Innovative Generator Design for NAU's Collegiate Wind Competition Team

Final Design Report

Naomi Echo: Project Manager, CAD and Manufacturing Engineer

Kaitlyn Redman: Logistics Manager, CAD and Manufacturing Engineer

Alonso Garcia: Dynamometer Manager and Test Engineer

Christian Brown: Dynamometer Manager, CAD and Testing Engineer

Javan Jake: Financial Manager and Manufacturing Engineer

Spring 2024 – Fall 2025

Project Sponsor: Professor David Willy

Instructor: Professor Armin Eilaghi

DISCLAIMER

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EXECUTIVE SUMMARY

This report presents the concept generation process behind the development of a novel generator design, guided by detailed analysis of three reference units: Mad Jenny, Mad Jennington, and Melon Motor. These pre-existing generators were provided as case studies to reverse-engineer, test, and evaluate. The goal was to identify functional strengths and weaknesses in existing commercial or prototype systems in order to inform and inspire a refined generator concept that meets specific performance and design objectives.

The project began with a comprehensive teardown and characterization of each given generator. Mechanical disassembly allowed for a thorough understanding of component layout, manufacturing choices, and material selection. Electrical testing and electromagnetic simulation were conducted to quantify key performance parameters such as back EMF, torque, ripple, resistance, and thermal response under varying loads. Mad Jenny, characterized by its compact construction and rugged build, offered insights into structural integration and magnetic circuit simplicity. Similar to Mad Jenny and manufactured by the same company, Mad Jennington shows how slight changes in the design of the generator can impact the characteristic Kv curve significantly. In contrast, the Melon Motor showcased an emphasis on high-efficiency operation and smooth output characteristics, with a more intricate winding scheme and finer tolerances.

Findings from these analyses were used to establish a clear set of performance benchmarks and design criteria. These included optimizing electromagnetic efficiency, reducing mechanical complexity, improving thermal dissipation, and ensuring manufacturability within reasonable cost and material constraints. Leveraging simulation tools such as ANSYS Maxwell and Motor CAD, we created multiple parametric models to explore alternative topologies, magnet placements, stator designs, and coil configurations. Each iteration was evaluated not only for theoretical performance but also for practical considerations such as assembly feasibility and component accessibility.

The concept generation process culminated in the selection of a final design that synthesizes the most successful elements from all three, Mad Jenny, Mad Jennington, and Melon Motor, while introducing original innovations aimed at addressing their limitations. Our proposed generator concept maintains a balance between performance, durability, and scalability, making it well-suited for both prototyping and real-world applications.

This report captures the full scope of our research and design journey, from the disassembly bench to the simulation environment, and provides a foundation for future prototyping, experimental validation, and refinements. The lessons learned from analyzing Mad Jenny, Mad Jennington, and Melon Motor not only shaped our final concept but also enriched our understanding of generator design as a multidisciplinary engineering challenge.

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1 BACKGROUND

In the background of the project, the project description, deliverables, and success metrics will be described. The project description explains what the project is about from the client proposal and meetings with the sponsor. The budget and fundraising targets will be discussed. Followed by why this project is important. The deliverables will describe the course, client, and competition for specific deliverables that dictate the requirements listed later in Section 2. The success metrics, i.e., assessments, testing, calculations, and major design requirements, will be discussed.

1.1 Project Description

This project tasks us with creating and modifying 3-phase PMSG's to be used in the CWC by the Energy Club here at NAU. It is referred to as the 3D Printed CWC-scale Generators project, but the 3D printed portion is a bit of a misnomer. It means these generators are small scale to be used in the CWC. NAU has experimented with custom generators in the past but has commonly ended up using drone motors that were later modified for the CWC. These generators have performed poorly and lead to problems with lead times and designing around commercially available products rather than custom ones built for the sole purpose of wind competition. To solve these problems, we will first test existing generators with the Energy Club's dynamometer to characterize their performance. Then we will simulate the generators in Ansys Maxwell and Motor CAD, make modifications to current generator designs, and design our own generators to meet the specific design requirements.

The client of the project is NAU Professor David Willy who advises clubs like BAJA and the Energy Club and has over 20 years in the field of renewable energy. He is providing us with $500 to complete this project, which will be divided amongst the future tasks of testing, modifying, and making generators. We are also tasked by the Capstone professor, Carson Pete, with fundraising at least $300 to further fund our project. Through a combination of physical and monetary donations through family, friends, and a GoFundMe page, this $300 goal has already been achieved. Further fundraising will continue to help our need for parts and sensors as the project progresses.

This project is important because it revolves around the renewable wind energy field. Wind energy is a fast-growing industry as it has over doubled the energy provided across the US from 4% in 2014 to 10% in 2023 [1]. The CWC helps students across the country get firsthand experience with this industry and the technology within it. Providing job experience and monetary support to continue succeeding in college and beyond. Producing the generators will help our NAU team perform better in the CWC, providing a greater chance of success in the competition. Helping the NAU team succeed helps NAU succeed. NAU's success will bring more opportunities to future engineering students, providing more resources and opportunities to help up and coming engineers in whatever field they pursue.

1.2 Deliverables

- Assembly (Weeks 4 - 5)
    - Wind coils on stator
    - Finish manufacturing that wasn't done during preparation
    - Assemble new shaft with epoxy to dynamometer (dyno)

- Calibrate dyno for torque measurements

- Preparation (Weeks 2 - 3)
  - Attend lab/shop training (if available)
  - Manufacture stator, shaft, casing, casing hub, and silicon steel
  - Practice winding coils on a 3D printed stator
  - Order wires, epoxy, bearings, and aluminum
  - Deconstruct and learn about the dyno's mechanisms
  - Rebuild dyno's shaft (and possibly 3D printed parts)

- Initialization (Week 1)
  - Assign roles and deadlines
  - Schedule lab/shop times
  - Confirm availability for tools and materials
  - Risk assessment and mitigation plan
  - Communication with the client

1.3 Success Metrics

The success of the CWC Generator project will be assessed through a combination of testing results, theoretical calculations, and adherence to major design requirements. Success will first be determined by the generator's ability to meet the core performance specifications established with the client, such as generating a maximum voltage of 48V, achieving a cut-in wind speed near 3 m/s, producing high magnetic flux density, and maintaining a low Kv rating around 150. Performance validation will involve experimental testing on the Energy Club's dynamometer, where outputs including voltage, current, torque, and efficiency will be measured and compared against simulation predictions from ANSYS Maxwell and Motor CAD. Success will also depend on the project's ability to stay within the $500 provided budget and integrate modifications such as minimizing cogging torque and optimizing stator-magnet ratios, validated through parametric studies and harmonics analysis. Furthermore, meeting fabrication goals, including manufacturability within practical tolerances such as achieving a 0.5 mm air gap and a 0.1636 stator width ratio, will be critical to the project's evaluation. Overall, the project will be deemed successful if the final prototype generator matches or exceeds the modified benchmark standards set by Mad Jenny, Mad Jennington, and Melon Motor, maintains reliable performance during dynamometer testing, and demonstrates a substantial improvement over previous generator designs used in the CWC.

2 REQUIREMENTS

This section includes key concepts of customer and engineering requirements for designing and developing a generator. A list of requirements was formed after an initial meeting with the client. Using these requirements, engineering specifications were obtained. The engineering specifications translate the given customer requirements into measurable design criteria.

2.1 Customer Requirements and Engineering Requirements

Table 1: Customer requirements and descriptions

Customer Requirements	Description
Low Voltage	Client set safety standard
Small Size	Intended for a small-scale wind turbine
High power	To perform well in the CWC
Under Budget	Limited to funds and donations
Ability to change easily	For future guideline changes and improvements
Up to CWC design standards	Eligible to be used in competition
3 phase AC Generator	Standard small scale generator design

Table 2: Engineering requirements and descriptions

Engineering Requirements	Description
Maximum 48 Volts	CWC guidelines and safety purposes
45 cm rotor diameter of the turbine	CWC guidelines
Low total resistance torque (Nm)	Higher efficiency at lower wind speeds
Low Kv rating	Below 150 is desired, this increases voltage
High magnetic flux (Tesla)	Increases power output
High turbine power output (W)	Output of 100 kW is desired for the power output
Number of coils	Determined by stator geometry and fill ratio
Tip speed ratio, between 7 and 8	This ratio produces a maximum power output
Diameter of the coil	The gauge to be used in the coil
Cut out speed, 25 (m/s)	CWC guidelines and safety purposes
Cut in speed, 3 (m/s)	CWC guidelines and higher efficiency

2.2 House of Quality (HoQ)

Minimize or Maximize																	
House Of Quality			Technical Specifications (How)														
			Maximum 48 Volts	45 cm Roter Diameter of Turbine	Low Total Resistant Torque	Low Kv Rating	Magnetic Flux	Turbine Power	Generator Power	Number of Coils	Tip Speed Ratio	Diemeter of coil	Cut Out Speed	Cut In Speed	Competitive Assessm		
	Customer Requirements (What)	Importance	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
1	Low Voltage	96	9	3	9	9	9	9	9	9	3	9	9	9	1	9	3
2	Small Size	60	3	9	3	1	3	9	3	9	9	9	1	1	1	9	1
3	High Power Generation	100	9	1	9	9	9	9	9	9	9	9	9	9	9	3	1
4	Under Budget	28	1	3	1	1	1	3	3	3	3	3	3	3	1	3	9
5	Ability to change easy	60	1	3	3	9	3	3	9	9	9	9	1	1	3	3	1
6	Up to design standards for CWC	102	9	9	9	9	9	9	9	3	9	9	9	9	9	9	3
7	3 phase AC	34	3	3	3	3	3	1	3	9	1	3	1	1	3	9	9
		Target	48 V	45 cm	2 N-m	150	1-3 T	100 kW	0.5-10 kW	6 coils	7 to 8	0.321-0.644 mm	25 m/s	3 m/s			

Figure 1: Quality Function Deployment

3 Research Within Your Design Space

3.1 Benchmarking

System-level benchmarking will be used by viewing the state-of-the-art (SOTA) for a turbine of PMSG. Three systems that have been considered SOTA which are 5012 IPE V3.0 Brushless Motor, Air Breeze Wind Turbine Generator, and Avian 3536-1200 Kv Outrunner Brushless Motor. These systems will be considered by comparing it with the customer/engineering requirements to ensure the important parts of the PMSG are fulfilled for the client.

3.1.1 MAD 5012 IPE V3.0 Brushless Motor [2]

The MAD 5012 was used in the Energy Club at NAU for the CWC and placed second. The MAD 5012 is SOTA as it was recently used in the CWC and is constantly reused in competitions due to its reliability and success. The MAD 5012 has a Kv rating of 160 and in Figure 1, the client wants a low Kv rating of 100 or below. With this information, the CWC generator team will consider this difference to ensure that the future design of the PMSG will be at least lower than MAD 5012's Kv rating or even lower than 100 Kv. The client also wants a high-power generator and with the MAD 5012, it produces a maximum of 882 W of power. This will be another item of an expected requirement for the PMSG so it can perform as well as the MAD 5012. Benchmarking with this motor is great for the future design of the PMSG as it was a winning generator in the CWC. These values are important as it will lead the CWC generator team to know what target values are to reach as they create their own generator.

3.1.2 Air Breeze Wind Turbine Generator [3]

The Air Breeze is SOTA as it is being constantly used by many buyers for their own energy generation, competitions, and much more. The Air Breeze has a power output of 160 W. In Figure 1, the client wants a high-power output. However, seeing the MAD 5012 having a max power output of 882 W, it is obvious that there is a significant difference between the two. With this, we must provide a higher power output of 160 W due to the MAD 5012 producing a power output of 882 W. However, the Air Breeze has a cut-in speed of 3.1 m/s. This a value that is significant for the PMSG design as the client wants a cut-in speed of 3 m/s. These values have a small difference and will be useful to compare when creating the PMSG design to ensure it gets at least below 3.1 m/s. In addition, the Air Breeze has a cut-out speed of 40.2 m/s. This is a high difference compared to the target value from the customer, which is 25 m/s. So, this will be considered in the design process to ensure we get a lower cut-out speed than the Air Breeze, which will then help the generator and turbine from further damage.

3.1.3 Avian 3536-1200 Kv Outrunner Brushless Motor [4]

The Avian 3536 is SOTA as it was released back in 2022 and is bought by many people for competitions. The Avian 3536 has a max power output of 310 W. This is a better upgrade than the Air Breeze, since the Air Breeze provided 160 W. However, it is still lower than the MAD 5012 and will be considered to make sure that the designs of the PMSG are comparable to the Avian 3536 and the MAD 5012. It is seen in the title of this section that it contains 1200 Kv, which is the highest out of the three systems that were seen. When benchmarking this motor, it is best for the CWC generator team to ensure that the Kv rating doesn't reach Avian's Kv since it is too high for the client's requirements. Also, it is best to ensure that when creating the PMSG, it must be at least 310 W to provide sufficient efficiency.

3.2 Literature Review

3.2.1 Naomi Echo

3.2.1.1 Books

[5] Wind Energy Explained, Chapters 2 and 3

Chapter 2 will be used to reference basic characteristics and mathematical modeling. Chapter 3 will be referencing the aerodynamics of the turbine as well as mathematical explanations.

[6] Performance comparison of electromagnetic generators based on different circular magnet arrangements

Reference for understanding how different magnetic pairings affect power generation.

3.2.1.2 Papers

[7] Preliminary Studies on Number of Coil Turns per Phase and Distance between the Magnet Pairs for AFPM Ironless Electricity Generator

Reference for understanding the relation between the number of turns within a coil and the power and torque output.

[8] Electric Generators Fitted to Wind Turbine Systems: An Up-to-Date Comparative Study

Reference for understanding how the generator will ingrate within the turbine system.

[9] Optimization and Comparison of Modern Offshore Wind Turbine Generators Using Generator SE 2.0

Reference for understanding where the current technology of wind turbines is currently.

3.2.1.3 Others

[10] How to Calculate Motor Kv & Motor Poles

Reference for understanding the direct correlation of Kv and number of turns in a coil.

[11] Basics of Armatures

Reference for understanding how amateurs work and the different ways they may be assembled.

3.2.2 Kaitlyn Redman

3.2.2.1 Books

[12] Chapter 7: Shafts and Shaft Components - Shigley's Mechanical Engineering Design

This chapter is relevant because it goes into detail about equations used to design shafts.

[13] Chapter 11: Rolling-Contact Bearings – Shigley's Mechanical Engineering Design

This chapter is relevant because it goes into detail about equations used to design bearings.

3.2.2.2 Journals

[14] Barings faults and limits in wind turbine generators

This journal is relevant because it goes into detail about the specific limits of wind turbine generators.

[15] Study of turbine-generator shaft parameters from the viewpoint of sub synchronous resonance

This journal is relevant because it goes into detail about shafts specifically in turbine generators.

[16] Optimal bearing configuration selection for power generation shaft-trains: A linear and nonlinear dynamics approach

This journal is relevant because it goes into detail about bearing configurations in power generated shaft train.

3.2.2.3 Online

[17] Mechanical Engineering Design Unit 9 – Power Transmission: Shafts & Bearings

This website is relevant because it goes into detail about shafts and bearings.

[18] Types of bearings: Uses & Working Mechanisms explained

This website is relevant because it describes the different types of bearings we can use in our design.

3.2.3 Christian Brown

3.2.3.1 Books

[19] Fundamentals of Applied Electromagnetics

This textbook gave an overview of laws, equations, applications of electro and magnetostatics, and electromagnetics. These equations are fundamental to understanding how the magnets and the generator will act. It gave many different examples to apply to the generators in the future once the proper data has been acquired from them.

[20] A Student's Guide to Maxwell's Equations

This textbook went in-depth about 4 sets of equations from Maxwell and Ampere to understand the electromagnetics of electric generators. These 4 equations are all integrals explaining how magnetic and electric fields interact with one another. These help our understanding of the generator as it creates electric currents due to magnetic fields.

[21] Brushless Permanent Magnet Motor Design Version 2 (Chapters 2, 7)

Chapters 2 and 7 from this textbook go into the workings of electromagnets and how they act. It also describes the different calculation strategies to figure out the flux, current, and impedance of electromagnets and the air gap within them. It helps our understanding by drawing similarities between electromagnets and regular circuits. For example, as resistors are energy dissipaters to circuits, magnets are energy storages on top circuits.

3.2.3.2 Papers

[22] Future research directions for the wind turbine generator system

This paper was a study of the aspects of modern-day wind generation systems and the benefits of PMSG's. It described the other different kinds of generators used in wind energy and how they compare. The different kinds of PMSG’s were described in detail, comparing the cored versus coreless generators and their difference in structure and usage.

[23] Electric generators and motors: An overview

This study went into the development and evolution of electric generators over the years. From the first kinds of electric generators and their limited uses to modern-day generators and the multiple applications they are used for. It described the evolution of our fundamental understanding of electromagnets and how these were applied over the years.

[24] Mathematical Modelling of Wind Turbine in a Wind Energy Conversion System: Power Coefficient Analysis

This paper studied the fundamental equations that are used to model power output of turbines. This will be useful when testing our generators in the future to be able to compare power curves to see the similarities and differences between the different generators. The calculations will also be applicable when calculating these variables.

3.2.3.3 Online

[25] Electromagnetics in Power Engineering Maxwell 3D Simulations of a Residential Wind Generator

This is a tutorial for one of the modeling software's to be used to generate data on the electric generators. Ansys Maxwell and the different capabilities are gone into step by step with helpful diagrams and instructions to create the generator. The generator in the tutorial will be one we study in the future to see the different outputs compared to our other generators.

[26] 3d-printed Halbach Motor – Building Instructions

This YouTube video is a full tutorial on creating your own small-scale generator. It goes into depth about the magnets that were used and how they were measured. The coiling strategy to properly construct the coils around the stator. It even shows the different parts they 3D-printed and how they accomplished the correct dimensions in drawing them up.

3.2.4 Alonso Garcia

3.2.4.1 Books

[27] Magnetostatic Fields, in Fundamentals of Electromagnetics with MATLAB

This chapter talks about the important properties of time-independent static magnetic fields. It mentions related topics to our project like electrical currents, magnetic forces, magnetic circuits, and inductance. These specific topics are applied to the project because this is the basic understanding of how rotors and stators interact with each other and how it creates power based on these forces and currents.

[28] Time-Varying Electromagnetic Fields, in Fundamentals of Electromagnetics with MATLAB

This chapter talks about the application of static electricity and magnetic fields for time-varying cases. The most important topic of this chapter is Maxwell's Equations. These equations are important and applicable to this project because it will help relate the electromagnetic fields of our future design of a PMSG.

3.2.4.2 Papers

[29] Research on cogging torque optimization design of permanent magnet synchronous wind turbine

This paper talks about using the Taguchi algorithm optimization process for suppressing cogging torque. This algorithm works by looking over local parameters of the generator and seeing what can be changed to decrease the cogging torque. This paper is applicable since it provides data to lowering cogging torque and which approach is more efficient.

[30] Cogging Torque Reduction Based on a New Pre-Slot Technique for a Small Wind Generator

This paper talks about methods of reducing cogging torque. The main methods are Pre-Slot and Manufacturing Aspects, which helped approve lowering cogging torque. The Pre-Slot method would help our project by making pre-allocated slots between the stator poles which will help reduce torque. Additionally, manufacturing aspects will be applicable too because if the manufacturing of a part we make is almost perfect, then it'll help lower cogging torque.

[31] Cogging torque analysis in permanent magnet synchronous generators using finite element analysis

This paper talks about machine-based optimizations of minimizing cogging torque (fragmented magnet structure, opening notch magnet, and more). The fragmented magnetic structure, opening notch magnet, and many other methods are applicable to this project since each of these showed improvement of lowering cogging torque. Also, they showed the drawbacks of these methods. So, we can use this information to determine which is the better approach we can take without losing other important aspects of the PMSG.

3.2.4.3 Online

[32] Module 29: Permanent Magnet Rotor Design (SPM & IPM)

This video talked about the overview of designs of permanent synchronous rotors with figures to show benefits/drawbacks. This is applicable to our project since it shows many applications of applied designs for PMSG, which will help with our design process.

[33] Cogging torque of the turbine generator analysis with Quick Field FEA software

This video works out the problem of finding cogging torque but explains with software to better understand why cogging torque exists. This is applicable to our project because we can use this to find results of our design, which in this case is finding a cogging torque.

3.2.5 Javan Jake

3.2.5.1 Books

[34] Electric Motors and Drives: Fundamentals, Types and Applications: Fundamentals, Types and Applications

This book explains the physics behind how electrical energy is converted to mechanical energy (motors) and vice versa (generators).

[35] Design of Rotating Electrical Machines, 2nd Edition

Explains how electric machines convert energy, a fundamental concept in generator design. Since generators operate on the principle of electromagnetic induction, understanding these basics is essential.

3.2.5.2 Papers

[36] Systematically study on the static power-angle characteristics of a high voltage cable-wound generator prototype

Provides mathematical models and simulations to predict how the generator will behave under different conditions, which is essential for designing and optimizing generator performance.

[37] The effect of electromagnetic load on the basic dimensions of induction salient pole generators

Explores how electromagnetic load affects the magnetic leakage factor and basic dimensions of an induction generator with a salient pole rotor, providing essential information for optimizing generator efficiency.

[38] Operating the induction motor as a generator mode by supplying DC voltage and investigation of the end voltage depending on the excitation current and RPM

Experimental insights into how a three-phase wound-rotor induction motor can function as a generator by applying DC excitation to the rotor, making it useful for repurposing existing motors.

3.2.5.3 Other

[39] Understanding KV rating in brushless motors

Provides the different factors determining KV, the impact it has on motor performance, and selecting the appropriate rating for different applications.

[40] What does 'Kv' mean on brushes motors? Kv explained!

In-depth researching the impacts of factor determining KV and specification application.

3.3 Mathematical Modeling

To support the design and evaluation of the proposed generator concept, mathematical modeling was used to predict electromagnetic behavior, mechanical performance, and thermal characteristics. These models were based on physical principles and informed by empirical data gathered from the Mad Jenny, Mad Jennington, and Melon Motor refence units.

3.3.1 Tip Speed Ratio

$$\lambda = \frac{Blade\ Tip\ Speed}{Wind\ Speed} = \frac{\Omega \cdot R}{U} \tag{1}$$

Ω = Rotational Speed of the Turbine [rad/s]

R = Radius of Blade [m]

U = Wind Speed [m/s]

The desired tip speed is 7-8, as this is industry standard [5]. Using Equation (1) and a typical wind speed of 12 m/s we can find that the blade tip speed will need to be 8 m/s.

3.3.2 Thrust Force

$$F_T = \frac{4\pi R^2 \rho U^2}{9} \tag{2}$$

F_T = Thrust Force [N]

R = Radius of Turbine blade [m]

ρ = Density of air [kg/m^3]

U = Air speed [m/s]

Equation (2) finds the thrust force created as the turbine is rotated by the air. It also considers the turbine to be operating at Betz Limit to allow conservative calculations by setting its inference factor, a, as 1/3. This is not listed above since this will allow an estimation for calculating this force.

3.3.3 Shaft Diameter

$$d = \left\{\frac{16n}{\pi}\left(\frac{2K_f M_a}{S_e} + \frac{1}{S_{ut}}\left[3\left(K_{fs}T_m\right)\right]^{\frac{1}{2}}\right)\right\}^{\frac{1}{3}} \tag{3}$$

d = Diameter of shaft [mm]

n = Safety factor

K_f = Fatigue stress concentration factor

M_a = Alternating moment [N-mm]

S_e = Endurance limit [MPa]

S_{ut} = Ultimate strength [MPa]

K_{fs} = Fatigue stress concentration factor

T_m = Mid-range torque [N-mm]

Equation (3) is the distortion energy (DE) Goodman equation that helps determine the diameter of a shaft with a pre-defined material that considers torque and moments acting on the shaft. However, (3) has been simplified due to the assumption that the shaft of the generator has constant torque and moments acting on the shaft [25].

3.3.4 Wire Diameter

$$J = \frac{I}{A} \tag{4}$$

J = Current Density [A/m^2]

I = Current [A]

A = Cross-sectional Area [m^2]

Equation (4) is used to find the cross-sectional area of the wire so that it can be used to find the diameter.

$$d = \sqrt{\frac{4A}{\pi}} \tag{5}$$

d = Diameter [m]

A = Cross-sectional Area [m^2]

Equation (5) is used to find the diameter of the wire; it is then cross referenced with the American Wire Gauge cart to find the Gauge number needed.

$$R = \rho \frac{L}{A} \tag{6}$$

R = Resistance of Wire [Ω]

ρ = Resistivity of Copper [Ωm]

L = Total Length of Wire [m]

A = Cross-sectional Area [m^2]

Equation (6) is used to find resistance so that it can be used to calculate power loss of the wire.

$$P_{copper} = I^2 R \tag{7}$$

P_{copper} = Power Loss of Copper [$A^2\Omega$]

R = Resistance of Wire [Ω]

I = Current [A]

Equation (7) is used to find the power loss of copper, with the goal of minimizing it as much as possible.

3.3.5 Magnetic Flux

$$B = \mu_o \cdot \frac{NI}{g} \tag{8}$$

B = Magnetic Flux Density [T]

μ_o = Permeability of Air [H/m]

N = Number of Turns

I = Current [A]

g = Air gap length [m]

Equation (8) is used to show the simplified equation for Ansys. This demonstrates the Magnetic Flux density and Cogging Torque in 3D vector form.

3.3.6 Cogging Torque

$$T_{cog} = -\frac{dW_c}{d\theta} = T_{cog}(\theta) = A_n \sin(n_1\theta) + \cdots \tag{9}$$

T_{cog} = Cogging Torque

W_c = Magnetic co-energy

θ = Rotor position

A = Amplitude

n = Harmonics Number

In equation (9), this supports the way to model cogging torque ripples. Both papers uploaded directly talk about using harmonic/Fourier series to model cogging torque (1). Real generators have multiple harmonics (28, 56, 84...).

4 Design Concepts

4.1 Functional Decomposition

The important function of this project is to ensure it meets the needs of the customer's requirements. These specific requirements are to make sure that the generator outputs a high voltage, high power, low Kv rating, and be able to change the parameters within the generator for the NAU CWC team. These requirements are important to the project since these are the basic requirements for a general generator, and the customer's needs are satisfied.

4.2 Concept Generation

4.2.1 Coils

The coils of the generator wrap around the stator's arms, and each generate electricity. The number of turns in a coil is one of the main components that determines the peak voltage and torque. These are the values that affect the Kv rating and power generation. From ANSYS simulation we were able to conclude that the high number of turns creates high voltage and torque. The main cons with a high number of turns are that it will increase the difficulty of the manufacturing process as well as make the generator more difficult to spin because of the increased torque.

4.2.2 Air Gap

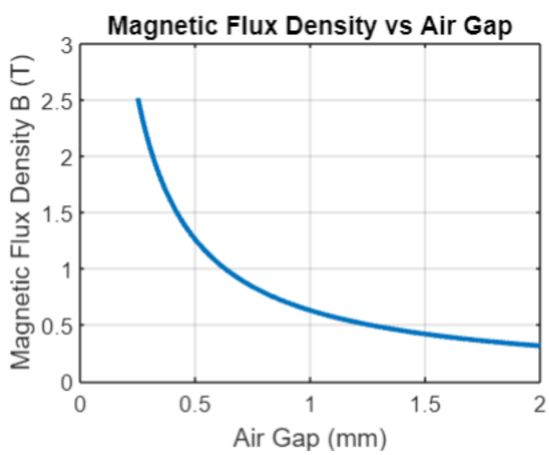


Figure 2: Magnetic Flux Density vs Air Gap

Figure 2 illustrates the effect of varying the air gap on magnetic flux density. As the air gap length decreases, the magnetic flux density increases significantly. This behavior is expected because a smaller air gap reduces magnetic reluctance, allowing more concentrated magnetic flux between the rotor and stator. The graph supports the optimization choice of designing for a minimized air gap, showing that reducing the air gap size improves magnetic performance, which is critical for maximizing generator efficiency. Through systematic variation of the air gap and stator slot width ratio, we identified that a 0.5 mm air gap configuration provided the highest magnetic flux density, thereby optimizing electromagnetic performance while maintaining practical manufacturing tolerances.

4.2.3 Magnet and Slot Ratio

The ratio of slots to magnets is important to consider when making any electrical motor or generator. It determines the performance of the generator and different ratios work better for different sizes and applications of generators. The two concepts being considered for this ratio are the same ratios in Mad Jenny and Melon Motor. Mad Jenny has a ratio of 24 slots to 28 magnets while Motor Melon has half of each, 12 slots and 14 magnets. The testing showed that each produces an even 3-phase distribution of magnetic flux and voltage, so further consideration is needed to determine which is better for our design constraints. The ratio of 24 slots and 28 magnets will be more difficult to manufacture than 12 and 14 due to increased complexity of the geometry and needing to fit more magnets into the same geometry. Though with more slots and magnets, there is less cogging frequency because the magnetic flux is distributed over more stator arms with smaller magnets. These will be important to consider when moving forward with the concept generation.

4.2.4 Shaft and Bearings

In Figure A1, it shows the inputs needed from the generator, shaft material, and turbine properties. These inputs are to be used for determining values like shear force, bending moment, torque, and diameter of shaft. After the code runs, it will display the shaft diameter needed based on the given inputs. With the current inputs, the shaft diameter was determined to be 4 mm for aluminum. With this shaft diameter, the bore diameter of the bearing can be chosen. This would be 4 mm as well.

Other concept generations within the shaft were bearings, thrust lip, and material. To start off, steel and aluminum were concepts for the shaft material. Steel is known for being a strong material, and we want the shaft to withstand the forces applied from the turbine. However, steel is magnetic and can disrupt the magnetic field while the generator is spinning. So, aluminum was the final choice since it is not magnetic and reliable choice from many other PMSGs. Next, the bearing selection was either deep-grooved or cross-roller bearings. Cross roller bearings are typically used within companies making rotors but are expensive compared to deep-grooved bearings. Deep-grooved bearings are the typical bearings seen anywhere in an engineering system, and it would best fit this project due to its cost and availability. Lastly, the thrust lip was introduced into this concept generation because the shaft can cause the bearings to slip along it, which can make the generator fail. So, a thrust lip was added, and the results can determine the thrust lip diameter.

4.3 Selection Criteria

4.3.1 Coils

The selection criteria for determining how many turns in a coil we will use only considering the number of turns that correlates to a wire gauge we are able to buy. As well as the voltage, torque, power, and Kv rating. An additional tool to analyze the voltage and torque in addition to the numerical values is analyzing the shape of the graphs. We are aiming for graphs that are consistent and symmetrical for voltage and current. To calculate the values, Motor CAD was used to simulate the results of the voltage, current, and torque. These results were then inputted into a MATLAB code to calculate the Kv and Power. The table below displays all of the numerical results.

Table 3: Number of Turns in a Coil Results

Number of Turns	Gauge Size	Voltage [V]	Torque [N-m]	Current [A]	Kv	Power [W]
30	21	10.36	.048	10	121.9	179.44
38	22	16.38	.06	10	77.1	263.7
49	23	28.6	.073	10	44.16	495.36

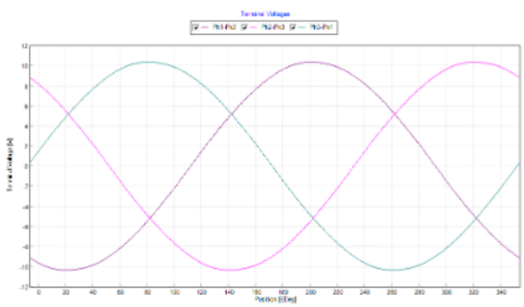


Figure 3: 30 Turns Voltage

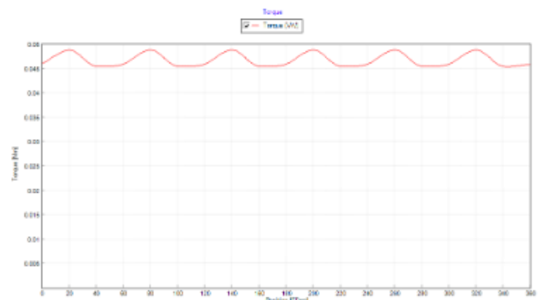


Figure 4: 30 Turns Torque

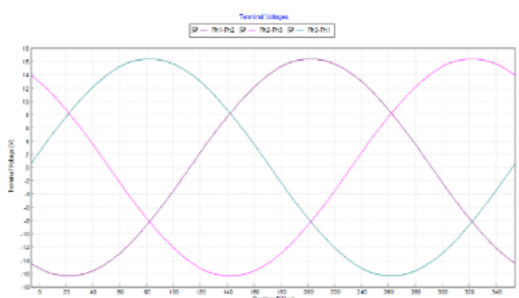


Figure 5: 38 Turn Voltage

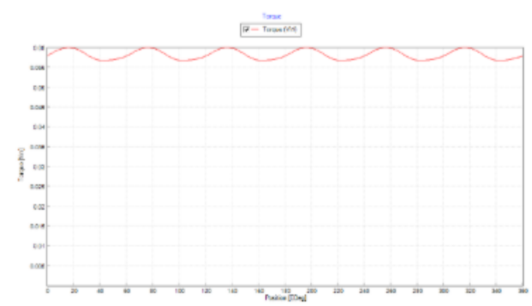


Figure 6: 38 Turn Torque

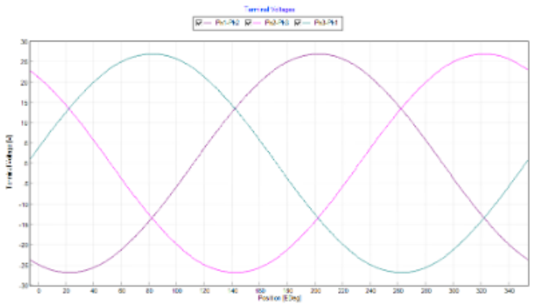


Figure 7: 49 Turn Voltage

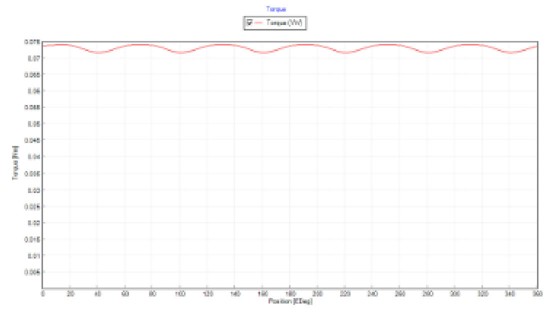


Figure 8: 49 Turn Torque

4.3.2 Magnet and Slot Ratio

An online resource was used to help with the magnet and slot ratio concept generation and selection of the final concept. The equation and table below were utilized from this resource [41]. One parameter that helps reduce the concept generation to the most optimal ratios is the q factor. The inputs are the number of slots, magnets, and phases.

$$q = \frac{N_s}{N_{ph} \cdot N_m} \tag{10}$$

Equation (10) above shows that q is the fraction of the slots per pole per phase of the generator. A q less than one denotes a concentrated winding generator, which is part of the 3-phase design. A q that is less than 0.25 is suboptimal as it means that the magnets are so small; multiple will go over the same stator arm at the same time. This produces conflicting magnetic fluxes as the magnets alternate between north and south around the rotor. A q greater than 0.5 is also suboptimal as it means a magnet will pass over multiple slots at the same time. This is no longer optimal for a concentrated winding and would be better applied to a distributed winding, where the coils wrap around the entire stator as opposed to a single stator arm. This combined with symmetry of magnets to slots and unbalanced ratios reduces the optimal concepts drastically.

Table 4: Cogging Frequency of Multiple Slot and Magnet Ratios

Ns	Nm													
	2	4	6	8	10	12	14	16	18	20	22	24	26	28
3	NoSym	NoSym	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25
6	q > 0.5	12	UnBal	24	q < 0.25	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25
9	q > 0.5	q > 0.5	18	NoSym	NoSym	36	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25	q < 0.25	q < 0.25	q < 0.25
12	q > 0.5	q > 0.5	UnBal	24	60	UnBal	84	48	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25
15	q > 0.5	q > 0.5	UnBal	q > 0.5	30	UnBal	NoSym	NoSym	UnBal	60	q < 0.25	UnBal	q < 0.25	q < 0.25
18	q > 0.5	q > 0.5	q > 0.5	q > 0.5	q > 0.5	36	126	144	UnBal	180	198	72	q < 0.25	q < 0.25
21	q > 0.5	q > 0.5	UnBal	q > 0.5	q > 0.5	UnBal	42	NoSym	UnBal	NoSym	NoSym	UnBal	NoSym	84
24	q > 0.5	q > 0.5	UnBal	q > 0.5	q > 0.5	UnBal	q > 0.5	48	UnBal	120	264	UnBal	312	168

Shown above in Table 4 is many different slot and magnet combinations from the absolute minimum of 2 magnets and 3 slots to Mad Jenny's ratio of 28 magnets and 24 slots. The ratios where q is in suboptimal range, the asymmetrical, and the unbalanced ratios are exempted from the calculation of the cogging frequency to narrow down the possible concepts. A higher cogging frequency is typically better when creating a generator. A higher cogging frequency correlates to a lower cogging torque at any single instance. This is due to the amplitude of the cogging torque reducing as the frequency increases, creating what is closer to a line rather than a sine wave of varying torque. Looking at the two initial concepts of Mad Jenny and Melon Motor's ratios, the 24 slots and 28 magnets ratio appears more optimal having twice the cogging frequency than 12 slots and 14 magnets. The Pugh chart will help decide between the concepts with the selected parameters.

4.3.3 Air Gap

The following figures show Flux Density with different sized Air Gaps; this data is collected from ANSYS.

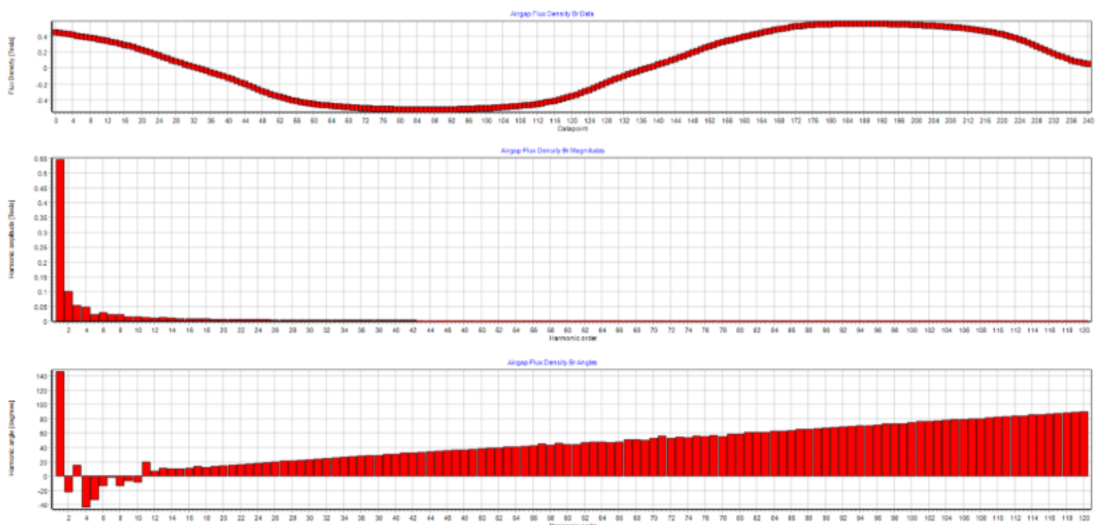


Figure 9: Flux Density with Air Gap 2 mm

This plot shows the variation of magnetic flux density (B) along the air gap of the generator or motor across different degrees of rotation (likely in electrical degrees or mechanical degrees). The x-axis represents position (or angular displacement), and the y-axis shows the flux density in Tesla (T). The wave-like shape indicates the periodic nature of the flux distribution across the air gap due to alternating poles of magnets. The smooth sinusoidal profile suggests good electromagnetic design with minimal distortion.

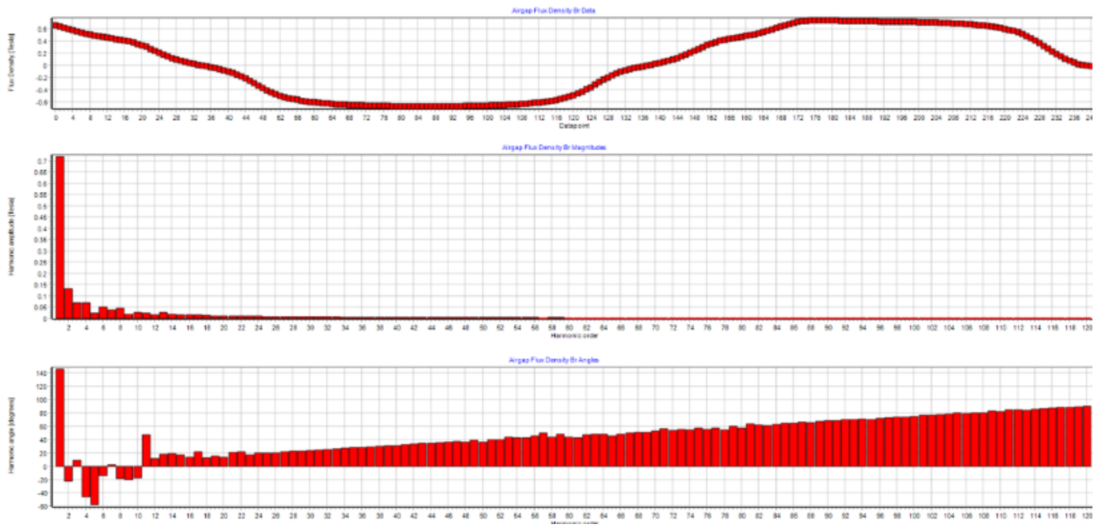


Figure 10: Flux Density with Air Gap 1 mm

This is a histogram of magnetic flux density magnitudes. It shows how frequently certain flux densities occur in the airgap. The majority of flux density values are concentrated around the lower end (left side of the graph), meaning that a large portion of the airgap experiences low-to-moderate flux. A few areas have high flux, corresponding to areas directly between stator and rotor poles

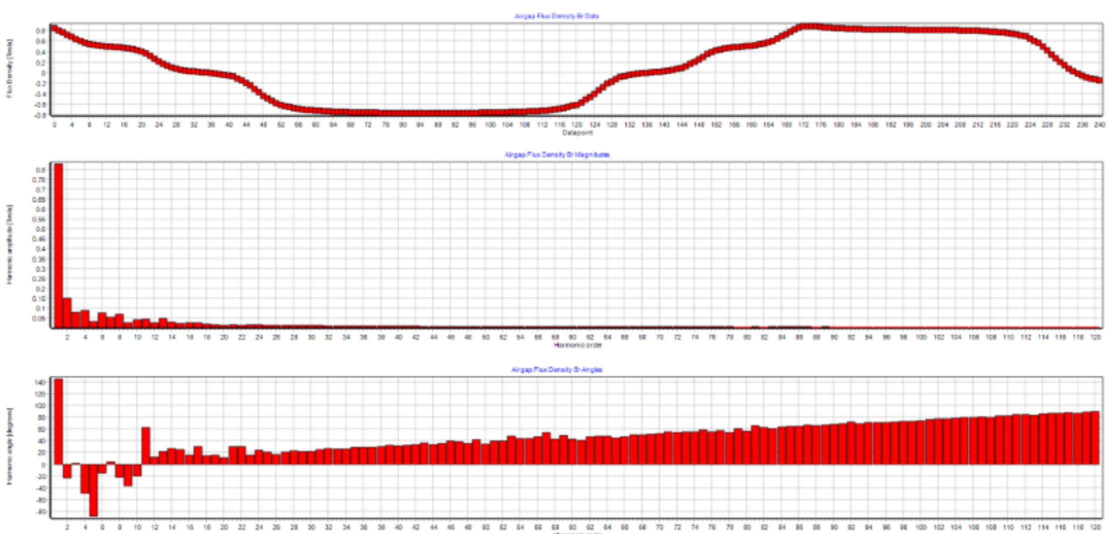


Figure 11: Flux Density with Air Gap 0.5 mm

This histogram shows the flux density variation as a function of angle. It visualizes the harmonic content of the flux wave by indicating how different angular components contribute to the flux density. The sharp peaks and increase in height across angle indices suggest that harmonic distortion is present. Lower-order harmonics dominate, which is typical of practical machines.

In addition to air gap optimization, the stator slot design was refined by increasing the stator width to 9 mm, which resulted in a gap between stators of 1.47 mm and a corresponding slot width ratio of 0.16. While literature recommends an ideal ratio between 0.13 and 0.15 for minimal cogging torque and optimal flux performance, manufacturing and machining limitations made achieving a 0.13 ratio impractical. Therefore, the selected configuration represents a balanced compromise between the best theoretical practices and realistic fabrication capabilities.

4.3.4 Shaft and Bearings

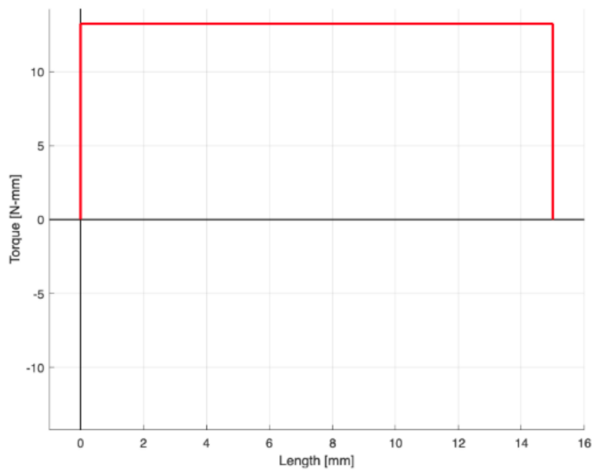


Figure 12: Torque Diagram Along Shaft

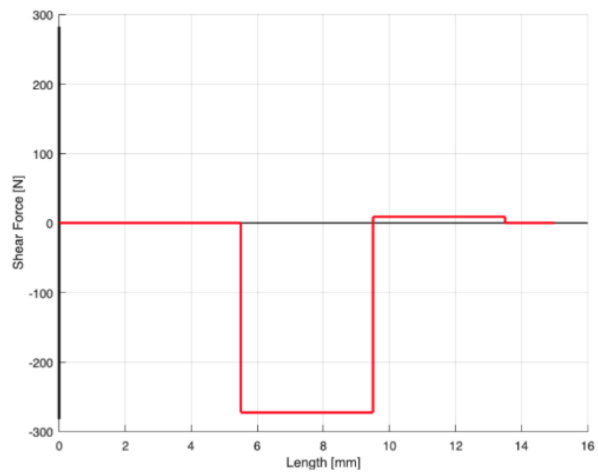


Figure 13: Shear Force Along Shaft

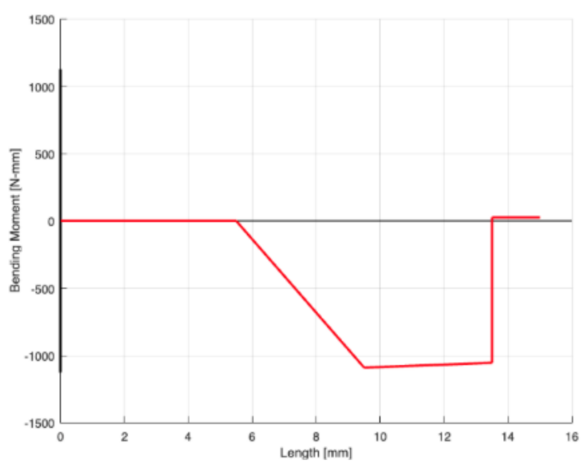


Figure 14: Bending Moment Along Shaft

In Figures 12-14, these graphs are needed to find the absolute maximum value point of stress acting along the shaft. After finding this value, it will be used to apply the DE-Goodman equation to find the diameter of the shaft so it can withstand the stresses in it. The result previously mentioned was a 4 mm shaft for a 15 mm length shaft. This length can change during the design process, but we saw it best fit to keep the length short, so there isn't any increasing bending moment, which will then cause deformation to the shaft.

4.4 Concept Selection

4.4.1 Coils

Table 5: Coils Pugh Chart

Characteristics	30 Turn	38 Turn	49 Turn
Voltage (Volts)	-	+	+
Current (amps)	0	0	0
Torque (N*m)	-	+	-
Kv	-	+	+
Power (Watts)	-	+	+
Manufacturing	+	+	-
Graph Shape	-	+	+
Total	1	6	4

The Pugh chart has calculated that the 38-turn generator performs the best, so this is what will be used in our design.

4.4.2 Magnet and Slot Ratio

Table 6: Magnet and Slot Ratio Pugh Chart

Characteristics	12 Slots 14 Magnets	24 Slots 28 Magnets
Cogging Frequency	-	+
Complex Geometry	+	-
Number of Magnets	+	-
Total	2	1

Based on the Pugh chart and the different parameters to consider mentioned in the concept generation section, the 12 slots and 14 magnets ratio is the concept that will be implemented into the final design.

4.4.3 Air Gap

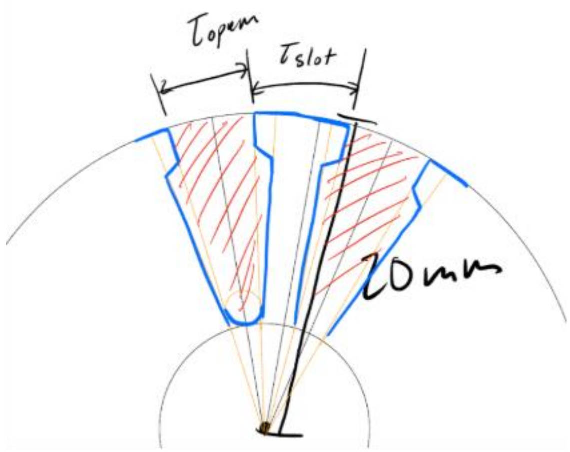


Figure 15: Diagram of Stator

In Figure 15, it shows where the T_{open} and T_{slot} are on the stator for reducing the cogging torque. This value will be the result of the stator ratio width in Table 7.

Table 7: Stator Ratio Width

Stator Width (mm)	Width Between Stators (mm)	Ratio Width
8	2.4720	0.3090
8.2500	2.2220	0.2693
8.5000	1.9720	0.2320
8.7500	1.7220	0.1968
9	1.4720	0.1636
9.2500	1.2220	0.1321
9.5000	0.9720	0.1023
9.7500	0.7220	0.0740

Table 7 presents a comparison of different stator slot width ratios, defined as the ratio of the open slot width to the total slot pitch. This ratio plays a critical role in determining the magnetic flux distribution and cogging torque behavior of the generator. The slot width ratio influences the air gap flux linkage, and the harmonic distortion present in the system.

4.4.4 Shaft and Bearing

Table 8: Material of shaft Pugh Chart

Characteristics	Steel	Aluminum
Strength	+	-
Cost	-	+
Non-Magnetic	-	+
Total	1	2

Table 9: Bearings Pugh Chart

Characteristics	Deep-Grooved	Cross Roller
Strength	+	+
Cost	+	-
Total	2	1

In Tables 8 and 9, the chosen material and bearings for the shaft are aluminum and deep-grooved, respectively. These were chosen to withstand the forces that the shaft will encounter. Aluminum was chosen since the shaft can't interfere with the magnetism within the generator as it can cause the generator to lose its efficiency. The deep-grooved bearing was chosen due to its cost and availability.

5 Schedule and Budget

5.1 Schedule

Testing				
Learn ANSYS	C.B./K.R.	100%	2/22/25	3/6/25
Learn MotorCAD	J.J./N.E.	100%	2/22/25	3/6/25
Build generator in ANSYS	Cristian Brown	100%	3/7/25	3/29/25
Build generator in ANSYS	Kaitlyn Redman	100%	3/7/25	3/29/25
Build generator in MotorCAD	Naomi Echo	100%	3/17/25	3/29/25
Build generator in MotorCAD	Javan Jake	100%	3/17/25	3/29/25
Build new gen in ANSYS	Kaitlyn Redman	100%	4/16/25	4/20/25
Expoxy vs super glue	Naomi Echo	100%	4/9/25	4/20/25
flux leakage al vs steel	Naomi Echo	100%	4/15/25	4/20/25
Test exsiting generator	C.B./J.J.	100%	3/10/25	4/4/25
Test Modify generator	Naomi Echo	100%	4/4/25	4/11/25
Test new generator	C.B./J.J.	100%	4/18/25	4/22/25
Evaluation/Deliverables				
Compare current generators	Everyone	100%	3/12/25	4/5/25
Magnetic Flux analysis, maxwell	Christian Brown	100%	3/24/25	4/3/25
Magnetic fluz analysis, motorcad	Javan Jake	100%	3/24/25	4/3/25
Coil analysis, motorcad	Naomi Echo	100%	3/24/25	4/3/25
Coil analysis, maxwell	Kaitlyn Redman	100%	3/24/25	4/3/25
Modified vs New gen.	Everyone	100%	4/23/25	5/5/25
Report 1	Everyone	100%	2/12/25	3/3/25
Report 2	Everyone	100%	3/30/25	4/25/25
Presentation 1	Everyone	100%	1/31/25	2/9/25
Presentation 2	Everyone	100%	3/10/25	3/14/25
Presentation 3	Everyone	100%	3/24/25	3/30/25
Prototype 2- super glue vs epoxy	Naomi Echo	100%	4/18/25	4/25/25
Prototype 2- negative stator with lam	C.B.	100%	4/18/25	4/25/25
Stator Cad	Christian Brown	100%	4/14/25	4/17/25
Negative Stator Cad	Christian Brown	100%	4/15/25	4/22/25
Case Cad	Javan Jake	100%	4/7/25	4/22/25
Website Check 1	Alonso Garcia	100%	3/3/25	3/9/25
Website Check 2	Alonso Garcia	100%	3/18/25	5/5/25
Initiation				
Define goals	Everyone	100%	1/23/25	1/24/25
Develop team charter	Everyone	100%	1/24/25	1/26/25
Do tutorials on SolidWorks	Everyone	100%	1/24/25	1/26/25
Meet with Dr. Willy	Everyone	100%	1/27/25	1/31/25
Initialize website	Alonso Garcia	100%	1/29/25	2/3/25
Meet with Kevin Bruns	Everyone	100%	1/31/25	2/4/25
Research cogging torque	Alonso Garcia	100%	1/31/25	2/10/25
Research Kv	Javan Jake	100%	1/31/25	2/10/25
Research tip speed ratio	Naomi Echo	100%	1/31/25	2/10/25
Research shaft & bearings	Kaitlyn Redman	100%	1/31/25	2/10/25
Research air gap size	Christian Brown	100%	1/31/25	2/10/25
Complete/rehearse presentation	Everyone	100%	1/31/25	2/10/25
Take apart generator and alternator	Everyone	100%	2/4/25	2/13/25
Planning and design				
Create schedule	Naomi Echo	100%	2/5/25	2/9/25
Identify deliverables	Naomi Echo	100%	2/7/25	2/12/25
Develop budget	Javan Jake	100%	2/12/25	2/15/25
Finish dyno	Alonso, Naomi	99%	2/12/25	3/15/25
Solder dyno	Naomi Echo	100%	2/14/25	3/7/25
Replace Dyno Screen	N.E.	100%	2/19/25	2/21/25
Electrical box for dyno	Naomi and Alonso	100%	2/14/25	3/10/25
4 mm Adaptor to test gen.	Kaitlyn Redman	100%	2/14/25	2/24/25
Tachometer Sensor	Naomi Echo	100%	2/21/25	2/25/25
Voltage Sensor	Javan Jake	100%	2/21/25	2/25/25
Current Sensor	Kaitlyn Redman	100%	2/21/25	2/25/25
Torqe Sensor	Christian Brown	100%	2/21/25	2/25/25
Arduino Code	Alonso Garcia	100%	2/21/25	3/8/25
Make Arduino Schematic	Alonso Garcia	100%	2/24/25	3/1/25
Build Ardunio Board	Naomi, Alonso	100%	3/10/25	3/14/25
Ch. 1,6,10	Naomi Echo	100%	2/17/25	3/1/25
Ch. 1,2,7,10	Christian Brown	100%	2/17/25	3/1/25
Ch. 1,8,10	Alonso Garcia	100%	2/17/25	4/4/25
Ch. 1,3,9,10	Javan Jake	100%	2/17/25	3/1/25
Ch. 1,5,10	Kaitlyn Redman	100%	2/17/25	3/1/25
make tachometer adapter	Naomi Echo	100%	3/24/25	3/31/25
make L bracket for generator	Alonso Garcia	100%	3/26/25	4/5/25
Make pegs for Arduino (possibly?)	Alonso Garcia	100%	4/1/25	4/6/25
make stand for the electrocookie	Alonso, Naomi	100%	3/30/25	4/6/25
concept gen for our own design	Naomi Echo	100%	4/3/25	4/10/25
concept gen for our own design	Alonso Garcia	100%	4/3/25	4/10/25
concept gen for our own design	Javan Jake	100%	4/3/25	4/10/25
concept gen for our own design	Kaitlyn Redman	100%	4/3/25	4/10/25
concept gen for our own design	Christian Brown	100%	4/3/25	4/10/25
Plan for manufactuering	Naomi Echo	100%	4/9/25	4/19/25
Modify generator	Naomi Echo	100%	3/8/25	4/5/25
Design new generator	Everyone	100%	4/1/25	4/15/25

Figure 16: Spring 2025 Gantt Chart

Initiation				
Update Dr. Willy on any progress during the summer	Everyone	100%	8/25/25	8/29/25
Revise CAD	N.E.	100%	8/25/25	9/1/25
Finalize CAD Drawings	K.R.	100%	8/28/25	9/1/25
Finish Dyno	A.G., C.B.	100%	8/28/25	9/14/25
UGRADS Registration	Everyone	100%	10/2/25	10/23/25
TBA	TBA			
Planning and design				
33+% Build	Everyone	100%	8/25/25	9/25/25
67+% Build	Everyone	100%	9/26/25	10/16/25
Draft of Poster	Everyone	100%	9/26/25	10/30/25
100+% Build	Everyone	100%	10/17/25	11/6/25
Final Poster	Everyone	100%	10/30/25	11/16/25
Inital Testing Results Video	Everyone	100%	11/7/25	11/20/25
Product Demo	Everyone	100%	11/7/25	12/4/25
Final Testing Results Video	Everyone	100%	11/21/25	11/26/25
Practice Presentation	Everyone	0%	11/7/25	11/16/25
TBA	TBA			
Testing				
Test Exisiting Generators	A.G., C.B., J.J.	100%	9/15/25	9/21/25
Test Our Generator	A.G., C.B.	100%	11/6/25	11/7/25
Hipot Test the Coil	K.R., N.E.	100%	9/14/25	9/21/25
Test fit all of the componests	Naomi Echo	100%	10/14/25	10/18/25
TBA	TBA			

Evaluation/Deliverables				
HW 00	Everyone (Individual)	100%	8/25/25	8/31/25
Project Management	Everyone	100%	8/25/25	8/30/25
Engineering Calculations	Everyone	100%	8/31/25	9/6/25
Self-Learning or Individual Analysis	Everyone (Individual)	100%	9/1/25	9/14/25
Peer Evaluations 1	Everyone (Individual)	100%	9/22/25	9/28/25
Machine Shop Training	J.J., A.G.	100%	8/26/25	9/14/25
Create Winding Process	K.R.	100%	8/31/25	9/20/25
Lazer Lamination Stack	N.E.	100%	8/30/25	9/10/25
Assemble Lamination Stack	N.E.	100%	9/10/25	9/20/25
Wind Coil Around Lamination Stack	K.R.	100%	9/14/25	9/21/25
Machine Case	Machine Shop/A.G./N	100%	9/21/25	10/12/25
Machine Hub	J.J., A.G., N.E	100%	9/21/25	10/12/25
Assemble Generator	Naomi Echo	100%	10/12/25	11/2/25
Website Check #1	AG	100%	10/6/25	10/12/25
Testing Plan	C.B., A.G., K.R.	100%	10/13/25	11/2/25
Peer Evaluations 2	Everyone (Individual)	100%	10/20/25	10/26/25
Peer Evaluations 3	Everyone (Individual)	100%	11/10/25	11/16/25
Final CAD Packet	Everyone	100%	11/17/25	11/23/25
Final Report	Everyone	90%	11/24/25	11/30/25
Final Website Check	AG	100%	11/24/25	11/30/25
Peer Evaluations 4	Everyone (Individual)	0%	12/8/25	12/14/25
Client Handoff	Everyone	0%	12/8/25	12/14/25
TBA	TBA			

Figure 17: Fall 2025 Gantt chart

5.2 Budget

Budget & Fundrasing			
Find No.	Company:	Description:	Amount:
1	Gofundme	Online donation for capstone team. Can be shared through friends, family, and social media.	$120.00
2	Team	Cash Donation	$ 80.00
3	Materials & tools	Tools and Materials that were donations throughout the course	$ 95.95
4	Northern Arizona Uni	Capstone budget	$500.00
		Total:	$795.95

Figure 18: Budget and Fundraising

The budget for the capstone is shown in Figure 18 of $700 and the rest is donations from third parties. These third parties given materials and tools to help with the project.

Dynamometer	Prototype 1	Prototype 2	Final Product
14%	21%	25%	40%

Figure 19: Future Expense

Figure 19 is for the future expenses for our prototypes where 14% already went to develop the dynamometer, and the rest is for next semester's product.

5.3 Bill of Materials (BoM)

Bill of Material				
Find No.	Company:	Description:	Cost	Purchase/Not Purchase
1	Amazon	IR Infrared Obstacle Avoidance Sensor IR transmitting Arduino	$ 9.99	Purchase
2	Amazon	5pcs 30A range current Sensor Module Arduino	$ 11.99	Purchase
3	Amazon	Electric Motor	$ 9.99	Purchase
4	Amazon	LCD Screen Display Module Blue Backlight X 2	$ 39.96	Purchase
5	Amazon	ElectroCookie Solerable Breadboard	$ 8.49	Purchase
6	Amazon	LeMotech Electrical Box 5.9"x3.9"x2.8"	$ 15.99	Purchase
7	The Home Depot	Black Rubber Cord	$ 2.64	Purchase
8	Harbor Feight	3pc Poxy Glue	$ 9.14	Purchase
9	Amazon	Ball Bearings Bore 4mm OD 10mm ID 5mm	$7.64	Purchase
		Total:	$108.19	

Figure 20: Up to Date Bill of Materials

Most of the expenses are updated for the course which was for the dynamometer. More materials will be considered next semester for the future products of the generators.

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

Potential failures of this design is the shaft experiencing much more effects that were not considered in the analysis. In short, the analysis used a high safety factor to consider the effects that were not included in the analysis.

6.1.1 Shaft Analysis

PMSG performance is critical for CWC high-end wind speeds of 13 m/s [5]. Therefore, the PMSG thrust force will be evaluated with 13 m/s to consider the worst case under normal operation. The following equations are used that help solve the load case:

$$W = mg \tag{11}$$

$$\Sigma F = 0 \tag{12}$$

$$\Sigma M = 0 \tag{13}$$

Equations (11-13) are the baseline equations that determine forces and moments for equations later explained, which helps determine the shaft size needed to support the forces.

$$P = T\omega \tag{14}$$

$$Kv = \frac{\omega}{V} \tag{15}$$

$$F_T = \frac{4\pi R^2 \rho U^2}{9} \tag{16}$$

Equations (14-16) are equations that help determine a reaction thrust force and reaction torque from the PMSG outputs, like voltage, Kv rating, and power provided. Also, the blade attached to the shaft is considered for determining the thrust force from the wind speeds.

$$S_e = k_a k_b k_c k_d k_e k_f S_e' \tag{17}$$

$$k_a = aS_{ut}^b \tag{18}$$

$$S_e' = 0.5S_{ut} \tag{19}$$

$$d = \left\{\frac{16n}{\pi}\left(\frac{2K_f M_a}{S_e} + \frac{1}{S_{ut}}\left[3\left(K_{fs}T_m\right)\right]^{\frac{1}{2}}\right)\right\}^{\frac{1}{3}} \tag{20}$$

$$D = 1.2d \tag{21}$$

$$r = \frac{d}{10} \tag{22}$$

Equations (20-22) are equations that determine the shaft geometry for the PMSG final design. For Equations (17-19), these are equations that characterize the type of shaft we want, like the conditions and material of the shaft.

Before discussing the solution, the solution is shown in Fig A1 in the appendix. The solution was derived by using the Matrix Laboratory (MATLAB). In Fig A1, the code near the top initializes variables that will be constant throughout the analysis. Then, it will execute all the equations mentioned above. It provides a shear force diagram and bending moment diagram along the shaft. With these diagrams, it will help solve Equation (20), since this is what will define the geometry of the PMSG shaft. After the program is executed, it outputs the shaft diameter, which is 5 mm. The shaft design can be seen in Fig 21.

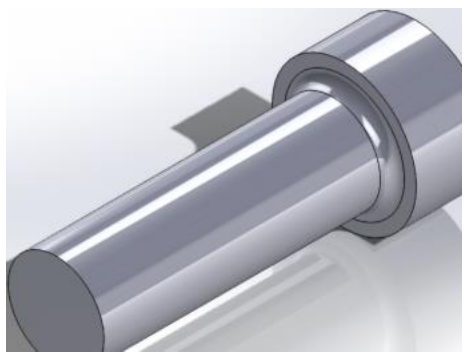


Figure 21: PMSG shaft

After obtaining a solution for defining the geometry of the shaft, the minimum factor can be determined for this sub-system. After doing hand calculations with the DE-Goodman Criterion equation, it is found that the minimum FoS is 4. Table 10 shows more descriptions based on the shaft and its minimum FoS.

Table 10: Minimum FoS for shaft

Sub-system	Part	Load Case Scenario	Material	Method of calculating FoS	Minimum FoS
Shaft					4
	Shaft	Wind turbine input of 13 m/s	Aluminum	MATLAB Calculations in Fig A1 and Fig A2	4

This solution informed the PMSG design by determining how the shaft will look. This also helps determine other parts' geometry of the PMSG, like bearings, casing, stator, etc. With this, it helps choosing other design choices easily.

6.1.2 Wire Gauge Analysis

The Load Case analyzed is at 10 A because this is the Peak operation for our generator. Equation (23) is used to find the following solutions: AWG 16 produced 20.58 V, with a power output of 285 W and a Kv rating of 61.38 RPM/V. While thermally safe, its voltage and torque (0.091 Nm) were too low for our needs. On the other end, AWG 24 reached a high voltage of 41.88 V and 580.31 W of power. However, it produced only 0.11 Nm of torque and would likely overheat due to its high resistance. AWG 22 and AWG 20 performed better, with voltages of 44.65 V and 35.68 V, and torques of 0.96 Nm and 0.57 Nm, respectively. AWG 18 offers a good balance, producing 28.67 V, 397.26 W of power, and 0.18 Nm of torque. Its KV rating of 44.01 RPM/V is ideal for our low-speed generator, and it stays within safe thermal limits. Any wire chosen will be covered with high voltage epoxy rated to handle 1600V. Given the magnitude of this, the rated voltage for each wire is negligible.

Table 11: Minimum FoS for Wire Gauge

Sub-system	Part	Load Case Scenario	Method of finding FoS	Minimum FoS
Wire Gauge				
	16 AWG	10A	$FoS = \frac{I_{allowable}}{I_{operating}}$ (23)	160
	18 AWG			160
	20 AWG			160
	22 AWG			160
	23 AWG			160
	24 AWG			160

AWG 23 is the most suitable winding choice because its small diameter allows a much higher number of turns per slot, improving magnetomotive force density and voltage control without exceeding the stator's geometric limits. The wire is mechanically flexible, easy to route in tight slots, and enables a higher slot-fill factor than thicker gauges. While its losses at 10 A are significant (6.76 W/m), this can be managed through short conductor lengths and forced cooling. In this application, where compactness, winding density, and manufacturability are critical, the advantages outweigh the penalty, making AWG 23 the best overall compromise.

6.2 Initial Prototyping

6.2.1 Super Glue vs Epoxy

Super glue or epoxy will be used to adhere the magnets to the rotor. The strength of easy material was tested as well as its ease of use. Knowing the capabilities of each material will greatly impact our design because it affects the durability of the generator, manufacturing process, as well as the design of the air gap. 919 super glue and ET5441 epoxy were used in this testing. The results below clearly show that the super glue was much stronger than the epoxy used.

Table 12: Epoxy Force Testing Results

Trial	Force Applied Until Failure (lbs)
1	72.2
2	81.3
3	91.1
4	81.1
5	55.4

Table 13: Super Glue Force Testing Results

Trial	Force Applied Until Failure (lbs)
1	126.1
2	133.4
3	167.3
4	187.2
5	143.3

The next aspect that was assessed was how easy it was to use. To activate the epoxy both components had to be mixed and then painted onto the steel being used in testing. This was very messy and time consuming, the epoxy also took a full twenty-four hours to fully cure. The super glue was much easier to use; I was able to apply a small dot of glue on to the area straight from the tube. The super glue cured almost immediately and was very easy to use. From our findings that the super glue was very quick and easy to use as well and was able to withstand a much larger force than the epoxy, we will be using it in our design to adhere the magnets to the rotor.

6.3 Other Engineering Calculations

6.3.1 Bearing Analysis

This section evaluates the life expectancy and suitability of the selected deep-groove ball bearings used to support the generator shaft. Two MR106-2RS bearings were installed in the design. These bearings were sourced from Amazon for initial prototyping; however, future iterations should use bearings purchased from a dedicated manufacturer that provides higher dynamic and static load ratings to improve reliability and extend service life.

$$P_0 = 0.6F_r + 0.5F_a \tag{24}$$

Equation (24) converts the applied radial and axial loads into a equivalent load that represents the worst-case loading conditions on the bearing. It ensures the bearing can safely withstand the combined forces without permanent deformation.

$$n_{static} = \frac{C_0}{P_0} \tag{25}$$

The static safety factor Equation (25) compares the bearings rated static load capacity to the applied load. A value greater than 1 means the bearing can safely support the static load without risk of permanent damage.

$$F_e = \sqrt{F_r^2 + F_a^2} \tag{26}$$

The dynamic equivalent load Equation (26) combines the axial and radial loads into dynamic load. This value is used for fatigue life calculations, because bearings fail due to repeated stress cycles

$$L_{10} = \left(\frac{C_{10}}{F_e}\right)^a \tag{27}$$

Equation (27) is to predict the number of revolutions a bearing will complete before 10% of bearings statistically fail due to fatigue. Where a = 3 for deep-groove ball bearings.

$$L_{10,hours} = \frac{L_{10} \times 10^6}{60 \times n} \tag{28}$$

Equation (28) converts the generator operates at known RPM, with the predicted bearing life in revolutions and then converts into hours. This makes it easier to evaluate real-world lifetime under operating conditions.

Table 14: Forces and Life Expectancy Ball Bearings Results

Quantity	Result
Axial load per bearing	108.25 N
Static equivalent load (P_0)	54.12 N
Static safety factor	3.21
Dynamic equivalent load (F_e)	108.25 N
L10 life	59.25 million rev
L10 life (hours)	395 hours
L10 life (days)	16 days

The end results are that the calculated bearing life of 395 hours at 2500 RPM is acceptable for early prototyping but is insufficient for long-term competition use. The primary limitation is the relatively low dynamic load rating of the Amazon sourced bearings.

For initial prototyping, the team selected MR106-2RS deep-groove ball bearings purchased from Amazon due to their low cost and rapid availability. While these bearings were sufficient for early testing, their relatively low static and dynamic load ratings limit the overall lifespan and reliability of the generator, particularly under the thrust-dominant loading conditions expected in competition. Moving forward, future purchases should transition to bearings sourced from reputable manufacturers such as NMB Minebea, or Boca Bearing, which offer higher-grade materials, tighter tolerances, and increased load capacities. Selecting bearings with dynamic load ratings above 1000 N, improved sealing will extend the operating life. This upgrade will ensure the generator meets long-term durability expectations and performs reliably under continuous high-speed operation in the CWC environment.

7 Final Hardware

7.1 Final Physical Design

The generator consists of two main components, the rotor and stator. In this design, the rotor contains magnets and shaft. The stator is made up of a hub and lamination stack. The two-bearing design is what conjoins the two components. The bearings are an interference fit to the shaft, and an interference fit to the stator.

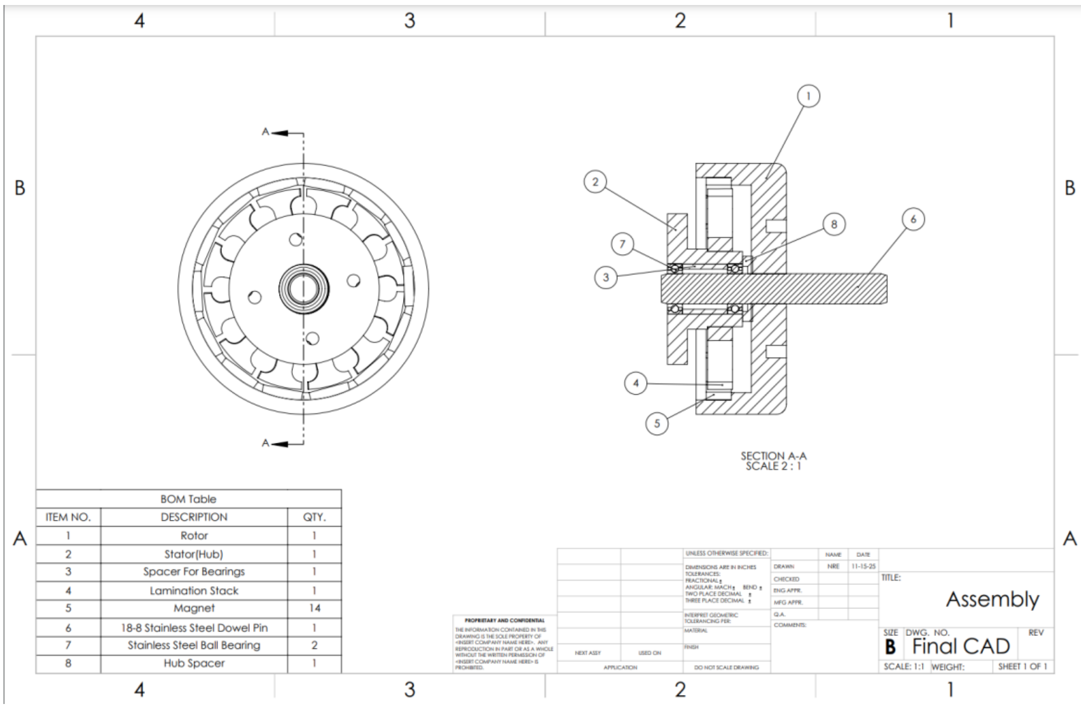


Figure 22: Final CAD Assembly

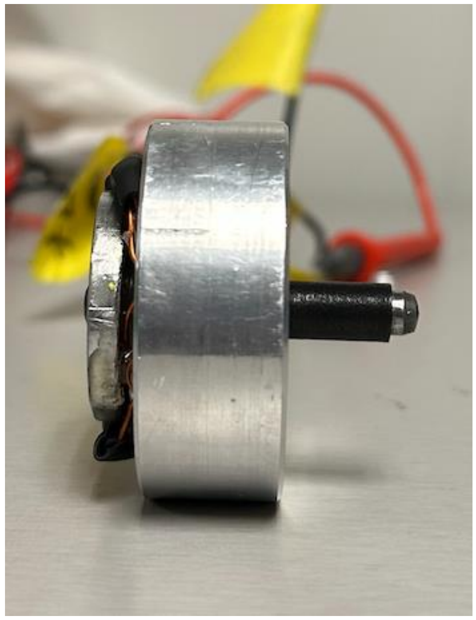


Figure 23: Full Assembly

Figure 24: Rotor

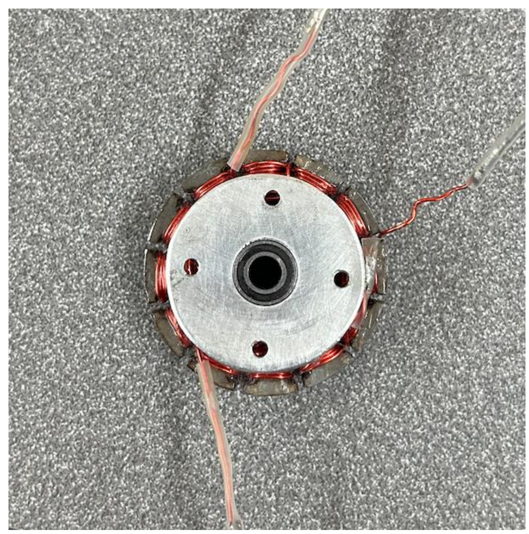


Figure 25: Stator

The lamination stack is made up of .007-inch silicon steel sheets to measure five millimeters tall. The layers are adhered together with 832-C epoxy, which is rated for 1500 volts. The lamination stack is what the coils are wound on. It is a delta configuration with 13 turns using a 22 AWG magnet wire.

Figure 26: Lamination Stack

Figure 27: Coils

8 Final Testing

8.1 Top Level Testing Summary Table

The following Tables entail the Customer and Engineering Requirements (CR & ER), respectively, as well as descriptions of each.

Table 15: Customer requirements and descriptions

Customer Requirements		Description
CR1	Low Voltage	Client set safety standard
CR2	Small Size	Intended for a small-scale wind turbine
CR3	High power	To perform well in the CWC
CR4	Under Budget	Limited to funds and donations
CR5	Adaptable Kv and power	For future guideline changes and improvements, tip speed ratio and power curve required
CR6	Up to CWC design standards	Eligible to be used in competition
CR7	3 phase AC Generator	Standard efficient small scale generator design
CR8	Tip speed ratio of 7	Efficient ratio for small scale wind turbines

Table 16: Engineering requirements and descriptions

Engineering Requirements		Description
ER1	Maximum 48 Volts	CWC guidelines and safety purposes
ER2	45 cm rotor diameter	CWC guidelines for turbines
ER3	Low total resistance torque (Nm) (cogging torque)	Higher efficiency at lower wind speeds
ER4	Low Kv rating	Below 150 is desired for our design, this increases voltage
ER5	High turbine power output (W)	Based on max wind speed
ER6	Number of coils	Determined by stator geometry and fill ratio
ER7	Diameter of the coil	The gauge to be used in the coil
ER8	Cut out speed	Based on peak rpm that generates 48 V

ER9	Cut in speed	CWC guidelines and higher efficiency
ER10	RPM	Range based on Tip Speed Ratio
ER11	Current	From Power Calcs
ER12	Generator Torque	Power & RPM from Kv rating
ER13	Stator Skew	Based on Calcs of range
ER14	Small Scale	Diameter, Thickness, etc.

Table 17: Test summary table

Experiment #	What is Tested	Relevant DRs
1	No load dynamometer sweep	CR1, CR5, ER1, ER3, ER4
2	Constant resistance dynamometer sweep	CR1, CR3, CR5, ER1, ER3, ER4
3	Constant current dynamometer sweep	CR1, CR3, CR5, ER1, ER3, ER4

8.2 Detailed Testing Plan

The following experiments will require the schematic and physical setup of the testing apparatus as shown in Figures 28 and 29.

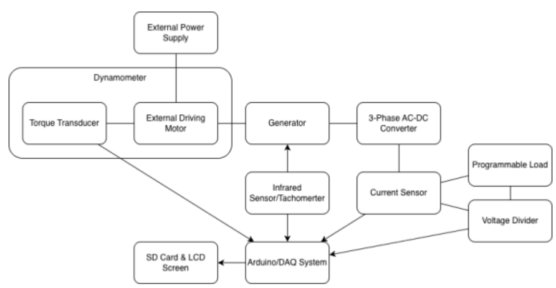


Figure 28: Schematic of testing apparatus

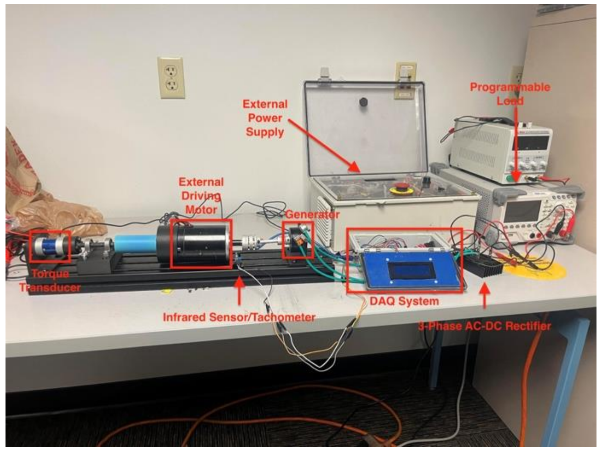


Figure 29: Physical testing apparatus

8.2.1 Test 1: No Load Dynamometer

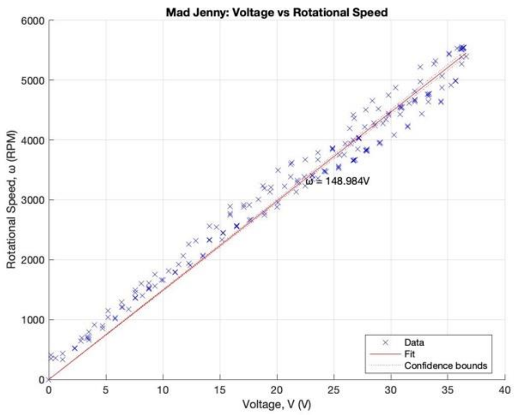
8.2.1.1 Summary

This no-load dynamometer experiment determines how much voltage the generator produces (CR1, ER1), how the Kv and power adapt with speed (CR5), how much resistive torque exists (ER3), and the Kv rating of the 3-phase PMSG (ER4). This experiment will require an Arduino Uno R3, three-phase AC-to-DC rectifier with voltage divider, infrared (IR) sensor, torque transducer, multi-meter, and dynamometer. With these equipment, voltage, rotational speed, and torque will be measured to help quantify Kv rating from voltage and rotational speed, and resistive torque from the torque data over time.

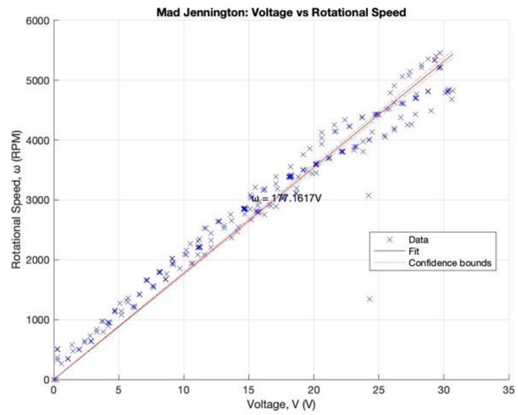
8.2.1.2 Procedure

1. Mount the generator securely and connect its shaft to the dynamometer motor through the coupler
2. Connect the generator's three-phase output wires to a 3-phase AC-to-DC rectifier to convert AC voltage to DC voltage
3. Wire the DC voltage output to the data acquisition (DAQ) system
4. Integrate the torque transducer, infrared (IR) sensor, and voltage divider with the DAQ system to measure torque, rotational speed, and voltage, respectively
5. Connect an external power supply to the dynamometer motor
6. Verify all electrical and mechanical connections before testing
7. Run the dynamometer motor and sweep the power supply input quasi-statically, collecting data points at each power step
8. After reaching the maximum throttle input, stop the dynamometer
9. Process the collected data to determine the Kv curve of the generator

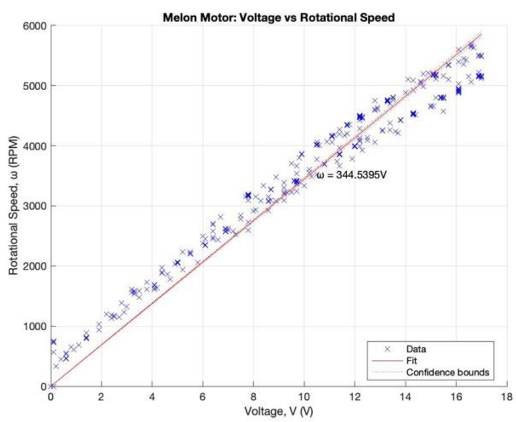
8.2.1.3 Results



(a) Mad Jenny



(b) Mad Jennington



(c) Melon Motor

Figure 30: Kv Curves

8.2.2 Test 2 & 3: Loaded Dynamometer

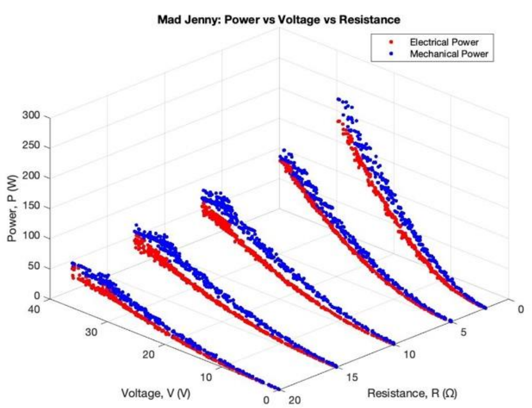
8.2.2.1 Summary

The loaded dynamometer sweeps follow the same procedure as the no-load test but include electrical loading to measure additional performance characteristics. These tests determine the Kv rating, peak voltage, resistive torque, electrical power, and mechanical power. The results will verify whether the generator achieves a low Kv rating (CR5, ER4), maximum voltage (CR1, ER1), low resistive torque (ER4), and high-power output (CR3). The setup includes an external motor to drive the generator, a torque transducer to measure torque, an infrared (IR) sensor to measure rotational speed, a Hall-effect current sensor to measure current, a 3-phase AC-to-DC rectifier to convert the generator output to DC, and a voltage divider to safely send voltage signals to the data acquisition (DAQ) system. Voltage and rotational speed data will be used to plot the loaded Kv curve. Torque and rotational speed will determine mechanical power, while voltage and current will determine electrical power.

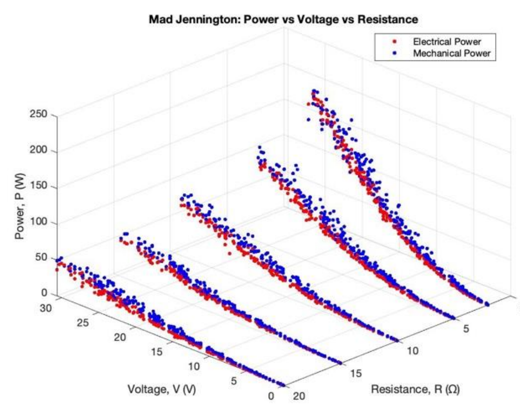
8.2.2.2 Procedure

1. Mount the generator securely and connect its shaft to the dynamometer motor through the coupler
2. Connect the generator's three-phase output to a 3-phase AC-to-DC rectifier to convert AC voltage to DC voltage.
3. Wire the DC voltage output to the DAQ system
4. Integrate the torque transducer, IR sensor, current sensor, and voltage divider with the DAQ system to measure torque, rotational speed, current, and voltage, respectively.
5. Connect an external power supply to the dynamometer motor
6. Verify all mechanical and electrical connections before operation.
7. Sweep the power supply input quasi-statically, recording data at each power step.
8. After reaching maximum throttle, stop the dynamometer.
9. Process the collected data to generate the mechanical and electrical power curves.

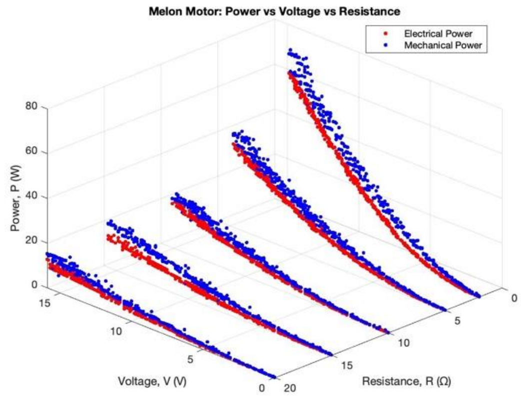
8.2.2.3 Results



(a) Mad Jenny

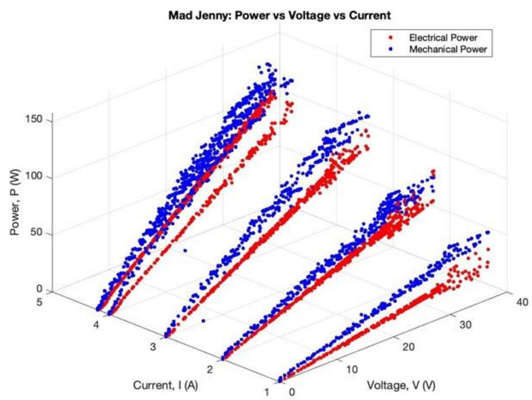


(b) Mad Jennington

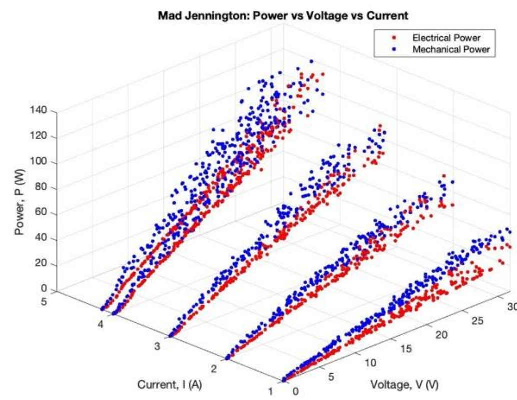


(c) Melon Motor

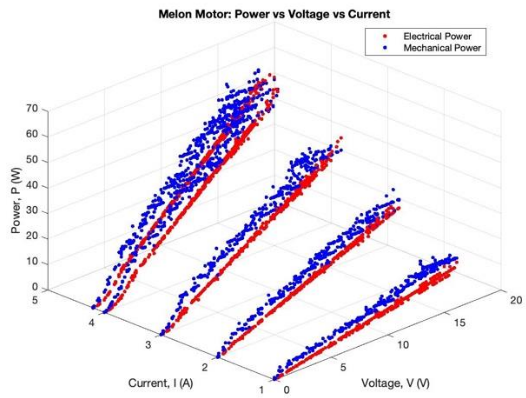
Figure 31: Constant resistance power curves



(a) Mad Jenny



(b) Mad Jennington



(c) Melon Motor

Figure 32: Constant current power curves

9 Future work

While the current design cycle produced a functional generator concept supported by simulation, prototyping, and preliminary testing, several opportunities exist to refine the system and further improve performance. These next steps would meaningfully advance the design toward being a competition-ready generator and enable future teams to continue development with a strong foundation.

9.1 Coil Winding Refinement and Thermal Characterization

Future teams should assess coil packing density, winding tension, and epoxy selection to increase slot fill ratio without compromising manufacturability. Additionally, phish paper can be used to more confidently ensure no continuity between the coils and the lamination stack and to protect the coils from the sharp corners when in the process of winding. Thermal modeling, validated through infrared imaging during dyno runs, will help determine safe continuous and peak operating currents. Exploring different AWG sizes or alternative insulation coatings could further reduce resistive losses.

9.2 Manufacturing and Assembly Process

To support the Energy Club's yearly iteration cycles, future teams should develop standardized jigs for coil winding, magnet alignment, lamination stacking, and bearing installation. Documenting detailed manufacturing workflows, including tolerances, tool lists, and curing times, will reduce variation between builds and improve repeatability. Selecting parts to purchase rather than manufacturing from scratch, like the shaft, will help with consistency but add lead time to the total manufacturing.

9.3 Testing with Turbine Blades

Once the generator is validated independently, it should be integrated with the final CWC-scale wind turbine to evaluate coupled performance. Testing the full drivetrain will allow measurement of cut-in behavior, power extraction efficiency across TSR, and generator loading effects on aerodynamic performance.

10 Conclusion

This project focused on designing, analyzing, and initiating prototyping for a custom 3-phase permanent magnet synchronous generator (PMSG) intended for NAU's Collegiate Wind Competition (CWC) team. The goal was to address the limitations of commercially modified drone motors, previously used by the team, by developing a generator tailored specifically to CWC performance requirements, student manufacturability, and future adaptability. Through detailed benchmarking of the MAD JENNY and Melon Motor generators, the team identified key performance targets: low Kv rating, minimized cogging torque, high power output, manufacturability within tight geometric tolerances, and reliable operation at competition wind speeds. Using Ansys Maxwell, Motor CAD, and MATLAB-based modeling, multiple concepts were evaluated, leading to the selection of a generator design featuring a 12-slot/14-magnet topology, a minimized 0.5 mm air gap, a 13-turn coil configuration, and a non-magnetic aluminum shaft sized through DE-Goodman fatigue analysis. Initial prototyping, including adhesive testing, lamination stacking, bearing analysis, and CAD refinement, supported feasibility of the final design and informed improvements to manufacturing processes. Simulations demonstrated strong electromagnetic performance consistent with project requirements, while mechanical analyses confirmed the structural reliability of the shaft and bearing system. The project remains positioned for full fabrication and dynamometer validation in the next development phase. The work completed this semester established a robust foundation for a fully custom generator that can exceed the performance of previous NAU CWC units, enhance the team's competitiveness, and provide future student teams with a clear pathway for continued improvement. The combination of analytical modeling, simulation validation, and practical prototyping ensures that the proposed design is both technically sound and realistically achievable within CWC constraints.

11 REFERENCES

[1] Climate Central, "A Decade of Growth in Solar and Wind Power: Trends Across the U.S. | Climate Central," www.climatecentral.org, Apr. 03, 2024. https://www.climatecentral.org/report/solar-and-wind-power-2024

[2] "5012 IPE v3.0 Brushless Motor," MAD COMPONENTS, https://mad-motor.com/products/mad-components-5012-ipe-v3?VariantsId=10417 (accessed Mar. 9, 2025).

[3] "Air Breeze wind turbine generator 160W / 12V 24V 48V w/ control panel," Solar Us Shop, https://solar-us-shop.com/products/primus-wind-power-air-breeze-wind-turbine-generator-160w-12v-24v-48v?srsltid=AfmBOoqXg5cTZUdE_E383RBNysW4iK1SsZNKz3FO2eRp8nowKWWe3rDr (accessed Mar. 9, 2025).

[4] Spektrum avian 3536-1200kv outrunner brushless motor, SPMXAM4620 : Amazon.com.au: Toys & games, https://www.amazon.com.au/Spektrum-3536-1200Kv-Outrunner-Brushless-SPMXAM4620/dp/B09TWKHL2H (accessed Mar. 9 2025).

[5] J. F. Manwell, J. G. McGowan, and A. L. Rogers, "Wind energy explained: Theory, design and Application," Wind Energy Explained, http://ee.tlu.edu.vn/Portals/0/2018/NLG/Sach_Tieng_Anh.pdf (accessed Feb. 2, 2025).

[6] Z. Li et al., "Performance comparison of electromagnetic generators based on different circular magnet arrangements," Energy, vol. 258, p. 124759, Nov. 2022. doi:10.1016/j.energy.2022.124759

[7] Y. W. Leong, A. R. Razali, G. Priyandoko, and N. I. Kasim, "(PDF) preliminary studies on number of coil turns per phase and ...," Preliminary Studies on Number of Coil Turns per Phase and Distance between the Magnet Pairs for AFPM Ironless Electricity Generator, https://www.researchgate.net/publication/290211986_Preliminary_Studies_on_Number_of_Coil_Turns_per_Phase_and_Distance_between_the_Magnet_Pairs_for_AFPM_Ironless_Electricity_Generator/fulltext/56996c9808ae6169e5518b25/Preliminary-Studies-on-Number-of-Coil-Turns-per-Phase-and-Distance-between-the-Magnet-Pairs-for-AFPM-Ironless-Electricity-Generator.pdf (accessed Feb. 3, 2025).

[8] A. kadir Lebsir, A. Bentounsi, M. Benbouzid, and H. Mangel, "electric generators fitted to wind turbine systems: An up-to-date comparative study," Electric Generators Fitted to Wind Turbine Systems: An Up-to-Date Comparative Study, https://www.researchgate.net/publication/282864467_Electric_Generators_Fitted_to_Wind_Turbine_Systems_An_Up-to-Date_Comparative_Study (accessed Feb. 3, 2025).

[9] L. Sethuraman, G. Barter, P. Bortolotti, J. Keller, and D. A. Torrey, "Optimization and comparison of modern offshore wind ...," Optimization and Comparison of Modern Offshore Wind Turbine Generators Using GeneratorSE 2.0, https://www.nrel.gov/docs/fy23osti/85599.pdf (accessed Feb. 3, 2025).

[10] L. Nagel, "How to calculate motor KV & Motor poles," Tyto Robotics, https://www.tytorobotics.com/blogs/articles/how-to-calculate-motor-poles-and-brushless-motor-kv#:~:text=As%20a%20general%20rule%2C%20as,more%20volts%20at%20lower%20current. (accessed Feb. 9, 2025).

[11] MSI, "Basics of armatures," Motor Specialty Inc., https://motorspecialty.com/news/basics-of-armatures/#:~:text=The%20armature%20is%20an%20integral,or%20due%20to%20electronic%20commutation. (accessed Feb. 9, 2025).

[12] R. G. Budynas and J. K. Nisbett, "Chapter 7: Shafts and Shaft Components," in *Shigley's Mechanical Engineering Design*, 10th ed, New York, NY: McGraw Hill, 2024

[13] R. G. Budynas and J. K. Nisbett, "Chapter 11: Rolling-Contact Bearings," in *Shigley's Mechanical Engineering Design*, 10th ed, New York, NY: McGraw Hill, 2024

[14] R. M. Arias Velásquez, "Bearings faults and limits in wind turbine generators," *Results in Engineering*, vol. 21, p. 101891, Mar. 2024. doi:10.1016/j.rineng.2024.101891

[15] F. de Mello, K. Chang, L. Hannett, J. Feltes, and J. Undrill, *Study of turbine-generator shaft parameters from the viewpoint of subsynchronous resonance*, Sep. 1982. doi:10.2172/7096888

[16] A. Chasalevris, I. Gavalas, and J. T. Sawicki, "Optimal bearing configuration selection for power generation shaft-trains: A linear and nonlinear dynamics approach," *Journal of Sound and Vibration*, vol. 599, p. 118907, Mar. 2024. doi:10.1016/j.jsv.2024.118907

[17] "Mechanical Engineering Design Unit 9 – Power Transmission: Shafts & Bearings," All 38 AP subjects, https://library.fiveable.me/elements-mechanical-engineering-design/unit-9 (accessed Jan. 28, 2025).

[18] "Types of bearings: Uses & Working Mechanisms explained," Fractory, https://fractory.com/types-of-bearings/ (accessed Jan. 28, 2025).

[19] F. T. Ulaby and Umberto Ravaioli, *Fundamentals of applied electromagnetics.* Harlow, Essex: Pearson, 2022.

[20] D. Fleisch, *A Student's Guide to Maxwell's Equations*. Cambridge University Press, 2008.

[21] D. C. Hanselman, Brushless Permanent Magnet Motor Design. Lebanon, OH: Magna Physics Publishing, 2006.

[22] M. M. Hossain and Mohd. H. Ali, "Future research directions for the wind turbine generator system," *Renewable and Sustainable Enrgy Reviews*, vol. 49, pp. 481–489, Sep. 2015, doi: https://doi.org/10.1016/j.rser.2015.04.126.

[23] I. Boldea, "Electric generators and motors: An overview," *CES Transactions on Electrical Machines and Systems*, vol. 1, no. 1, pp. 3–14, Mar. 2017, doi: https://doi.org/10.23919/tems.2017.7911104.

[24] G. Ofualagba and E. U. Ubeku, "Wind energy conversion system- wind turbine modeling," *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, Jul. 2008. doi:10.1109/pes.2008.4596699

[25] D. Willy, *Electromagnetics in Power Engineering Maxwell 3D Simulations of a Residential Wind Generator*. Northern Arizona University, 2018. Accessed: Feb. 07, 2025. [Online]. Available: https://in.nau.edu/wp-content/uploads/sites/156/2018/08/Air-X_Maxwell_Simulation_Student_Procedures-ek.pdf

[26] Christoph Laimer, "3d-printed Halbach Motor - Building Instructions," *YouTube*, May 03, 2017. https://www.youtube.com/watch?v=YsSm65DAcCg (accessed Feb. 06, 2025).

[27] K. E. Longren, S. V. Savov, and R. J. Jost, "Chapter 3 Magnetostatic Fields," in Fundamentals of Electromagnetics with MATLAB, Raleigh, North Carolina: SciTech Publishing, 2007, pp. 123–171

[28] K. E. Longren, S. V. Savov, and R. J. Jost, "Chapter 5 Time-Varying Electromagnetic Fields," in

Fundamentals of Electromagnetics with MATLAB, Raleigh, North Carolina: SciTech Publishing, 2007, pp. 257–293

[29] L. Chen, Z. Xing, D. Wang, Y. Gao, and X. Wang, “Research on cogging torque optimization design of permanent magnet synchronous wind turbine,” E3S Web Of Conferences, https://www.e3s-conferences.org/articles/e3sconf/pdf/2021/76/e3sconf_icepese2021_01001.pdf (accessed Feb. 8, 2025).

[30] M. Garcia-Gracia, A. J. Romero, J. H. Ciudad, and S. M. Arroyo, “Cogging Torque Reduction Based on a New Pre-Slot Technique for a Small Wind Generator,” ResearchGate, https://www.researchgate.net/publication/328457151_Cogging_Torque_Reduction_Based_on_a_New_Pre-Slot_Technique_for_a_Small_Wind_Generator (accessed Feb. 8, 2025).

[31] A. Dalcali, “Cogging torque analysis in permanent magnet sycnhronous generators using finite element analysis,” Wiley Online Library, https://onlinelibrary.wiley.com/doi/abs/10.1002/2050-7038.12588 (accessed Feb. 8, 2025).

[32] CUSP, “Module 29: Permanent Magnet Rotor Design (SPM & IPM),” YouTube, https://www.youtube.com/watch?v=ZfVoeJFX_O4 (accessed Feb. 8, 2025).

[33] QuickFieldSupport, “Cogging torque of the turbine generator analysis with QuickField FEA software,” YouTube, https://www.youtube.com/watch?v=8UMi2b6BPuc (accessed Feb. 8, 2025).

[34] W. Drury, Electric Motors and Drives: Fundamentals, Types and Applications: Fundamentals, Types and Applications. San Diego, UNITED KINGDOM: Newnes, 2019.

[35] J. Pyrhonen, T. Jokinen, and V. Hrabovcova, Design of Rotating Electrical Machines, 2nd Edition. John Wiley & Sons, 2013.

[36] Tao Dajun, Ge Baojun, Lv Yanling, and Zhang Zhiqiang, “Systematically study on the static power-angle characteristics of a high voltage cable-wound generator prototype,” 2009 International Conference on Sustainable Power Generation and Supply, pp. 1–5, Apr. 2009. doi:10.1109/supergen.2009.5347979

[37] A. M. Rusakov, A. M. Sugrobov, N. A. Okuneeva, and A. N. Solomin, “The effect of electromagnetic load on the basic dimensions of induction salient pole generators,” Russian Electrical Engineering, vol. 87, no. 3, pp. 130–133, Mar. 2016. doi:10.3103/s1068371216030093

[38] M. A. Özçelik, “Operating the induction motor as a generator mode by supplying DC voltage and investigation of the end voltage depending on the excitation current and RPM,” International Journal of Energy Research, vol. 2023, pp. 1–8, Jul. 2023. doi:10.1155/2023/9967218

[39] M. B., “Mark B.,” HobbyGradeRC.com, https://hobbygraderc.com/understanding-kv-rating-in-brushless-motors/ (accessed Feb. 7, 2025).

[40] “What does ‘Kv’ mean on brushess motors? Kv explained!,” YouTube, https://www.youtube.com/watch?v=zHpFGPvmibM&t=68s (accessed Feb. 8, 2025).

[41] R. Parsons, “Things in Motion: Selecting the best pole and slot combination for a BLDC (PMSM) motor with concentrated windings,” Things in Motion, Jan. 27, 2019. https://things-in-motion.blogspot.com/2019/01/selecting-best-pole-and-slot.html

12 APPENDICES

12.1 Appendix A: MATLAB Code

Inputs

Generator

V - Voltage output from generator

P - Power output from generator

Kv - Constant voltage rating from generator

```
V = 48; % V
P = 10; % kW
Kv = 150; % Kv Rating
```

Turbine

D_b - Diameter of turbine blade

m_b - Total mass of blades and hub

h - Distance from centerline of shaft to thrust force

```
D_b = 45; % cm
m_b = 2; % lb (rough approx from Willy)
h = 7; % cm Distance for aerodynamic forces (thrust)
```

Shaft

L_lip - Length of thrust lip

L_b_b - Length of bearing to bearings from the outside part of them (Look in FBD)

L_hub - Length of hub

rho_al - Density of shaft material (Use aluminum)

Su - Material ultimate strength

K - Stress concentration factors

NOTE: Additional tables will be provided to help determine numbers for this estimation

```
L_lip = 3; % mm (subject to change)
L_b_b = 9; % mm (Length from end of bearing to other end of bearing)
L_hub = 3; % mm (Length where connection from blade will occur)
rho_al = 2830; % kg/m^3

Su = 324; % MPa (2011 Aluminum in Table A-22)
Kt = 1.7; % Assuming we're using a rounded filet in Table 7-1
Kts = 1.5; % Assuming we're using a rounded filet in Table 7-1
Kf = Kt; % Quick Conservative test
Kfs = Kts; % Quick Conservative test

a = 2.7; % Table 6-2
b = -0.265; % Table 6-2

Ka = a * Su^b; % Eq. 6-19
Kb = 0.9; % Guess
Kc = 1;
Kd = Kc;
Ke = Kd;

n = 3;
```

Figure A1: Shaft Analysis Code

```
%Thrust Force
R = 45*10^-2; %[meters] Radius of turbine
p = 1.225; %[kg/m^3] density of Air
U = 25; %[m/s] cut out speed of turbine

Ft = (4*pi*R^2*p*U^2)/9; %EQ for thrust force
```

Bearing life

```
%% INPUTS

% Bearing ratings
```

```
C10 = 422;     % Dynamic load rating [N]
C0  = 174;     % Static load rating [N]

% Applied loads on bearing pair/set
Fr_total = 0;        % Total radial load [N]
Fa_total = 216.5;    % Total axial (thrust) load [N]

% Number of bearings sharing the load
numBearings = 2;

% Speed
n_rpm = 2500;         % Rotational speed [rev/min]

% Life exponent for deep groove ball bearings
a = 3;

%% LOAD SHARING

Fr_each = Fr_total / numBearings;
Fa_each = Fa_total / numBearings;

%% STATIC LOAD & STATIC SAFETY FACTOR

P0_each = 0.6*Fr_each + 0.5*Fa_each;   % Equivalent static load
n_static = C0 / P0_each;               % Static safety factor

%% DYNAMIC EQUIVALENT LOAD

Fe_each = sqrt(Fr_each^2 + Fa_each^2);   % Combined dynamic load

%% L10 LIFE CALCULATIONS

L10_mrev = (C10 / Fe_each)^a;     % L10 life in million revolutions
L10_rev  = L10_mrev * 1e6;        % L10 life in revolutions
L10_hours = L10_rev / (60*n_rpm); % L10 life in hours
L10_days = L10_hours/24;          % L10 life in days
%% OUTPUTS

disp("Bearing Life Results")
```

Bearing Life Results

```
fprintf("Radial load per bearing:          %.2f N\n", Fr_each);
```

Radial load per bearing: 0.00 N

```
fprintf("Axial load per bearing:           %.2f N\n", Fa_each);
```

Axial load per bearing: 108.25 N

```

fprintf("Static equivalent load P0:        %.2f N\n", P0_each);
```

Static equivalent load P0:   54.12 N

```
fprintf("Static safety factor:             %.2f\n", n_static);
```

Static safety factor: 3.21

```

fprintf("Dynamic equivalent load Fe:       %.2f N\n", Fe_each);
```

Dynamic equivalent load Fe: 108.25 N

```

fprintf("L10 life:                         %.2f million rev\n", L10_mrev);
```

L10 life: 59.25 million rev

```
fprintf("L10 life:                         %.0f rev\n", L10_rev);
```

L10 life: 59245264 rev

```
fprintf("L10 life:                         %.1f hours\n", L10_hours);
```

L10 life: 395.0 hours

```
fprintf("L10 life:                         %.0f days\n",L10_days);
```

L10 life: 16 days

Figure A2: Bearings Analysis Code