TAFLab Fall 2025 Semester Research Report

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Characterization of Micro-Wind Generator Efficiency and Electronic Integration

1. Introduction

The objective of this semester's research was to establish a testing framework for determining the efficiency and effectiveness of small-scale wind turbine generators. The project focused on the comparative analysis of different motor topologies—specifically Stepper motors (NEMA 17 and 23)—to determine their viability as power generators in micro-wind applications. Key goals included the design of a custom rectification circuit, the development of a Python-based Data Acquisition (DAQ) pipeline, and the characterization of power curves under varying load conditions.

2. Experimental Setup & Methodology

2.1 Hardware Architecture

To evaluate generator performance, we utilized an Arduino microcontroller as the central interface for sensor data. The sensing module relied on the INA219 Power Sensor, selected for its ability to provide simultaneous voltage and current readings via I2C.

- **Generators Tested:** NEMA 17 Stepper, NEMA 23 Single Stack Stepper, and NEMA 23 Double Stack Stepper.
- **RPM Measurement:** A magnetic encoder was integrated into the rear shaft of the motors to provide real-time rotational speed data without the mechanical constraints of photointerrupters.
- **Drive Simulation:** To isolate the generator performance from wind variability, a mechanical drive system (high-torque drill) was used to simulate various input wind speeds.

2.2 Circuit Design

A custom circuit was fabricated to convert the AC output of the motors into measurable DC power.

- **Rectification:** For the stepper motors, 2 full-bridge rectifiers were employed for each motor coil.
- **Signal Conditioning:** Smoothing capacitors were introduced to stabilize the DC signal.
- **Load Testing:** A resistive load was utilized to dissipate power.

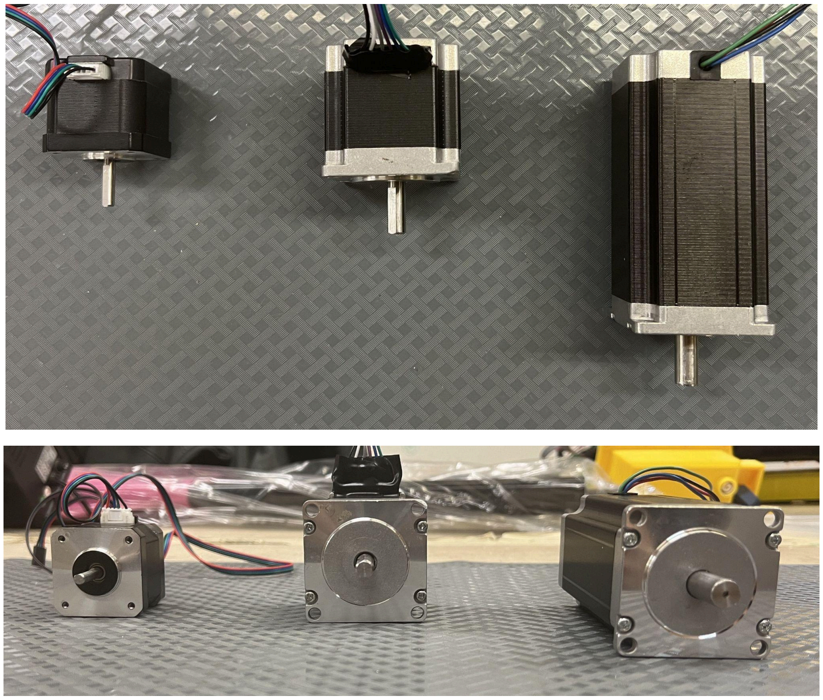


Figure 1. Tested Generators: NEMA 17, NEMA 23 Single Stack, NEMA 23 Double Stack

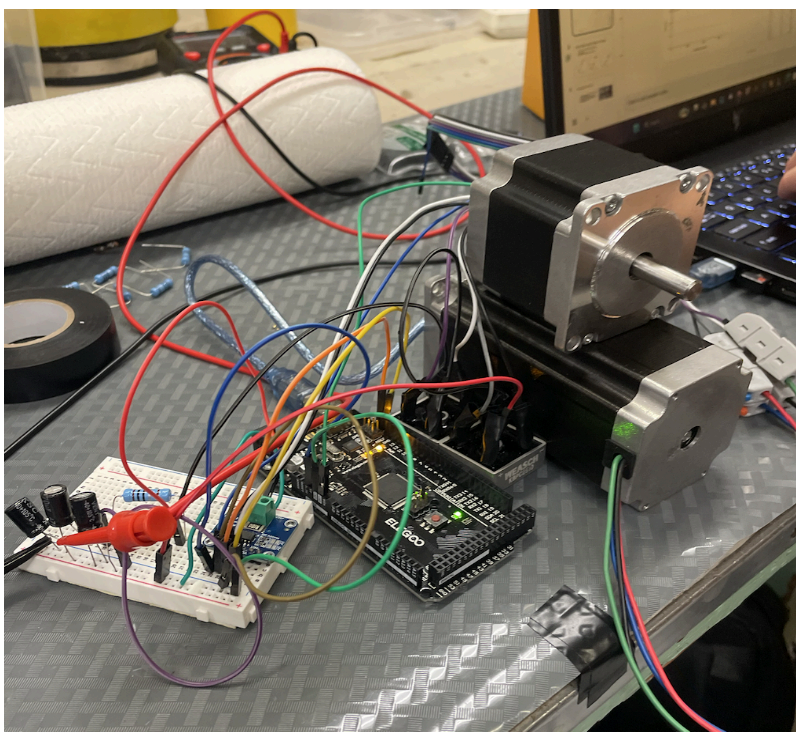


Figure 2. Full Setup of Circuit and Motors

2.3 Software & Data Acquisition

A custom Python script was developed to interface with the Arduino serial stream. This automated the data collection process, logging Voltage, Current, and RPM to CSV files for post-processing.

```python
import serial
import time



SERIAL_PORT = 'COM10'
BAUD_RATE = 115200

# File Name Configuration
motor = 'nema23A'
resistance = '1ohm'
FILENAME = f'datalog_{motor}_{resistance}.csv'

print(f"Connecting to Arduino on port: {SERIAL_PORT}")
print(f"Data will be saved to: {FILENAME}")
print("Press Ctrl+C to stop logging.")

try:
    ser = serial.Serial(SERIAL_PORT, BAUD_RATE, timeout=1)
    time.sleep(2)

    with open(FILENAME, 'w', newline='') as f:
        # Write the header defined in this script
        f.write("Timestamp,Power (mW),Rotational Speed (rpm),Errors\n")
        f.flush() # Ensure the header is written immediately
        print("CSV file created and header written.")
```

Figure 3. Screenshot of Python Code for Generating CSV Files

Data is collected using the INA219 and AS5600 respective libraries. Rotational speed is determined by taking the difference between the magnet's angular orientation between measurements and dividing by the time step.

2.4 Sensor Validation & Calculation Methodology

To verify the accuracy of the INA219 sensor module prior to full data collection, we devised a control experiment. The motor-rectifier subsystem (which produces variable, noisy AC-to-DC signals) was temporarily replaced with a calibrated laboratory DC power supply. This allowed us to inject known voltage and current values into the circuit to determine sensor drift.

Comparing the INA219 telemetry against the power supply and reference multimeters (refer to Appendix: Calibration Dataset Sheet 2) revealed a significant discrepancy:

- **Current (I):** High accuracy, with an average error of **1.645%**.
- **Voltage (V):** High inaccuracy, with an average error of **53.097%**.

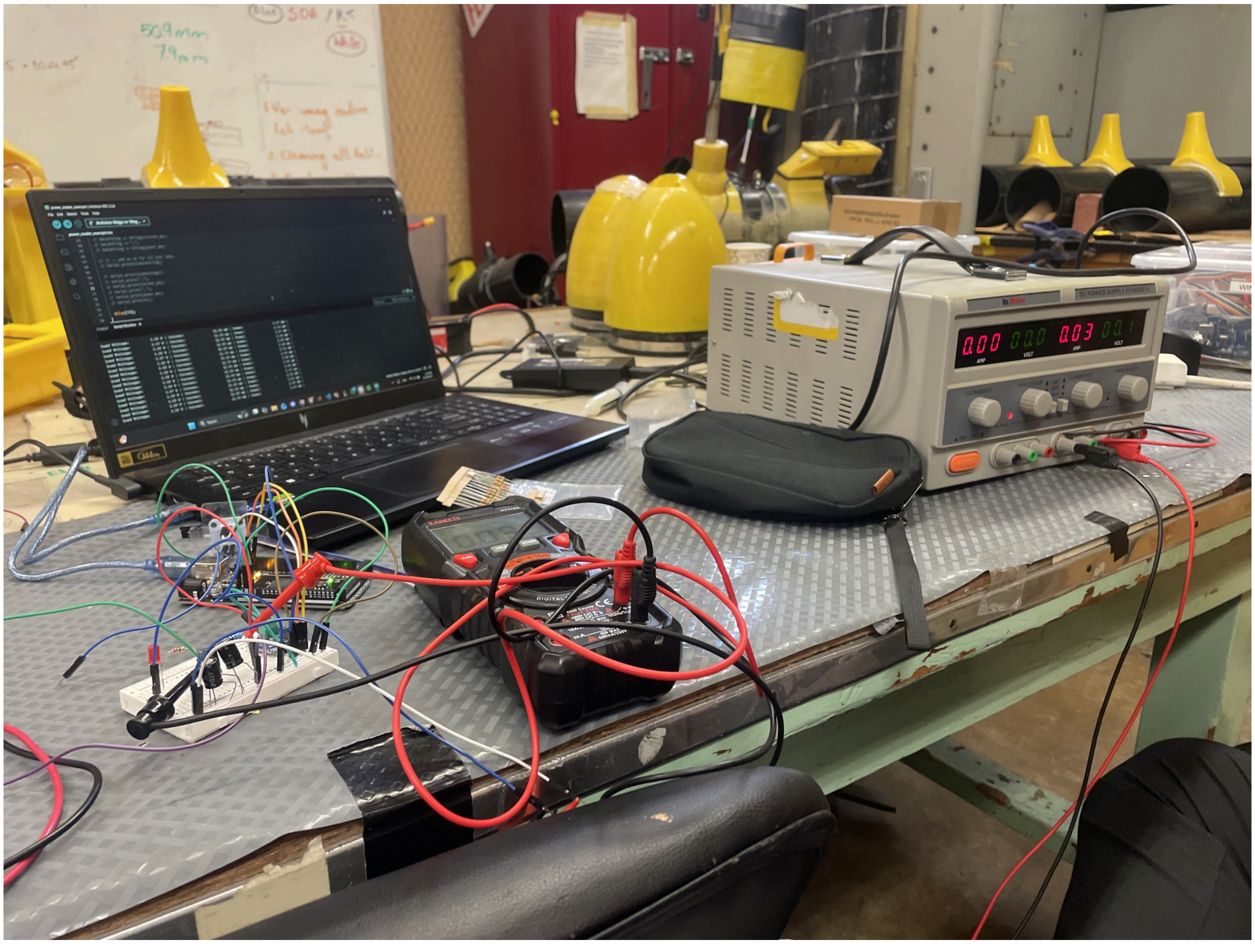


Figure 4. Power Reading Circuit Powered by DC Power Supply

The high voltage error was likely introduced by signal noise from the rectification process or sampling timing mismatches. Consequently, the standard power calculation $P = VI$ was deemed unreliable for this specific setup. We pivoted to the current-squared definition of power $P_{load} = I^2R_{load}$.

The load resistance (R_{load}) was measured statically using a precision multimeter. This method relies on the highly accurate current reading and the fixed resistance, isolating the power calculation from the voltage sensing instability.

3. Technical Challenges & Implementation Details

3.1 Signal Integrity & Noise Characterization

Early testing revealed significant noise in the voltage readings. A root-cause analysis identified connection issues and high contact resistance in the breadboard prototype. The circuit was refactored with soldered connections and Wago Lever Nuts to minimize parasitic resistance and improve connection stability.

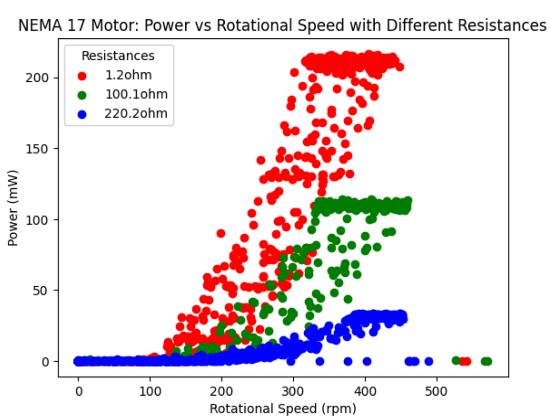
Significant noise persists in the simultaneous collection of rotational speed data. This artifact manifests as rapid spikes in the calculated RPM value. Two primary sources have been identified:

- Differentiation Error: The software calculates angular velocity by differentiating the position signal ($\omega = \frac{\Delta\theta}{\Delta t}$). This mathematical operation inherently amplifies any minor jitter in the position sensor.
- Vibration: At high speeds, the magnetic encoder setup experiences mechanical vibration, causing the magnet's alignment relative to the AS5600 sensor to fluctuate, introducing false position changes.

4. Results and Analysis

Data collection focused on characterizing the NEMA 17 and NEMA 23 Single Stack stepper motors under simulated wind loads.

Note on Data Quality: It should be noted that due to the mechanical vibration issues detailed in Section 3.1, the raw RPM data exhibits high-frequency noise. Work is ongoing to resolve the mechanical source of this noise for future datasets.



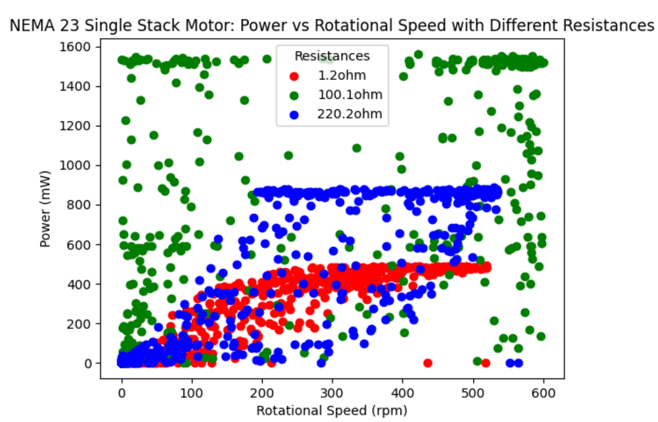


Figure 5. Power vs. Rotational Speed for NEMA 17 and NEMA 23 Single Stack Motor at Various Resistances

4.1 Impedance Matching & Load Sensitivity

A sensitivity analysis was conducted to determine which circuit parameters most heavily influenced generation efficiency.

- Capacitance: Variation in smoothing capacitance showed negligible effect on the average power yield.
- Resistance: Load resistance had a dominant impact on power output. As shown in Figure 5, the peak power point shifts significantly depending on the resistive load. For the NEMA 23 motor, though the noise does not reveal a distinct trend between power and rotational speed when supplied to the 100.1Ω resistor, it shows a clear power peak of ~1500mW, greater than the peak for both the 1.2Ω and 220.2Ω resistor loads. This confirms that impedance matching—tuning the load resistance to match the internal impedance of the generator—is the governing factor for maximizing efficiency in micro-wind systems.

4.2 Motor Characterization (Stepper Motors)

Power vs. RPM curves were generated for the NEMA 17 and NEMA 23 motors. The data indicates that stepper motors provide high torque and easy mechanical integration (due to the exposed rear shaft).

4.3 BLDC Infrastructure Status

While the Brushless DC (BLDC) motor is currently in procurement, the electrical infrastructure for its characterization is complete. A custom 3-phase bridge rectifier has been fabricated and tested for continuity. This system is designed to rectify the 3-phase AC output characteristic of BLDC motors, which is expected to offer smoother operation and lower frictional losses at high RPMs compared to the stepper motor baseline.

5. Conclusion & Future Work

This semester culminated in the development of a fully functional, automated wind turbine testing rig. The system successfully logs RPM and power generation in real-time, utilizing a validated $P=I^2R$ methodology to mitigate sensor noise.

To improve the fidelity of the characterization curves, future iterations of the project will focus on three key areas:

1. **Signal Integrity:** Implementation of hardware low-pass filters to reduce analog noise before it reaches the microcontroller, aiming to resolve the voltage sensing discrepancy.
2. **Instrumentation Resolution:** The AS5600 magnetic encoder mounting will be redesigned. Improved spacing and rigid mounting will reduce vibration-induced measurement errors and improve RPM resolution.
3. **Drive Consistency:** Refinement of the drive simulation procedure. Current data suggests that rotor inertia and discrete acceleration steps from the drill affect readings; a more automated, constant-velocity drive train will ensure consistent steady-state measurements.

Appendix:

Calibration Dataset:
https://docs.google.com/spreadsheets/d/1VptmoBM1Y1bnwlumf94-4k_0kVF6XEoEkg85CE8OqiA/edit?gid=2090232138#gid=2090232138

Weekly Progress Log

9/14 – 9/20: Orientation & Project Scope Definition

- **Lab Introduction:** Gained access to the physical workspace and learned about the structure of the labwork.
- **Scope Definition:** Defined the semester's primary objective: establishing a reliable testing rig to measure the power output and efficiency of various small-scale generators.

9/21 – 9/27: System Architecture & Component Selection

- **Hardware Selection:** Evaluated microcontroller options and selected the **Arduino** platform due to its robust library support for sensor integration.
- **Motor/Generator Strategy:** Initiated a comparative study of motor types for power generation.
    - *Decision:* Selected **NEMA 17 Stepper Motors** as the baseline for testing due to their high torque at low speeds and availability.
- **Sensor Integration:**
    - **Power:** Selected the **INA219** module (High-Side DC Current/Power Sensor) to streamline data collection. This integrates both a voltmeter and ammeter via I2C, reducing wiring complexity compared to discrete multimeters.
    - **RPM (Rotational Speed):** Evaluated optical photointerrupters vs. magnetic encoders.
    - *Decision:* Chosen **Magnetic Encoders** for seamless integration. Since stepper motors feature an exposed rear shaft, we can mount the magnet directly without the complex brackets required for optical sensors.

9/28 – 10/4: Firmware Development & Environment Setup

- **Legacy Analysis:** Received circuit diagrams from the previous team. Analyzed the schematic to understand power conversion and measurement.
- **Development Environment:** Configured the Arduino IDE for the specific DAQ requirements. Installed necessary libraries for the INA219 power module and AS5600 magnetic encoders and established reliable serial communication protocols.

10/5 – 10/11: Circuit Prototyping & Refactoring

- **Circuit Redesign:** Refactored the inherited circuit to better suit our specific needs. Simplified the topology to its core components to reduce failure points:
    - **Rectification:** Full-bridge rectifiers to convert AC motor output to DC.
    - **Conditioning:** Smoothing capacitors to reduce ripple.
    - **Load:** Resistive load bank for power dissipation.
    - **Sensing:** Integration points for the INA219.
- **Proof of Concept:** Assembled the first prototype board and successfully attached it to a NEMA 17 motor for initial spin tests.

10/12 – 10/18: Troubleshooting & Signal Integrity Analysis

- **Initial Testing:** Conducted live tests with the prototype circuit.
- **Anomaly Detection:** Observed erratic data and strange noise voltage readings during operation.
- **Root Cause Analysis:** Traced the issue to a small miswiring mishap. Spent the remainder of the week debugging the physical connections to ensure signal fidelity.

10/19 – 10/25: Automated Data Acquisition (DAQ) Pipeline

- **Software Engineering:** Developed a Python script to interface with the Arduino serial stream.
- **Data Serialization:** The script captures real-time sensor data and automatically generates formatted CSV files. This pipeline allows for high-resolution plotting and post-processing, eliminating manual data entry.
- **Milestone:** Generated the first verified CSV files featuring power outputs from the wind simulation rig.

10/26 – 11/1: Data Validation & Calibration (Sheet 1)

- **Calibration Dataset "Sheet 1":** Collected the first substantial dataset to calibrate the sensors.
- **Verification:** Cross-referenced the INA219 readings against theoretical expectations for the motor class.
- **Conclusion:** The values appeared consistent with the motor specifications, validating the accuracy of the Python DAQ script.

11/2 – 11/8: Controlled Drive Simulation

- **Methodology Update:** To characterize the motor's power curve accurately, we needed consistent input speed, which variable wind cannot provide.
- **Implementation:** Adopted a mechanical coupling approach using a high-torque drill to drive the generator. This allows us to hold RPM constant while measuring power output, enabling the creation of a precise **Power vs. RPM** characteristic curve.

11/9 – 11/15: Comparative Analysis & Impedance Matching

- **Motor Comparison:** Expanded testing to include **NEMA 23** and **NEMA 23 Double Stack** motors to evaluate scaling effects.
  - *Hypothesis:* The Double Stack, having similar winding geometry but increased mass/wire length, should theoretically yield approximately double the power output.
- **Load Sensitivity Analysis:** Investigated the variables disrupting power measurements.
  - *Capacitance:* Found that varying smoothing capacitance had minimal effect on average power yield.
  - *Resistance:* Uncovered a massive correlation between load resistance and measured power. This highlighted the critical importance of **impedance matching**—tuning the load resistance to match the internal resistance of the generator to maximize power transfer.

11/16 – 11/22: BLDC Integration & Holistic Measurement (Sheet 2)

- **Hardware Transition:** Ordered and received a **Brushless DC (BLDC)** motor to compare efficiency against the Stepper motors.
- **Circuit Adaptation:** Assembled a 3-phase bridge rectifier to accommodate the 3-phase AC output of the BLDC.
- **Calibration Dataset "Sheet 2":** We recollected data using a more rigorous approach:
  - Digital logging via INA219 (Bus Voltage, Shunt Voltage, Current).
  - Analog logging via calibrated multimeters (Voltage and Current).
- This data provided a comprehensive view of the circuit and helped identify discrepancies between digital and analog measurement methods.

11/23 – 11/29: Methodological Refinement

- **Data Analysis:** Isolated inconsistencies in the voltmeter readings at high frequencies.
- **Calculation Adjustment:** Pivoted the power calculation method. Instead of relying on the fluctuating voltage reading ($P = IV$), we utilized the current-squared definition: $P = I^2R$
  using the known fixed resistance of the load. This resulted in significantly cleaner data trends.
- **Code Revision:** Updated the Python DAQ to capture a wider array of variables (Bus Voltage, Shunt Voltage, Current, RPM) to support this new calculation method.

11/30 – 12/6: Hardware Stabilization & Current Status

- **Maintenance:** Repaired intermittent connections that were causing data dropouts during testing.

- **Status:** Successfully collecting high-resolution data with the revised setup.
- **Next Steps:** The current focus is on reducing signal noise further to improve the resolution of the motor characterization curves.