into a digital copy. If a new or outdated version of a software is being used, the owner of the original could make a copy with a different file extension so other teammates can open such document on their own.

The process of prototyping generators granted three important technical lessons for the team. The first technical lesson learned was 3D printing usable components. Since the project required 3D printing, the team obtained a new 3D printer to practice printing more complex shapes and exotic materials. The second technical lesson was the ability to use the software MotorCAD. This software was used to create a simulation-based design working from our CAD design and known input parameters. The final technical lesson obtained was the skills to properly solder wires and electrical components together. This was developed through practice, and the team's ability to follow different generator wiring configurations and testing components. Our team has ascertained a much higher level of detailed understanding of additive manufacturing, generator modeling, general electrical engineering, as well as what to achieve the finalization of a successful micro wind turbine 3D printed design.

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12 APPENDICES

12.1 Appendix A: HoQ

System QFD

Project: CWC 3D Printed Generator
Date: 1/23/2021
Input areas are in yellow

Legend
A MAD 5010
B MAD 5012

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www.robuststrategy.com
kevin_n_otto@yahoo.com
http://www.kevinotto.com/RSS/templates/QFD Template.xls
Modified from a template from Design4X Inc.

	Voltage	Power Produced	Power Rating	Price	Weight	Current	Resistance	Reliability	Durability
Voltage		+							
Power Produced	+								
Power Rating	+	+							
Price									
Weight	+/-	+/-	+	+					
Current	-	+	+						
Resistance	+	-	-	+		-			
Reliability				-					+
Durability				+			+	+	

Customer Needs	Customer Weight	Voltage	Power Produced	Power Rating	Price	Weight	Current	Resistance	Reliability	Durability	1 Poor	2	3 Acceptable	4	5 Excellent
Within optimal power range	4	3	9	3		1	3	3	3					AB	
Reasonable voltge output	3	9	3	9		1	3	3	3						AB
Withstand speed	4	3		3	1	3			3	3					AB
Must be a brushless motor	4		3	1	1	1				1					AB
Must integrate with CWC wind turbine	2	9	3	9		3	1	1		3			AB		
Multiple components must be 3D printed	5		3	1	9	9	1	1	3	9		AB			
Minimal (almost zero) cogging torque	3	1	1	1	3	3								AB	
Standardized CWC mounting pattern	4				1	1			1				AB		
Compact Size	4	3	3	9	9	9	3	3	3	3				AB	
Cost within Budget	4				9	9		1	3	9				AB	
Durable and robust design	5				9	3		1	3	9				AB	
Reliable design	4		1	1	9	3			9	9				AB	
Safe to operate	5	9	3	3			9	3	1	1					AB
Technical Requirement Units		Voltage (V)	Power (W)	KV (RPM/V)	$	Weight (g)	Current (A)	Resistance (Ohms)	Reliability (revolutions)	Durability (rpm)					
Technical Requirement Targets		<=48	300-400	125-240	<300	<1000	2.89	166	10^6 revolutions	> 6000 rpm					
Absolute Technical Importance		129	112	112	####	162	85	64	132	201					
Relative Technical Importance		5	6	7	2	3	8	9	4	1					

Figure 40: HoQ Table

12.2 Appendix B: Full FMEA Table

Table 5: Full FMEA Part 1

Final Generator Design Outer Rotor Generator Rotor, Stator, Magnets, Winding Systems, E-Clip/Bushing	Team 21Spr07-CWC3DGen				
Subsystem #, Functions, and Parts	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)
Subsystem #1: Rotor					
Shaft (Transmits Rotor Rotation)	High Cycle Fatigue	Shaft Bend/Break and Flying Debris	7	Poor Material Construction	2
	Corrosion Fatigue	Shaft Weakened-Break, Loss of Function, Debris	7	Exposure to Elements, No Protective Coating	2
	Surface Fatigue	Propogation of Cracking, Sheering, Hindering Rotation	6	Material too Soft, Tolerancing	2
	Brittle Fracture	Shaft Fracture at Speeds, Complete Loss of Power, Debris	7	Weakened Segment of Shaft Part	2
Rotor Body (3D Printed Structure of Rotor)	Temperature Induced Deformation	Friction with other Components, Loss of Rotation	6	PLA Overheating During Run Time	3
	Temperature Fatigue	Break in Component, Possible Debris Emitted	7	Heating and Cooling During Cycles, Part Structure Compromised	2
	Brittle Fracture	Flying Magnet Debris	7	Weak Part Construction	4
Bearings (Allow Rotational Capacity of Rotor)	High Cycle Fatigue	Frictional Buildup and Rotational Efficiency Compromised	5	Life of the Bearings Exceeded	3
	Thermal Fatigue	Loss of Rotation, Possible Debris Omitted	8	Max Lubricaiton Temp. Exceeded	3
	Fretting Fatigue	Loss of Rotational Ability, Power Loss of Generator	7	Too much Radial and Tansverse Loading on Shaft to Bearings	2
Subsystem #2: Windings					
Coil Wire (Transmit Current/Induced EMF)	Ductile Rupture	Loss of Current, System Instability	5	Inproper Winding/Damaged Wire	1
	Pitting Corrosion	Instablilty in Maximum Current Transmission	4	Age of Wire, Exposure to Elements	3
	Corrosion Fatigue	Possible Break in Wire, Inability to Generate Power	5	Age of Wire, Exposure to Elements	3
	Thermal Fatigue	Inability to Run Effectively, Current Obstructed, Fire	7	Wire Diameter Not High Enough for Polonged Current	2
Teflon Tape (Hold Windings Together)	Surface Fatigue	Unwrapping, Coils Could Become Loose, Potential Stoppage of Device	4	Teflon Tape Becomes Brittle, Not Suitable for Condtions of Generator	3
	Thermal Fatigue	Serverance in Tape, Coils Could Become Loose	4	Age of Tape, Repeated Heating and Cooling During Cycles	3
	Corrosion Fatigue	Tape would Disintegrate, Possible Movment of Coils During Operation, Friciton	4	Exposure of Tape to Outside Compounds During Testing	2
Solder (Connections Between Coils)	Tensile Rupture	Disconnection of Generated Power to Exterior Application	7	Inproper Soldering, Attachment Wire of Insignificant Length	3
	Galvanic Corrosion	Weakened Solder Connection due to Elements and Electrical Current	6	Extended Age of Solder and Generator Use Cycles	2
Subsystem #3: Magnets					
Neodymium Magnets (Produce Magnetic Field)	Corrosion Fatigue	Loss of Full Magntitude of Magnetic Field Produced, Less Efficient Power	5	Magnets Exposure to Elements and Formation of Rust	2
	Brittle Fracture	Inability to Run Effectively, Magnetic Field Inturrupted, Possible Debris Emmitted at Speeds	6	Handling Magets, Any Force Applied During Construction	4
	Pitting Corrosion	Magnetic Poles Affected, Power Produced Affected	5	Prolonged Esposure of Magnets to Elements	2
	Selective Leeching	Magetic Field Hindered, Power Produced Affected	5	Reaction in Magetic to Zinc Surface Coating	1
Glue Adhesive (Hold the Magnets to the Rotor)	High Cycle Fatigue	Loss of Magnets from Stator Over Time, Possibe Debris at High RPM	7	Adhension Lost Over Time, Not Enough Applied	2
	Thermal Fatigue	Glue Compromised, Indiviual Magnet Loss While Running	7	Heat Causes Improper Adhesion while Running	2
	Ductile Rupture	Break in Cured Adhesive, Causes Loss of Magnet, System Compromised	6	Weak Point in Adhesion, Not Spread Uniformly	3
	Interfacial Bond Loss	Weakened Adhesion, Causes Magnet to Separate from Rotor, Loss of motor Function	7	Expansion and Shrink of Adhesive, Improper Surface Application	5
	Adhesion Failure	At High Speed - Potentially Harmful Debris	7	Attachment/Adherance	3
	Brittle Fracture	Cause the Loss of the Magnets Held into Rotor Part, Cause them to Loosen	5	Hard Setted Adherance causes Fracture due to Forces of Motion and Weakened Application of Area(s)	2
Subsystem #4: Stator					
Stator Body (Outisde of Generator, Holds Windings)	Brittle Fracture	Cause Friciton, Loss of Function	5	Weak Part Construction	2
	Temperature Induced Deformation	May Cause in Balance During Operation, Possible Stoppage of Device	5	PLA Material Heating Beyond Capacity Due to Spinning Outer Rotor/Current	1
	Ductile Rupture	Outside of Generator Could Collapse, Possible Debris Emitted, Loss of Function if Strutural	6	Heat Leading to Crack Propagation of the Thin Exterior Wall	2
	Corrosion Fatigue	Weakened Stator, Possible Breakage of Part During Operation	6	Exposure to Various Compounds to see Results of Corrosion on Part	3
	Degradation	Weakened Part, Dongerous at High Speeds, Possible Breakage	7	Exposure to Sunlight/Elements that Cause Plastic Structure to become Comprimised	3
Mounting Plate (Sets Stator to the Wind Turbine)	Stress Cracking	Generator May Break from Base, Cause Damage to Wind Turbine	7	Too Thin of a Plate, Insufficient Tolerancing of Holes	3
	Ductile Rupture	High Speeds, Loss of Generator Control and Debris	7	Not Enough Materail in 3D Printed Part to Handle Forces	2
	Brittle Fracture	Cause the Generator to be Inoperable without Secure Mounting	7	Tightened Beyond Specifications Leading to Mounting Plate Break	3
	Deformation Yeilding	Generator Moves a bit and Imbalance is Created in Shaft Rotation	5	Strain of the Generator Function Leads to Yeilding of Mount	2
Screws (Hold Device Together)	Corrosion Fatigue	Generator to Break Apart, Possible Debris if Running	6	Deteriation Due to Age and Enviormental Factors	1
Subsystem #5: E-Clip, Bushing					
E-Clip (Mounted via Groove into the Shaft)	Corrosion Fatigue	Break clip, cuase weakened clip structure, loss of connection at interface with shaft	3	The spring steel phosphate reacting with the elements/environment of operation, no surface protection	3
	Ductile Rupture	Seperation from Shaft Causing Rotor to Move out of Backplate During Operation	5	Too High of Operation RPM Suddenly, Causing a Large Froce to Break Clip	1
	High Cycle Deformation	Clip Becomes Loose and Eventually Falls off Shaft Component	5	Could Happen Due to Extended Period of Operation, Causing Rotor to Walk Out of Backplate	2
Nylon Bushing (Between E-Clip and Shaft)	Thermal Fatigue	Bushing Starts to Deform or Melt into Bearing Causing Increased Torque	6	Long Duration of Operation Thermal Heat Increases from Friction	3
	Compressive Rupture	Bushing Splits and Causes a Jam in the Rotation Ability of the Rotor	5	A Sudden and Sustained Increase in Angular Velocity and Substantial Force on Bushing	2
	High Cycle Fatigue	Deformation of the Bushing Nylon Material, Increased Friciton and more Torque Needed	3	Time Operation the Generator Model	4

Table 6: FMEA Full Table Part 2

Date: 12/3/2021

Current Design Controls Test	Detection (D)	RPN	Recommended Action
Maximum Torque Rating	2	28	Revised Material Specification and Geometry
Chemical Bath for Choosen Shaft Material	1	14	Find an Effective Less Corrosive Material, Protective Coating
Subject to High Stress to Determine Maximum	2	24	Find a Material for Shaft with Higher Modulus of Elasticity
Complete Maximum Shaft Stress Test for a Multitude of Pieces	3	42	Redesign Exterior Attachment Mechanism, Material Selection Change
Spin PLA Component at High Speed Against Surface to cause Heat	3	54	Determine better Geometry to Manage Heat Transfer, Other Material than PLA
Heat Gun to 3D Part then Ice Bath-Repeated Process	3	42	Figure out Better Material for the 3D Parts Undergoing Heating and Cooling Process
Test Multiple 3D Prints of Part at High RPM	4	112	3D Part Infill, Geometry, Material Combination Revisited
Run Bearings at Extended Period Upper Limit of 6000 RPM	4	60	Select Bearings of Similar Geometry from Catalog for Higher Life Cycles
Run at (or Above) Max RPM for Extended Period of Time	2	48	Bearing Selection Revisited
Run the set of Selectied Bearings Under Loads Expected	3	42	Stronger Bearing Needed for the Forces Involved
Winding Hold Up Against Impact Test	5	25	Investigate Winding Method, Additonal Attachment Mechanism, Wire Diameter Adjustment
Subject Test Coil to Various Harsh Elements/Chemical Bath	2	24	Ensure the Caoting on Next Wire Choice is Stronger/Better Against Copper Corrosion
Subject Test Coil to Various Harsh Elements/Chemical Bath	2	30	Wrapping of Coils, Better Slection of Coated Coil Choice
Run Current through Wire Sample for Calculated Maximum Current Produced	2	28	Choose a New Wire Guage that is Lower in Value to Meet Current Production
Subject Teflon Tape to Tensile Force of Wrapping and Heat Treatment	2	24	Move from Typical Teflon Tape to another Option
Expose Tape Sample to Direct Heat/Sunlight for Extended Time	3	36	Create more Layers of the Tape, Select Another Option
See if Teflon Tape Reacts to Acids and Bases that could Contact Generator	3	24	Based on Test Results, Determine if Different Selection for Tape Material is Necessary
Solder Mutliple Leads off Coils and Test the Tensile Strength with Applied Force	2	42	Use Solder Combined with Shrink Wrap or Combine Wire to Enable Stronger Connection
Expose the Solder Joints to Elevated Current while in Chemical Bath	2	24	Posssibly Try Different Solder Compound, Enusure Wire is Low Enough Gauge
Testing the Outsourced Magnets Ability to withstand Corrosion using Chemicals	1	10	If Magnets do Corrode, Finding Neodymium Magnets with Better Properties for Rust Prevention
Insertion of Magnets in Various Ways to Avoid Breakage	2	48	Change the Stator Part Geometry to Allow for Easier Magnet Insertion, Upscale Magnet Size
See if Pitting Occurs for Applied Chemicals to Magnet Surface	3	30	Apply Surface Resin Coat to Magnets Used to Help Stop this Process
Provide Treatment to Magnet Test to Speed up Corrosion Process	4	20	Faulty Magnets if this Occurs so New Outsourced Magnets to be Selected
Test Various Glue Compoiunds and Spin Magnets in Rotor at High RPM Value	3	42	Revise the Magnet Holding Geometry of the Rotor Component
Test how Hot the Generator Becomes at High RPM Over Time, Compare to Glue Recommended Temperature Range	2	28	Choose a Adhesive that is able to Withstand Found Temperature Requirements of Generator Operation
Examine the Strength of Cured Glue, Apply Forced in Multiple Directions	2	36	If Glue does not Accommodate Enough Streqth, Prep Surfaces Better/Choose a Stronger Glue
Try Different Magnet/Rotor Preperation Techniques, Test with Load on Adhesion	3	105	Revise the Rotor Magnet Placement to Depend Less on Adhesion
Undulating RPM, with Higher Range Above Max RPM Value	3	63	New Methods of Attachment to Stator
Similar to Ductile, Work on Simulation of Forces at Play to Emulate Where the Crack May Occur	2	20	Find Methods that set the Glue with the Least Likely Failure Based on Tests
Test Component over Duration of Running Time	5	50	3D Part Infill, Geometry, Material Combination Revisited
With the Knowledge of PLA Properties-Test the Part Temperature Range Experimentally (Heat Gun)	2	10	Choose a Material other than PLA that can more Effectively Transfer Heat
Heat Gun to 3D Part then Ice Bath-Repeated Process	3	36	If Test Prove to Create Cracking, Revise Infill Properties and Material Selection
Figure out which Outer Elements Cause the 3D Printer Material to Corrode	2	36	Revisit the Material Selection for Printing if Necessary
Bake Parts to Emulate Prolonged Exposure to Elements	3	63	None, Age will Affect all Materials, Might Try UV Resistant Coat or Specify that Generator is for Covered Conditions
Create Several CWC Mounting Options and Test Attachment Ability and Strength	3	63	Redesign the choosen Base Plate Mount
Apply Torque Emulated by Generator Dynamometer Tests to Plate	2	28	May Call for Redisign of Mounting Geometry
Find the Max Torque Screw/Nut Setting for Generator Base Plate	1	21	Revisit the Torque Specs that the Plate Geometry can Handle
Apply Torque Emulated by Generator Dynamometer Tests to Plate, Determine if Shear or Yeilding Occurs	1	10	If Yeilding, Geometry of Plate Needs to be Revisited
Subject Choosen Screws to Corrosive Chemical Tests	2	12	Choose New Screw Material Properties
Testing a Secondary E-Clip Part and its Corrosion Poperties in Vinigar and Salt Bath	3	27	Upgrade, at a Higher Cost, the Material of the E-Clip to Resist Corrosion
Rotor Forward Force Exterted During Operation at Hogh Speed (Simulation)	4	20	Increase the Clip Size and Groove to Improve Force Compensation
High Cycle Durability Testing	2	20	Design Change May be Nesessary Such as a Closed C-Clip with Similar Structural Magnitude
High Cycle Test, Melting Temperature of Bushing Using Variable Heat Plate	2	36	Choose Steel Bushing Instead, Add in Metal Washer to Decrease Friction
Compressive Test of Bushing Part with Weights	2	20	Stronger Compressive Material for Avoiding this Breakage
Spinning the Bushing for Prolonged Period of Time to see Affects	3	36	Change the Bushing Material to Handle Wear and Prolonged Rotation

12.3 Appendix C: Bill of Materials

Table 7: Bill of Materials Final Generator Design

ITEM NO.	COMPPONENT	DESCRIPTION	QTY	COST
1	ROTOR	ABS PLASTIC 3D PRINTED ROTOR	1	$11.70
2	BEARINGS	8MM BALL BEARINGS	2	$8.74
3	MAGNETS	NEODYMIUM N-52 MAGNETS	24	$42.86
4	STATOR	MAGNETIC IRON-BORE 3D PRINTED PLA	1	$12.43
5	BACKPLATE	ABS 3D PRINTED ABS	1	$5.85
6	BUSHING	8MM NYLON BUSHING	1	$1.75
7	E-CLIP	5/16" E-CLIP RETAINING RING	1	$0.33
8	8MM SHAFT	1055 CARBON STEEL 8MM SHAFT	1	$7.00
9	COPPER COILS	AWG 24 GAUGE COPPER WIRE	1	$4.40

12.4 Appendix D: Load Test Results

Table 8: Load Test One, at 7.65k Ω

	RPM	DCV	DCC	Power	Resistance Ω
1	420	0.05	5.90E-06	2.95E-07	7.65k
2	1200	0.11	1.45E-05	1.60E-06	7.65k
3	1560	0.15	1.95E-05	2.93E-06	7.65k
4	2040	0.21	2.73E-05	5.73E-06	7.65k
5	2525	0.26	3.40E-05	8.84E-06	7.65k
6	3000	0.33	4.35E-05	1.44E-05	7.65k
7	3600	0.43	5.62E-05	2.42E-05	7.65k

Table 9: Load Test Two, at 36.5 Ω

	RPM	DCV	DCC	Power	Resistance Ω
1	420	4.0E-04	8.90E-06	3.56E-09	36.5
2	1200	7.0E-04	1.67E-05	1.17E-08	36.5
3	1560	9.0E-04	2.18E-05	1.96E-08	36.5
4	2040	1.1E-03	3.05E-05	3.36E-08	36.5
5	2525	1.4E-03	3.81E-05	5.33E-08	36.5
6	3000	1.8E-03	5.00E-05	9.00E-08	36.5
7	3600	2.3E-03	6.33E-05	1.46E-07	36.5

Table 10: Load Test Three, at 12.6 Ω

	RPM	DCV	DCC	Power	Resistance Ω
1	420	1.00E-04	9.10E-06	9.1E-10	12.6
2	1200	2.00E-04	1.72E-05	3.44E-09	12.6
3	1560	3.00E-04	2.20E-05	6.6E-09	12.6
4	2040	3.00E-04	3.10E-05	9.3E-09	12.6
5	2520	4.00E-04	3.83E-05	1.532E-08	12.6
6	3000	6.00E-04	5.06E-05	3.036E-08	12.6
7	3600	7.00E-04	6.55E-05	4.585E-08	12.6

Table 11: Load Test Four, at 2500 Ω

	RPM	DCV	DCC	Power	Resistance Ω
1	420	1.87E-02	7.10E-06	1.33E-07	2500
2	1200	3.81E-02	1.49E-05	5.68E-07	2500
3	1560	4.99E-02	2.00E-05	9.98E-07	2500
4	2040	7.09E-02	2.80E-05	1.99E-06	2500
5	2520	8.82E-02	3.52E-05	3.10E-06	2500
6	3000	1.20E-01	4.53E-05	5.44E-06	2500
7	3600	1.50E-01	5.93E-05	8.90E-06	2500