CWC Generator

Initial Design Report

Naomi Echo – Project Manager & Manufacturing Engineer

Alonso Garcia - CAD & Manufacturing Engineer

Javan Jake – Financial & Test Engineer

Christian Brown – CAD & Test Engineer

Kaitlyn Redman – Logistics Manager

Spring 2025 – Fall 2025

Project Sponsor: David Willy

Faculty Advisor: David Willy

Sponsor Mentor: Kevin Bruns

Instructor: Carson Pete

DISCLAIMER

EXECUTIVE SUMMARY

We have been tasked with creating and modifying generators for the Collegiate Wind Competition (CWC) team here at Northern Arizona University (NAU). The CWC tasks college students with wind and renewable energy goals to better prepare them for jobs in these fields and real-world experiences with the technology. The NAU CWC team has a poor track record placing in the competition due to the previous generators used in the turbines. It is our goal to make custom generators best suited for wind energy performance that will be modular enough to be changed per future CWC guidelines. We have been given a budget of $500 with a mandatory fundraising goal of $300 dollars, for a total projected amount of at least $800 to put toward researching, testing, modifying, and building these generators. Our client is Professor David Willy who has lots of experience in the energy field. So not only does he give good client requirements, but valuable engineering requirements.

The main requirement for the generators is they must be 3-phase permanent magnet synchronous generators (PMSG's). This is a standard specification amongst wind energy turbines. The generator must have a low cut in speed to perform well. The cut in speed is the lowest speed of wind required to turn the motor, which is based on the cogging torque of the generator. All the internal forces of the generator, the bearing friction, the magnetic forces, and the electrical resistance add up to be the total cogging torque. As a safety requirement, the generator is to stay in low voltage ranges during operation. The generator must also be modular enough to follow the CWC guidelines as they change in the future.

Research has been conducted on the current state-of-the-art of 3-phase PMSG's and the fundamental equations that drive these generators. Maxwell's equations are among these that explain the interaction of magnetic and electric fields and how they propagate. These interactions are further explained by the field of electromagnetism. Explaining how magnets, coils of copper wire, and iron plates interact with each other to generate an electric current. In short, magic. The different kinds of 3-phase PMSG's and how to make them were also researched. The difference in cored versus coreless and what makes them generators as opposed to motors was also necessary to know. Wind energy and how it is harnessed were researched as well to help the understanding of the renewable energy field these generators will be used in. The equations that will be applied during testing were researched. These include finding the tip speed ratio, the stresses due to rotation, and the voltage constant of the generator. Variables like these are to be found by the use of the dynamometer.

Rather than moving on to testing and design generation, a roadblock has occurred in our project. The dynamometer, which Professor Willy believed to be working when he gave us this project, has a completely fried Arduino board, rendering it useless. It is now our job to complete this old capstone project before continuing our own. The dynamometer is a custom test bench for the generators. It is driven by an electric motor that is hooked up to a power supply that has a variable voltage control. There is a torque transducer that counteracts the torque of the motor to keep the test bench steady. An Arduino with different sensors is used to measure the outputs from the generator and torque transducer. This is what is currently in development. Acquiring the proper sensors and working Arduino, writing the code to make them work together, and implementing them into the dynamometer is the current course of action.

TABLE OF CONTENTS

Contents

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 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 MotorCAD, 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 in 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

For this project we have deliverables for the class and specific deliverables given to us by our client. These deliverables are:

Week 5: Presentation One

Presentation one entails project description, initial research, customer requirements, engineering requirements, mathematical modeling, benchmarking, scheduling, and our budget.

Week 7: Initial research

Completing initial research for our client entails reading the Fundamentals of Electromagnetics and Brushless Permanent Magnet Motor Design. As well as doing research on the Maxwell equations, and machine design elements.

Week 8: Presentation Two

Presentation two entails engineering calculations, new project requirements, background on the dynamometer, sensors being used in the dynamometer, how those sensors will be included within the Arduino, as well as the new schedule and budget.

Week 8: Report One

Report one includes all of the work we have done to date. This includes all initial modeling, mathematical modeling, dynamometer modifications, schedule, and budget.

Week 8: Website check

This website check is to ensure our website is functional, professional, as well as have separate pages for the project description, Team/About Us, Gallery, and for Documents.

Week 10: Finish Dynamometer

To finish the dynamometer includes redoing the Arduino and making an electrical box to house the Arduino UNO. The Arduino board will have sensors so we can get outputs of rotations per minute (RPM), torque, voltage, and current.

Week 10: Analytical Analysis Memo

The Analytical Analysis Memo will include what topic each team member will be doing for the Individual Analysis assignment.

Week 11: Presentation 3

Presentation three will include the project description, design requirements, initial testing results, simulations, and concept generation.

Week 12: Finish Initial Testing

To Finishing initial testing, we will be testing the two generators we already have on the dynamometer and see how they compare to each other.

Week 12: Initial Simulations

Initial simulations will be done of the two generators we already have. We will be using ANSYS Maxwell as well as MotorCAD to model and test these designs.

Week 13: Modify existing design

Using ANSYS Maxwell or MotorCAD we will modify one of the preexisting generators, this will entail changing the number of magnetic pairings, number of turns in the coil, or the diameter of the wire used in the coil.

Week 14: Report 2

Report Two will include background on the project, customer requirements, engineering requirements, research done to date, mathematical modeling done to date, initial testing results, modified generator, and concept generation.

Week 14: Individual Analysis

Each team member will take on one topic and justify its importance in reference to our project.

Week 15: Generate our own design

To generate our own design, we will use ANSYS or MotorCad to develop and model our design.

Week 15: Website Check 2

This website check will include all work done up to date. This entails simulations, prototypes, and mathematical modeling.

1.3 Success Metrics

The success of this project will be determined by how effectively the designed generators meet the key performance and competition requirements set forth by the client, the CWC guidelines, and industry standards for small-scale wind turbine generators. Success will be evaluated based on a combination of assessments, testing results, calculations, and the ability to meet modular design requirements. The generator design must be modular enough to adapt to future changes in CWC guidelines, including ease of component replacement or adjustment. This will be evaluated based on the number of interchangeable components and design flexibility assessed during assembly and integration.

The generator must operate within a low voltage range not exceeding 48V, maintain a low Kv rating, and produce high power output compared to previous CWC solutions. Successful calculation and validation of these performance values through empirical testing and simulation are essential. The generator must demonstrate a low cut-in speed (target ~3 m/s) to ensure early energy harvesting during low wind conditions. This must be achieved by optimizing the cogging torque, bearing friction, and magnetic resistance, verified through dynamometer testing. We will also need to create a fully functional dynamometer and maintain results for future engineers that will be utilizing this tool. The accuracy of ANSYS Maxwell and MotorCAD simulations compared to real-world dynamometer testing results will serve as a benchmark for verifying theoretical performance and ensuring engineering design validation. Structural integrity of the shaft, bearings, and housing components must support rotational stresses under competition conditions. This will be assessed through mathematical modeling and material selection analysis. The final solution must remain within the $800 budget, including both the client-provided funding and raised funds, without compromising on performance. A cost-performance ratio analysis will be included to quantify efficiency. The final generator must be fully integrated with the CWC turbine and demonstrate competitive performance during testing trials. Comparing performance to prior years' generators will be used as a baseline. Additionally, a successful handoff and documentation package for future teams will be considered part of long-term project success.

Together, these success metrics will ensure that our generator solution not only meets immediate technical requirements but also contributes to NAU's long-term success in renewable energy education and competition performance.

2 *Requirements*

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

2.1 *Customer Requirements (CRs)*

Our client is requiring us to make a generator that is:

- Low Voltage
- Small Size
- High power generation
- Under budget
- Ability to change easily
- Up to the CWC design standards
- 3 Phase AC generator

Required Process from Client:

- Analyze one generator from the Energy Club and one bought online
    - See how many number of turns in the coil
    - Diameter of wire used in the coil
    - Number of magnetic pairings
- Model both existing generators in ANSYS
- Modify one of the existing generators
- Develop our own design in ANSYS
- Compare our design to the modified generator
- Build the generator that preforms the best

2.2 *Engineering Requirements (ERs)*

The engineering requirements for this project are-

- Maximum 48 Volts
- 45 cm rotor diameter of the turbine
- Low total resistance torque (Nm)
- Low Kv rating
- High magnetic flux (Tesla)
- High turbine power output (W)
- Number of coils
- Tip speed ratio, between 7 and 8

- Diameter of the coil
- Cut out speed, 25 (m/s)
- Cut in speed, 3 (m/s)

2.3 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 (Nm)	Low Kv Rating	Magnetic Flux(Tesla)	Turbine Power(W)	Generator Power(W)	Number of Coil	Tip Speed Ratio	Diemeter of coil(mm)	Cut Out Speed(m/s)	Cut In Speed(m/s)	Competitive Assessment		
	Customer Requirements (What)	Importance	1	2	3	4	5	6	7	8	9	10	11	12	1	2	
1	Low Voltage	2	9	3	9	9	9	9	9	9	3	9	9	9	1	9	
2	Small Size	3	3	9	3	1	3	9	3	9	9	9	1	1	1	9	
3	High Power Generation	4	9	1	9	9	9	9	9	9	9	9	9	9	9	3	
4	Under Budget	2	1	3	1	1	1	3	3	3	3	3	3	3	1	3	
5	Ability to change easy	3	1	3	3	9	3	3	9	9	9	9	1	1	3	3	
6	Up to design standards	5	9	9	9	9	9	9	9	3	9	9	9	9	9	9	
7	3 phase AC	4	3	3	3	3	3	1	3	9	1	3	1	1	3	9	
		Target	48 V	45 cm	2 Nm	TBD	TBD	TBD	TBD	TBD	7 to 8	TBD	25 m/s	3 m/s			
		Importance	35	31	37	41	37	43	45	51	43	51	33	33			

Figure 1: QFD

3 Research Within Your Design Space

This section will include cumulative research to date into the relevant fields for completing this project. This includes looking at different generators and their specifications, multiple sources into the different niches of generators, and initial mathematical modeling to better understand the defining calculations of this field.

3.1 Benchmarking

System-level benchmarking will be used by viewing the state-of-the-art (SOTA) for a turbine 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 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 the 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

<u>Books</u>

[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 the mathematical explanations.

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

Reference for understanding how different magnetic pairings effect power generation.

<u>Papers</u>

[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 GeneratorSE 2.0

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

<u>Other</u>

[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 armatures work and different ways they may be assembled.

3.2.2 Kaitlyn Redman

<u>Books:</u>

[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.

<u>Journals:</u>

[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-trains.

<u>Website:</u>

[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

<u>Books</u>

[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 created 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 airgap within them. It helps our understanding by drawing similarities between the electromagnets and regular circuits. For example, as resistors are energy dissipaters to circuits, magnets are energy storages top circuits.

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 the 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.

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

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.

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.

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 QuickField 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 cogging torque.

3.2.5 Javan Jake

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.

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.

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 of the impacts of factor determining KV and specification application.

3.3 Mathematical Modeling

3.3.1 Tip Speed Ratio – Naomi Echo

$$\lambda = \frac{Blade\ tip\ speed}{Wind\ speed} = \frac{\Omega R}{U} \tag{1}$$

U = wind speed [$\frac{m}{s}$]

R = radius of blade [m]

Ω = rotational speed of the turbine [$\frac{rad}{s}$]

The desired tip speed is 7-8, as this is industry standard [5]. Using a typical wind speed of 12 m/s we can find that the blade tip speed will need to be 84 m/s.

3.3.2 Shafts and Bearings – Kaitlyn Redman

<u>Torsional Stress:</u>

$$\tau = \frac{Tr}{J} \tag{2}$$

T, Torque [N-m]
r, Distance from Neutral Axis [m]
J, Polar Moment of Inertia [m^4]

<u>Power:</u>

$$P = T\omega \tag{3}$$

T, Torque [N-m]
ω , Angular Velocity [$\frac{rad}{s}$]

<u>Bending Stress:</u>

$$\sigma = \frac{My}{I} \tag{4}$$

M, Moment [N-m]
y, Distance to Center [m]
I, Moment of Inertia [m^4]

These are the basic equations for designing the shaft and bearings component of a generator.

3.3.3 Constant Voltage and Voltage Divider Method – Javan Jake

$$\text{Kv} = \frac{rpm}{V} = \frac{Revolutions\ per\ minute}{Volts} \tag{5}$$

The constant voltage measures the number of revolutions per minute that a motor turns when 1Volts is applied with no load [40]. Where our target constant voltage is 100 to 200. Our max voltage is 48V DC. Therefore, the motor must have a range of 4800 to 9600 revolutions per minute to get our targeted Kv.

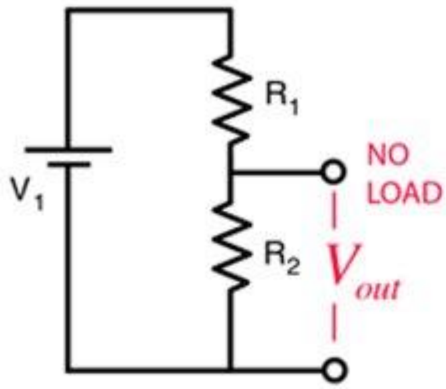

Figure 2: Voltage divider method diagram

$$V_{out} = V_1 \frac{R_2}{R_1+R_2} \tag{6}$$

V_{out}, Output Voltage [V]
V_1, Input Voltage [V]
R , Resistance [$k\Omega$]

The voltage divider is a simple method used to downsize the voltage using two resistors. In this case, the goal is to reduce the voltage output of 48V from our generator to approximately under 5V. The available resistor on stock is a 1 and 10 kilo-ohms (R1=10 $k\Omega$ & R2 =1 $k\Omega$). The voltage out is 4.36V which is safe for powering the Arduino.

3.3.4 Optimum Air Gap Size – Christian Brown

$$B_m = \frac{2g\mu_0 B_r H_c}{B_r\delta + 2g\mu_0 H_c} \tag{7}$$

$\mu_0 = 4\pi.10^{-7}$, Air Permeability Constant for the Air Gap [$\frac{H}{m}$]
H, External Magnetic Field Strength from the Magnets [T]
m, Magnetic Moment of the Magnets [$A - m^4$]
B_m, Max Flux Density in Airgap [T]
g, Thickness of Magnet [m]
δ, Air-Gap Length [m]
B_r, Remanence (Residual Magnetism of the Ferrous Material) [T]
H_c, Coercivity of Magnet (The Magnets' Resistance to External Field without Demagnetizing) [$\frac{A}{m}$]

With the size of our generators and magnets, the optimum air gap size will be in the millimeters.

3.3.5 Cogging Torque – Alonso Garcia

$$T_{cog} = -\frac{1}{2}\emptyset_m^2 \frac{dR}{d\theta} \tag{8}$$

T_{cog}, Cogging Torque [N-m]
$\emptyset_m$, Flux due to the Magnets Crossing the Air Gap [T]

R , Reluctance viewed by the Magnetomotive Force [$\frac{A-turn}{Wb}$]
θ , Angular Position of the Rotor [degree]

4 *Dynamometer*

Due to unforeseen circumstances, rather than a concept generation section, we have had to divert our efforts to repairing the dynamometer. It is integral to the success of our project and has taken precedence over everything else. This section will go into the inner workings of the dynamometer and the different sensors we are implementing to bring it back to full working capacity. This includes the integral equations that will be coded into the Arduino UNO that will receive all of the dynamometer data.

4.1 *Dynamometer Introduction*

A dynamometer is used to test the generators and get an output of RPM, torque, current, and voltage. Having a dynamometer is a critical part of our project because it will allow us to get accurate results in our testing. This will allow us to build a powerful generator because we will have these results to base our design off. When our client gave us this project, he was not aware that the dynamometer was not functional because the electrical system was fried. Due to this we had to shift our project description to fix the dynamometer to remake the Arduino to be able to get the outputs of RPM, torque, current, and voltage. We will be using the same power supply, programable load, and dynamometer apparatuses. Our client has asked us to make an electrical box that is easy transport that will house the new Arduino.

This dynamometer is driven by an electric motor, it has a torque transducer on the rear end of it. The torque transducer produces torque in the opposite direction of the torque being produced by the electric motor. This makes the dynamometer steady during testing and the torque output of the generator will be measured off of the torque transducer. On the front end of the electric motor is the coupler that is used to hookup the generator to the dynamometer.

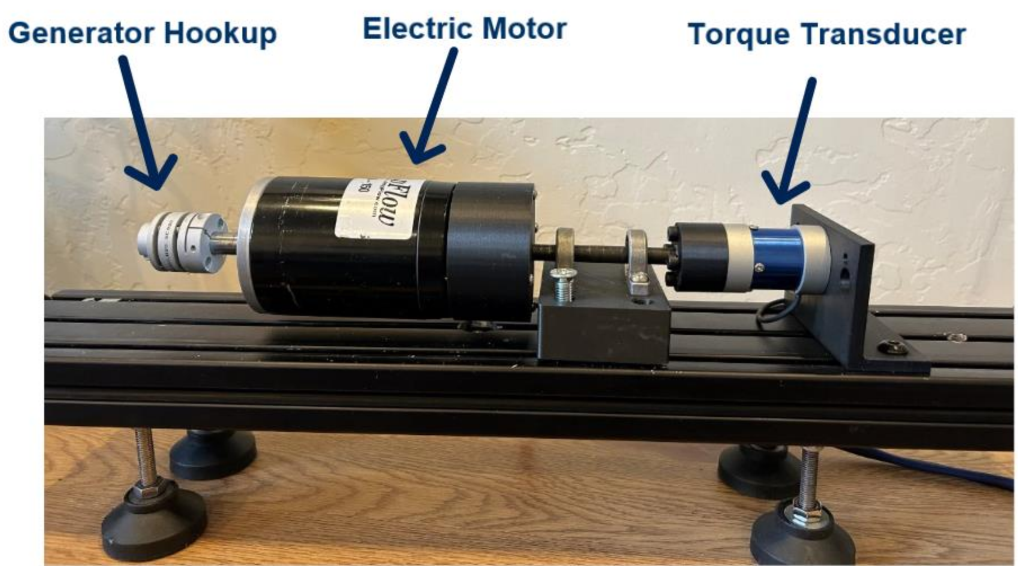

Figure 3: Dynamometer

4.2 *Sensors*

4.2.1 *Infrared (IR) Tachometer*

An IR Tachometer uses infrared light that can sense a reflected marker that will be on the shaft of the generator hook up. The sensor needs to be secured parallel to the shaft within 4 inches to get an accurate reading.

Figure 4: IR Tachometer

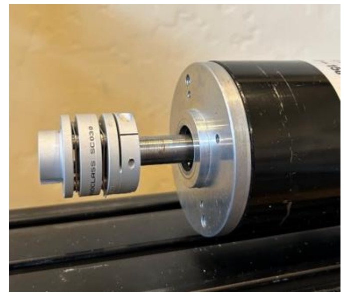

Figure 5: Generator Hookup

The IR sensor has three connection points. The first is the ground that will be connected to the 'GND' pin. The second is for power, which will be connected to the 5 Volt pin. Lastly, the signal output will be connected to a 'Digital Output' pin. Digital Output pins are the ones that allow the outputs to be iterative within the Arduino code. The schematic below shows how all three connections are incorporated:

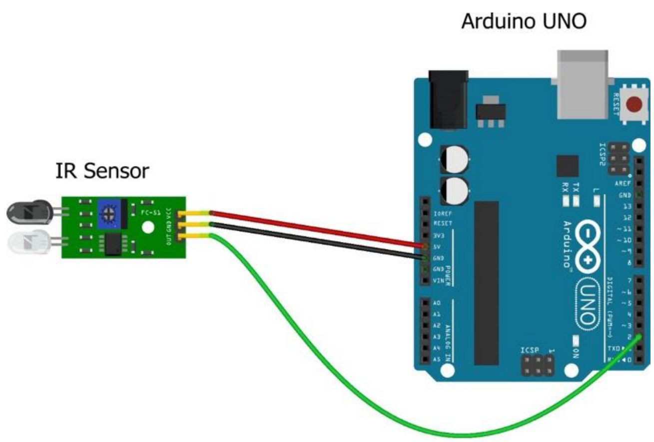

Figure 6: Diagram of the IR Tachometer within an Arduino UNO

4.2.2 *ACS712 30A Range Current Sensor*

This Current Sensor provides accurate solutions for both AC and DC sensing. Typical applications of this sensor include motor control, load detection, and load management. It has a current range of 30A, this means it has around a 0.066 V/A sensitivity in the sensor.

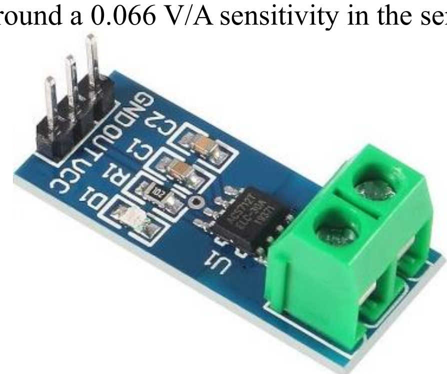

Figure 7: ACS712 30A Range Current Sensor

Putting this sensor into an Arduino simulation, it has five connections to the Arduino UNO board. The first connection is to the ground "GND" pin, then the power supply, the 5V pin, and three analog inputs (A0, A4, and A5). Both the sensor and Arduino board were wired to a liquid crystal display (LCD) screen so that the current values can be displayed.

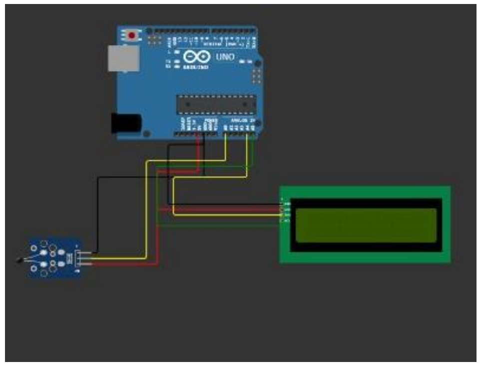

Figure 8: Current Sensor Wired to the Arduino

4.2.3 *HX711 24 Bit Load Cell Amp*

This load cell amplifier takes the minute changes in voltage from the torque transducer and amplifies and digitally converts it for the Arduino. With changes in the millivolt range, the voltage needs to be multiplied by some gain number for the Arduino to read it. The gain can be 32, 64, or 128 and has an operating voltage range of 2.6 - 5.5V, which is perfect for the 5V operating Arduino.

Figure 9: HX711 24 Bit Load Cell Amp

Implementing this sensor with the torque transducer in an Arduino simulator shows what connections need to be made. The 5v and GND pins from the amp to the Arduino need to be connected. Then for the data to be transmitted the DT (data) and SCK (clock) pins need to be connected for the data to be read and timed from the torque transducer. This data can then be displayed on an LCD screen or be output to an SD card.

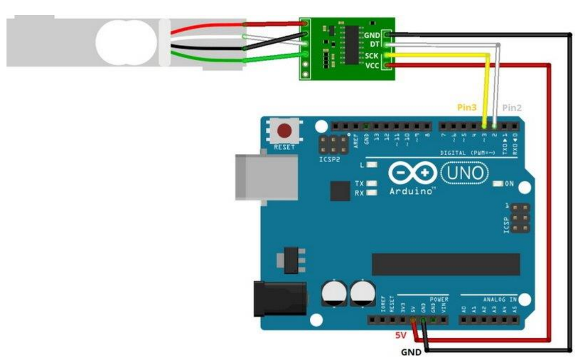

Figure 10: Diagram of Torque Transducer Connected to the Amp to the Arduino

4.3 *Mathematical Modeling/Arduino*

4.3.1 Obtaining Data for Arduino – Alonso Garcia

$$count = \frac{V_{in}}{V_{ref}} \cdot 1023 \tag{9}$$

$$V_{in} = count \cdot \frac{V_{ref}}{1023} \tag{10}$$

$count$, Analog to Digital Converter (ADC) Resolution
V_{in}, Input Voltage [V]
V_{ref}, Reference Voltage [V]

To obtain data for an Arduino, voltage is sent through an ADC and must be converted back to analog in the Arduino. It is done by equation 9 and 10, where 9 is what the Arduino gives us in the code and equation 10 is how we can get the true input voltage based on the output of equation 9. With this, we can get any input that can come from the analog pins for other readings like voltage and current.

4.3.2 Obtaining Voltage for Arduino – Alonso Garcia and Javan Jake

$$M = \frac{R_1 + R_2}{R_2} \tag{11}$$

$$V_{total} = V_{in} \cdot M \tag{12}$$

M , Multiplier
R , Resistance [Ω]
V_{total}, Total Voltage [V]
V_{in}, Input Voltage [V]

After getting voltage input from the analog pins based on the equations in 3.3.5, we can now find total voltage. To find total voltage, we use the resistors applied to the voltage divider to get a multiplier. So, the input voltage is the inverse of the multiplier times the total voltage, which is what the voltage divider sends to the Arduino. Now, we multiply the multiplier and the input voltage to get total voltage from the power supply. In figure 11, this equation was applied in Tinkercad by implementing code and circuits. The circuit includes a power supply that goes through a voltage divider to send the voltage to the Arduino. Once the Arduino gets the voltage, it applies the equations in this section, then displays it in the LCD screen.

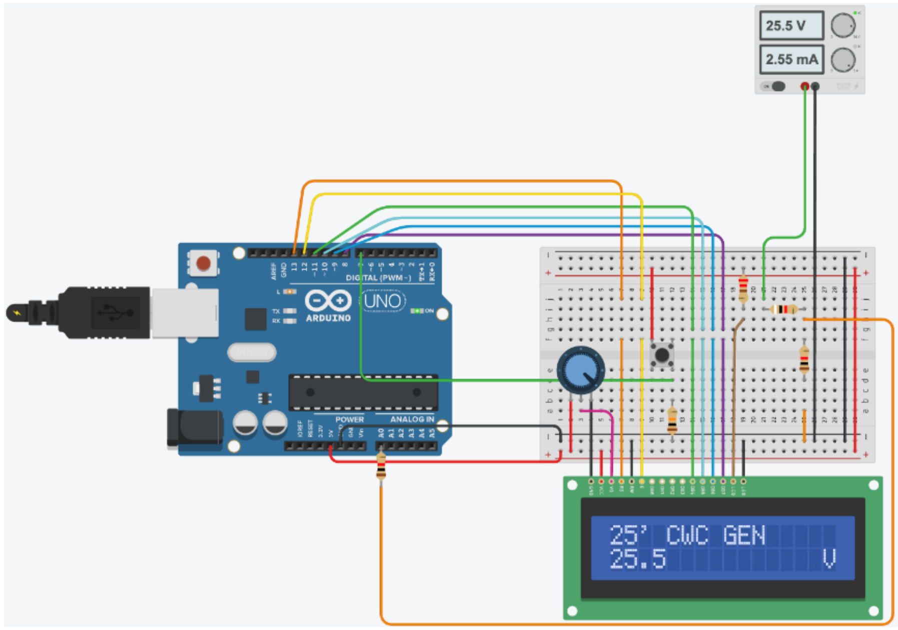

Figure 11: Output of getting voltage from a power supply

4.3.3 Obtaining RPM for Arduino – Alonso Garcia and Naomi Echo

$$RPM = \frac{F}{PPR} \cdot 60\,\frac{sec}{min} \tag{13}$$

RPM , Rotations per Minute [RPM]
F , Frequency [Hz]
PPR, Pulse per Rotation

Obtaining RPM is simple since an IR sensor will track how many times it has seen a rotation. However, this is implemented by using "interrupts", which is when a change happens. In this case, when the sensor sees a rotation, then it stops the main code and does something else on the side. With this, every time it sees a rotation, it adds to a counter, which would be our frequency in equation 13. After getting the frequency, PPR can be determined by how many "poles" are in the object. In this case, it'll be one due to a generator only having one "pole". After determining that, RPM can be calculated in the Arduino.

4.3.4 Obtaining Current for Arduino – Alonso Garcia and Kaitlyn Redman

$$I = \frac{V_{out} - \frac{V_{cc}}{2}}{S} \tag{14}$$

I , Current [A]
V_{out}, Output Voltage from Sensor [V]
V_{cc}, Supply Voltage to Senor [V]
S , Sensor Sensitivity $[\frac{V}{A}]$

Getting current is the same process as 4.3.1, where it converts the ADC count to analog voltage. However, when dealing with a current sensor, it has a sensitivity that helps determine the actual current running through a circuit. So, the current sensor outputs a voltage to the analog pin and with that voltage, the current can be determined with equation 14.

4.3.5 Torque Transducer – Christian Brown

The Wheatstone Bridge is a circuit utilized in the torque transducer to output a change in voltage due to strain gauges changing length from the induced torque.

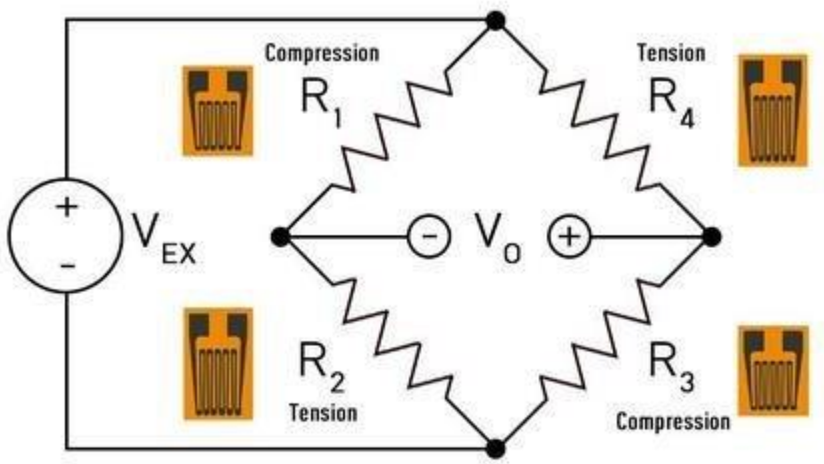

Figure 12: Wheatstone Bridge Circuit

$$V_{out} = \left(\frac{R_1}{R_1+R_2} - \frac{R_4}{R_3+R_4}\right) V_S \quad (15)$$

Below is an example of a change in voltage due to the change in resistance of the strain gauges resulting in an answer in millivolts.

$$\delta R_1 = +40\,\Omega \quad \delta R_2 = -40\,\Omega \quad \delta R_3 = +40\,\Omega \quad \delta R_4 = -40\,\Omega$$

$$E_o = E_i\left(\frac{R_1}{R_1 + R_2} - \frac{R_3}{R_3 + R_4}\right)$$

$$= 50\text{ V}\left(\frac{5040\,\Omega}{5040\,\Omega + 4960\,\Omega} - \frac{8040\,\Omega}{8040\,\Omega + 7960\,\Omega}\right) = +0.0750\text{ V}$$

4.4 Arduino Schematic

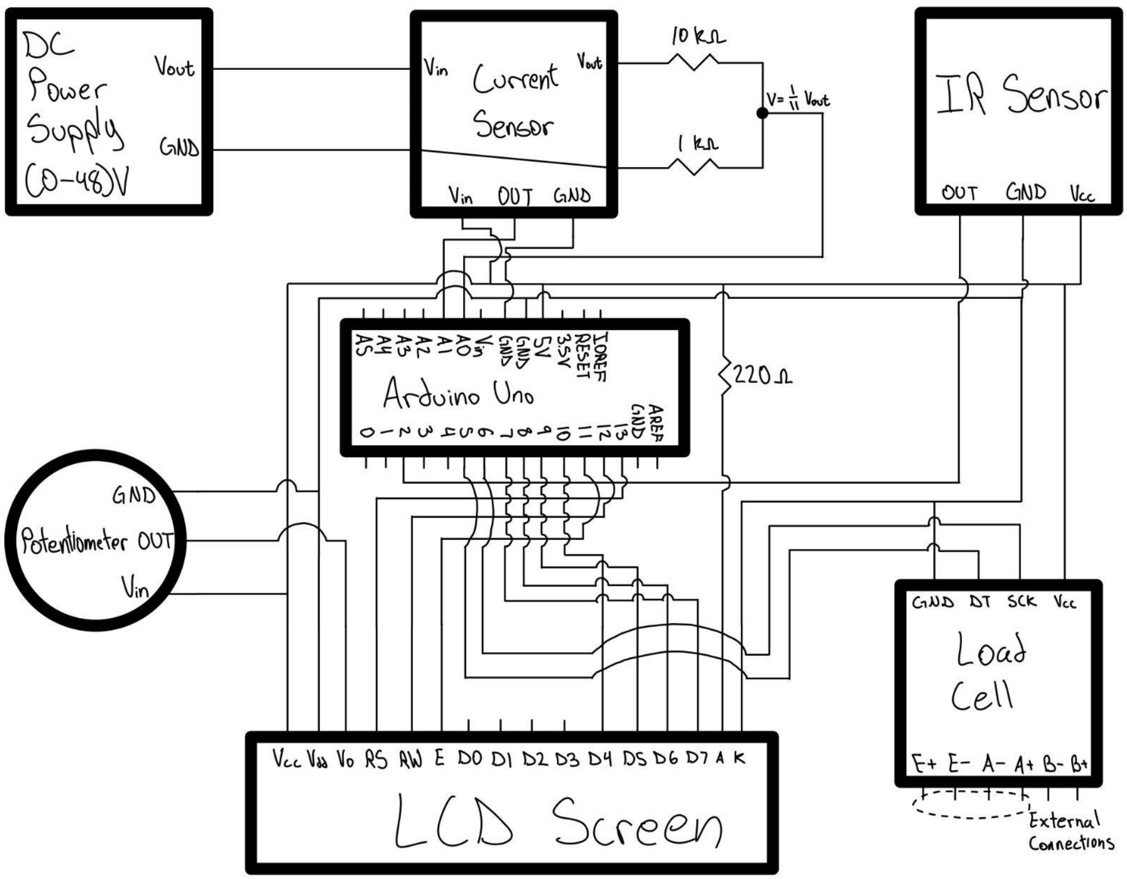

Figure 13: Arduino Schematic

In Figure 13, an Arduino schematic is shown which implements all sensors and techniques to measure RPM, current, torque, and voltage. Two things in this schematic were simplified. The DC power supply is the dynamometer's AC voltage which is then converted to DC. This was simplified because we know that the voltage will be between a range of zero volts and 48 volts. The load cell is part of the dynamometer, but there are only four connections to it, so we can ignore the connections since it has been clarified in greater detail in Section 4.2.3. As for the other sensors and technique, the voltage divider is used to help the Arduino from being damaged from excess voltage. In this case, it'll take an eleventh of the voltage supplied from the generator to the Arduino. The current sensor is applied to a circuit with the voltage divider to get the current sent from the generator. So, both current and voltage measurements are sent into the analog pins for the Arduino to calculate both of them. Next, the liquid crystal display (LCD) screen and potentiometer are part of one another, where the potentiometer helps the LCD screen's brightness level, and the LCD screen displays the measured values. Lastly, load cell sends torque data to the Arduino, which is explained in Section 4.3.5. It does not go through the analog pins in this case since this data will need to be accessed for calibration.

5 CONCLUSIONS

In conclusion, 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. 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.

We are tasked with many deliverables that include fixing our Dynamometer to help with our testing phase. We will utilize test generators and modify them to improve their performance and then generate a PMSG based on the previous testing and modifications. As for defining success, we will ensure we fulfill the client's requirements, follow CWC guidelines, and construct the PMSG up to industry standards. These requirements include a small size, high power generation, increased modularity, and be within budget. We have done research within our design space, which includes benchmarking successful and relevant products that are the SOTA. Researching aspects of a PMSG that can help lower cogging torque, lower Kv, and lower resistive forces like bearing friction. Understanding these forces, currents, and reluctance that are acting on the PMSG, and determining the necessary number of coils are also important.

Before doing more research on the PMSG, we must first work on the dynamometer to ensure it works correctly. To do this, we used sensors and methods to get current, RPM, torque, and voltage. These sensors are used to help measure data from the generator that the dynamometer sent to the Arduino via voltage or decibel pins.

The final solution proposed for this project will be finishing up the dynamometer by remaking the Arduino that calculates current, RPM, torque, and voltage from the generator. This will be done by testing the circuitry on a solderless breadboard. Once we know the circuitry works, we can start making a permanent circuit by using solder and putting it all in an electrical box. After that is assembled, we will use the Arduino to test generators given to us by the Energy Club and modify the generators to improve their performance and better understand how the generator is operating. After getting enough data through modifications and initial design testing, we can start working on a final design of a PMSG that will fulfill the customer's requirements and allow the CWC to succeed in future competitions by the PMSG's adaptability and high efficiency.

6 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).