ECE 128B - Renewable Energy & Power Grid

Project Phase 2 - Wind Turbine System with MPPT Algorithm

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Table of Contents

Introduction:

This project focuses on designing and simulating a wind energy conversion system that efficiently converts wind power into electrical energy for battery storage. The system integrates an Interleaved Buck-Boost Converter and a Maximum Power Point Tracking (MPPT) algorithm to ensure optimal energy extraction and stable power delivery. Due to the variable nature of wind speeds, the turbine's optimal operating point continuously changes, and without MPPT, power losses and inefficiencies can occur.

To address this challenge, the Perturbation and Observation (P&O) MPPT algorithm is implemented to dynamically adjust the generator speed and electrical load, ensuring maximum power extraction. The system also incorporates Proportional-Integral (PI) controllers to regulate voltage and current, maintaining stable operation. A Pulse-Width Modulation (PWM) generator converts control signals into switching commands for the Buck-Boost Converter, which regulates voltage levels for efficient power transfer to the battery.

The project will be simulated using PSIM to evaluate system performance, including power tracking efficiency, voltage regulation, and response time under varying wind conditions. By ensuring optimal energy conversion and stable power delivery, this system enhances the efficiency and reliability of wind energy storage applications.

Problem Definition

Wind energy conversion faces the challenge of extracting maximum power despite fluctuating wind speeds. Without a proper tracking mechanism, the system may operate inefficiently, leading to significant power losses. This project addresses this issue by designing a wind energy conversion system that efficiently regulates power transfer using an Interleaved Buck-Boost Converter and a Maximum Power Point Tracking (MPPT) algorithm. The system is designed to dynamically adjust the wind turbine's operating conditions to optimize energy capture and ensure stable power delivery to the battery.

The Perturbation and Observation (P&O) MPPT algorithm is implemented to continuously track the maximum power point (MPP) by adjusting the generator speed and electrical load. To achieve efficient power regulation, the system incorporates current and voltage control loops with Proportional-Integral (PI) controllers, which minimize the error between desired and actual values, ensuring smooth operation. The Pulse-Width Modulation (PWM) generator converts the control signals into precise switching commands for the Interleaved Buck-Boost Converter, which adjusts voltage and current levels based on system requirements.

The design process follows a structured approach: first, the wind turbine and Permanent Magnet Generator (PMG) characteristics are analyzed, including parameters such as rated power (20 kW), rated speed (211 rpm), and stator resistance (0.1764 Ω). Next, the Interleaved Buck-Boost Converter is designed to handle variable input conditions while ensuring an output voltage of 100V for battery storage. The PI controllers are then tuned to regulate system stability, followed by the integration of the MPPT algorithm. The complete system is simulated in PSIM to evaluate power tracking efficiency, voltage regulation, and system response under different wind speeds (e.g., 8 m/s, 12 m/s, and 16 m/s).

Several design constraints must be considered, including a switching frequency of 10 kHz, inductor size of 400 μH, and a low internal resistance of 50 mΩ to minimize power losses. The system must efficiently regulate energy transfer by stepping up or down the voltage while ensuring rapid response to wind speed variations. By addressing these challenges, this project aims to develop a high-efficiency wind energy conversion system that maximizes power extraction and ensures reliable operation for battery storage applications.

Solution

The wind energy conversion system is designed and simulated in PSIM, integrating three key components: current control, voltage control, and MPPT integration. Each component plays a crucial role in ensuring optimal energy extraction and stable power transfer, allowing the system to dynamically regulate power flow and maintain efficiency. The design and implementation of these control strategies are essential for maintaining system reliability and stability under varying wind speed conditions.

The first step in validating the system is analyzing the wind turbine and Permanent Magnet Generator (PMG) characteristics. In order to observe and record the output power versus rotational speed, modifying a built in example circuit ensures accurate detection and records the variations in torque and speed of the shaft due to change in wind speed.

Shaft Speed vs Power for wind speeds of 8, 12, and 16m/s:

The Power vs. Shaft Speed (P-ω) curves are generated for different wind speeds (8 m/s, 12 m/s, and 16 m/s) to identify the maximum power point (MPP) at each condition. These plots provide the necessary parameters for the Perturbation and Observation (P&O) MPPT algorithm, ensuring the system continuously adjusts the generator speed to maximize power extraction. The wind turbine is simulated under varying wind speeds to verify its performance and efficiency in delivering stable power to the battery via the interleaved buck-boost converter.

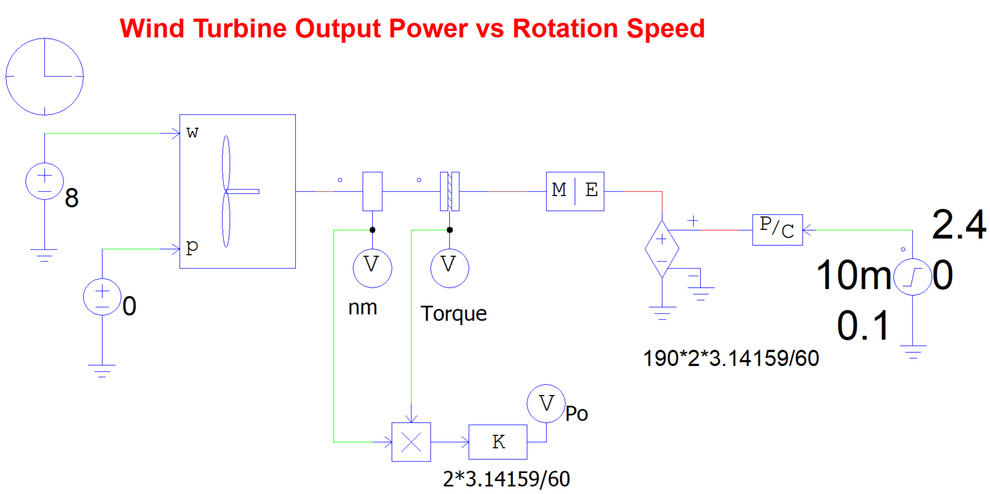

Figure 1: Wind Turbine Ideal schematic

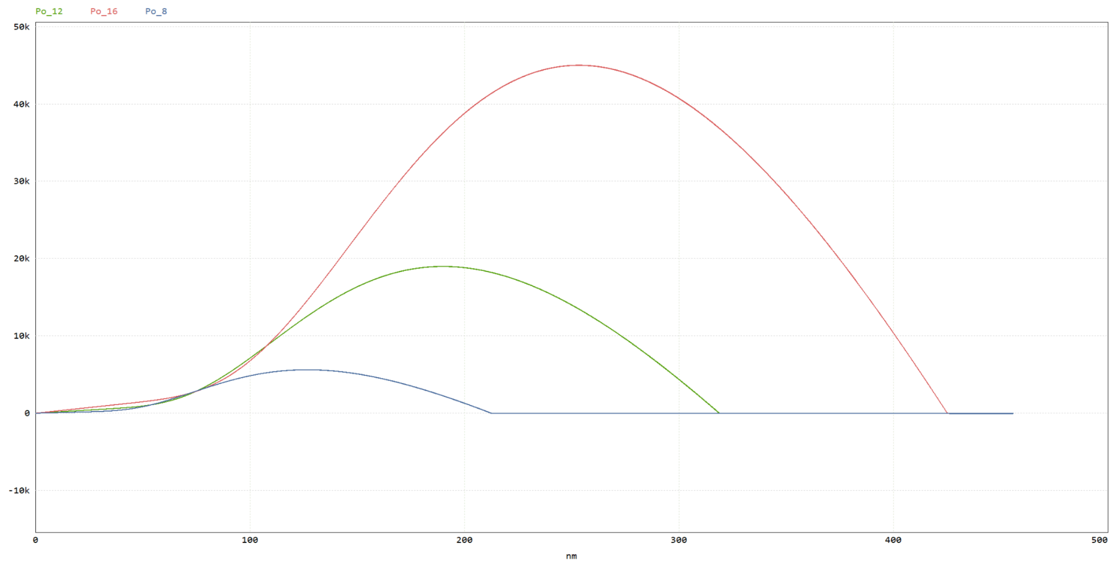

Figure 2: Overlaid Po_max vs Shaft Speed

Value Table:

$Wind\ Speed\ (m/s)$	$P_{o\ max}\ (kW)$	$Shaft\ Speed\ (\frac{rad}{s})$
8	5.63163	126.768
12	19	190.061
16	25.045	253.455

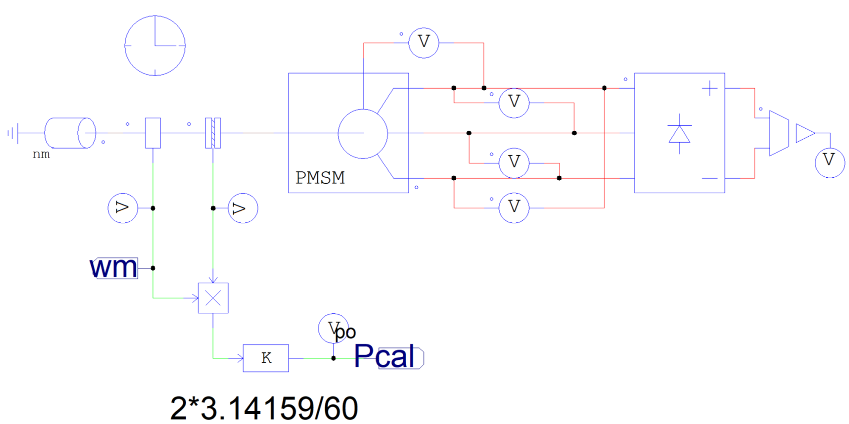

Figure 3: Permanent Magnet Generator Characteristic circuit

Using a constant speed block with the 3-phase PMG output connected to a Full Wave Diode rectifier, the ideal rectified output voltage can be recorded and characteristics observed.

The PMG converts mechanical energy from the wind turbine into three-phase AC voltage, with each phase shifted by 120° due to the stator winding arrangement. This AC output is then fed into a three-phase full-wave diode rectifier, which converts it to nearly constant DC voltage by allowing current to flow in only one direction and selecting the highest instantaneous phase voltage at any given moment. This process ensures a continuous and relatively smooth DC output, which is then regulated by the interleaved Buck-Boost converter to meet the system's power requirements.

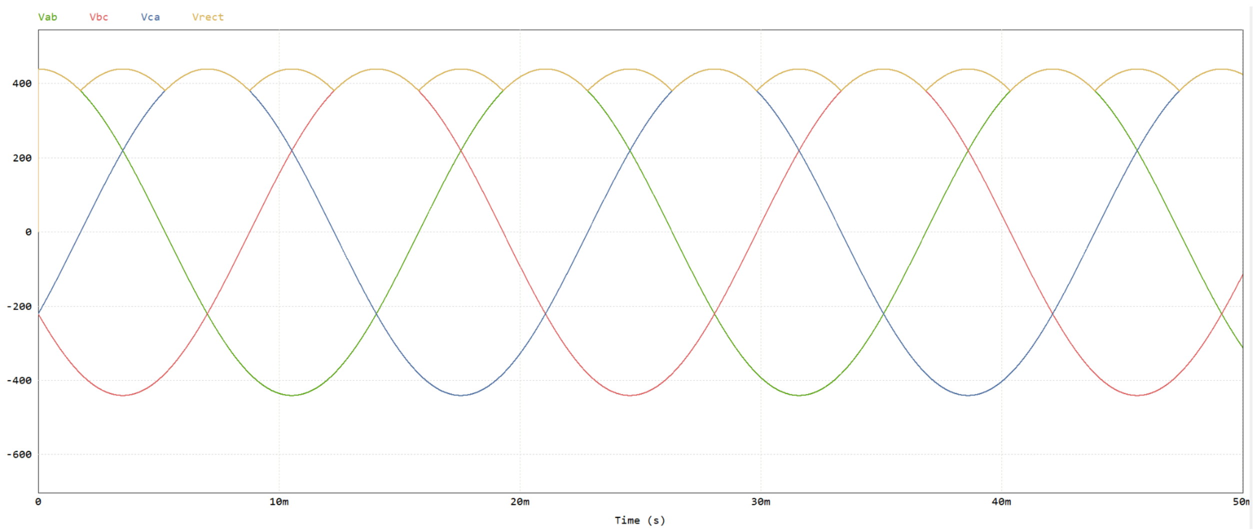

Figure 4: Phase Voltages and Rectified Output Voltage

Using the base rotational speed of 190 rad/s, an output voltage of around 405V is recorded, which is higher than the rated 355V line voltage, most likely due to the high frequency system and inaccuracy of the diode rectifier.

<u>Speed Control:</u>

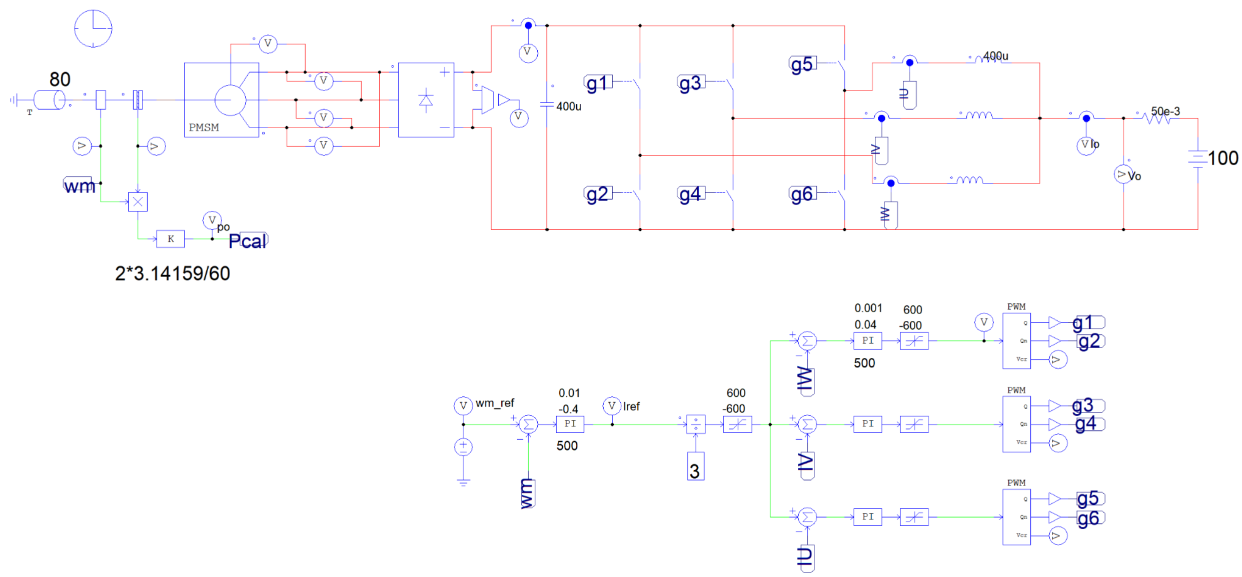

Figure 5: Speed Control Schematic

Now implementing the Buck-Boost converter and speed control branch with a constant torque connected to the PMG and Diode rectifier, speed can now be tracked and adjusted dynamically. In the speed control branch, PI controllers regulate the PMSM speed by adjusting the phase currents. The speed PI controller minimizes the error between the reference and actual speed, generating a current reference. The current PI controllers ensure the inverter supplies the correct phase currents by generating PWM signals for the switches, enabling precise torque and speed control. Adjusting the PI controllers changes how the system responds to speed and current errors. Increasing the proportional gain (Kp) makes the response faster but can cause oscillations if too high. Increasing the time constant (t) eliminates steady-state error but can slow the response and cause overshoot if excessive. Proper tuning of Kp and t ensures fast, stable, and accurate speed control, while poor tuning can lead to instability, slow response, or excessive oscillations in the PMSM drive.

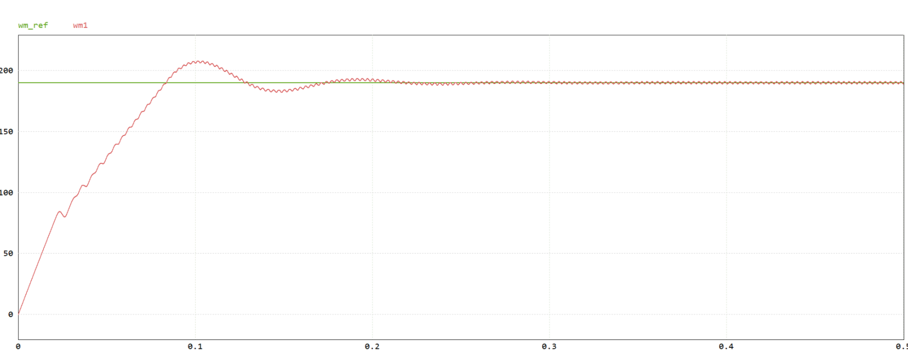

Figure 6: Gain of 0.4 and time constant of 0.1

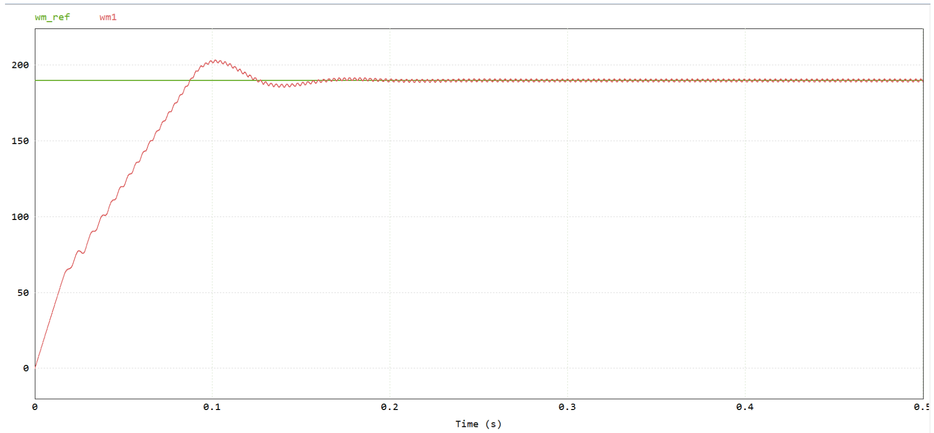

Figure 7: Gain of 0.6 and time constant 0.1

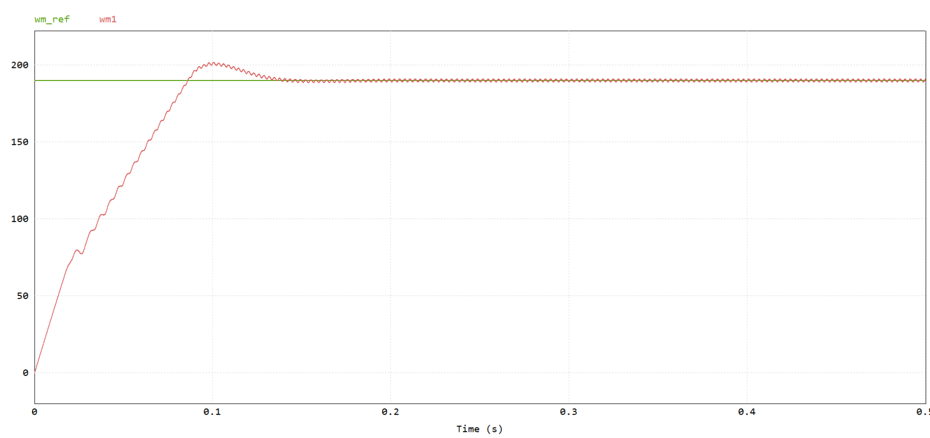

Figure 8: Gain of 0.9 and time constant 0.1

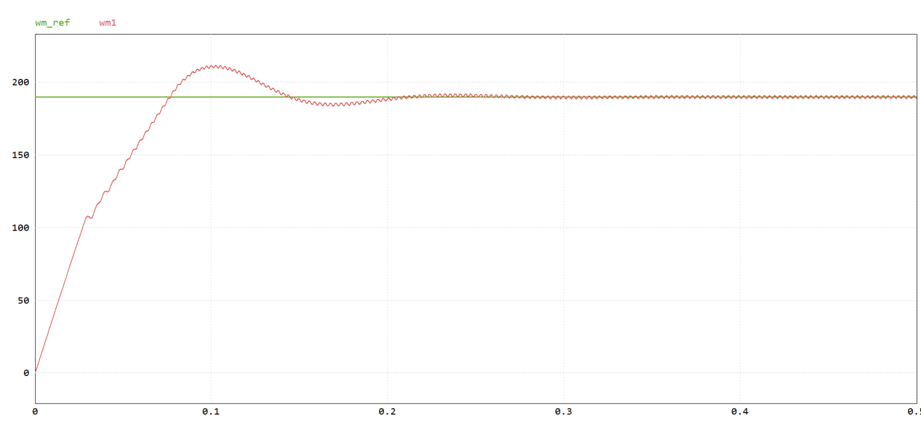

Figure 9: Gain of 0.4 and time constant of 0.2

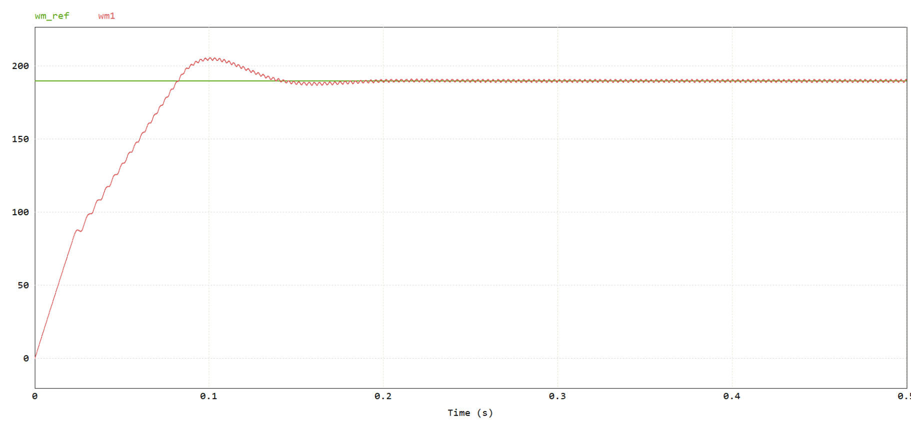

Figure 10: Gain of 0.6 and time constant 0.2

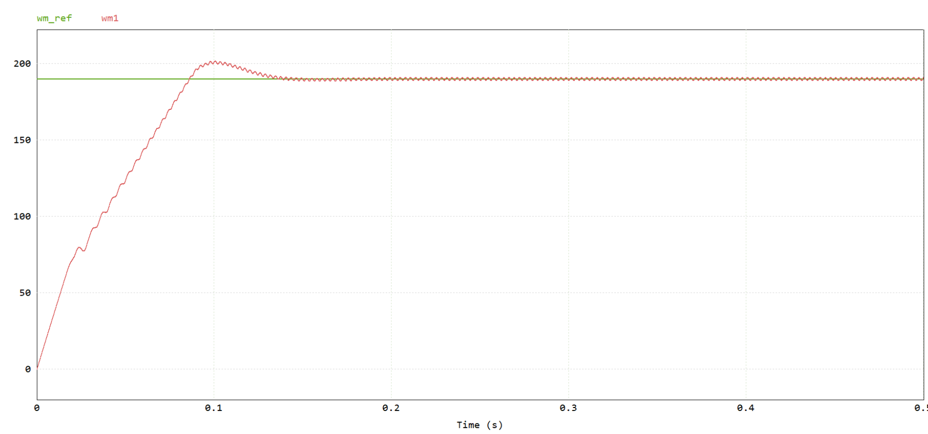

Figure 11: Gain of 0.9 and time constant 0.2

Tabulated Values:

$Gain$	τ	$Speed\ Overshoot$	$Settling\ time$
0.4	0.01	9.368%	0.363 s
0.6	0.01	7.07%	0.239 s
0.9	0.01	4.357%	0.1685 s
0.4	0.02	11.39%	0.311 s
0.6	0.02	8.3%	0.231 s
0.9	0.02	6.14%	0.1878 s

Note the PI blocks in the current branch set to 10% of Gain and Time constant of speed control PI. It is observed that the most efficient gain and time constant having the lowest overshoot and settling time was 0.9 and 0.01 respectively.

Speed Control with turbine:

The speed control with turbine system operates by dynamically adjusting the generator's shaft speed ω_m to match the reference speed ω_{ref}, which is determined by the MPPT algorithm. A Proportional-Integral (PI) controller is used to minimize the error $e(t) = \omega_{ref} - \omega_m$, generating a current reference that drives the converter switches. The controller output follows the standard PI control law:

$$u(t) = K_p e(t) + K_i \int e(t)dt$$

where K_p is the proportional gain, and $K_i = \frac{K_p}{\tau}$ is the integral gain based on the selected time constant τ. These control signals regulate the torque applied by the generator and adjust the power delivered to the load.

When the turbine is introduced into the system, the dynamic response differs from the constant torque case due to the mechanical inertia and aerodynamic properties of the turbine. The plots of ω_{ref} vs. ω_m indicate that higher proportional gains result in faster response times but at the cost of increased overshoot. As shown in the results, a gain of 0.9 with a time constant of 0.01 yielded the lowest settling time of 0.1058 s while maintaining an overshoot of 44.97%. In contrast, lower gains exhibited slower convergence to ω_{ref}, while higher time constants led to increased settling times.

A comparison between the speed control with turbine system and the constant torque model reveals that the turbine introduces additional transient effects, leading to increased settling time and overshoot. However, the controller effectively compensates for these disturbances, allowing the system to stabilize and track the reference speed under varying operating conditions. These results validate the robustness of the PI-based speed control strategy, demonstrating its ability to regulate turbine-driven generators while maintaining efficient and stable operation.

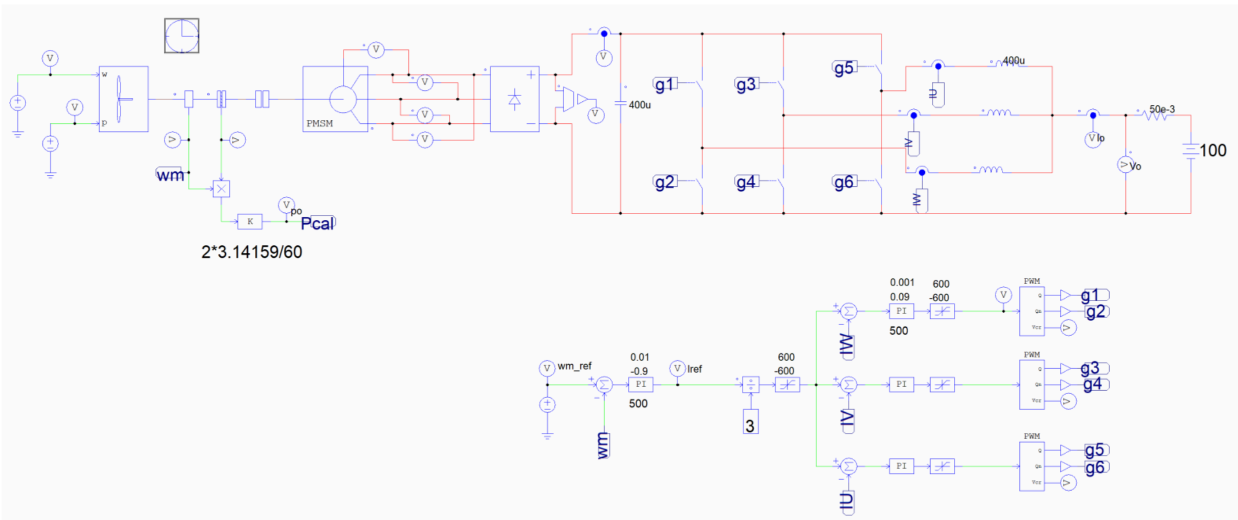

Figure 12: Turbine Speed Control Schematic

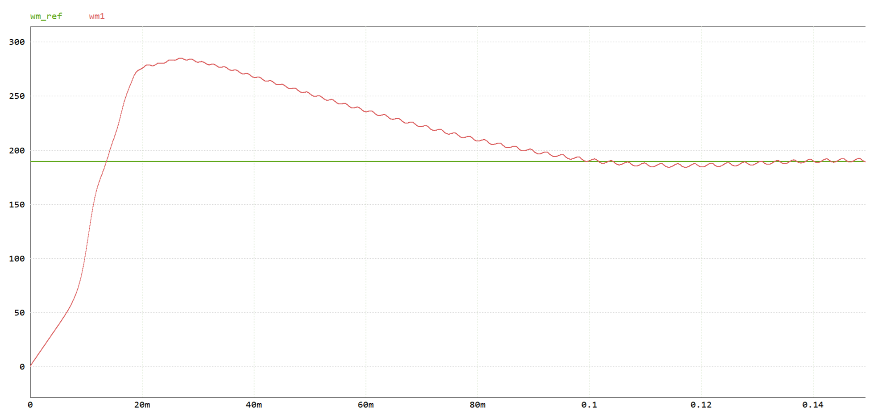

Figure 13: Gain of 0.4 and time constant of 0.1

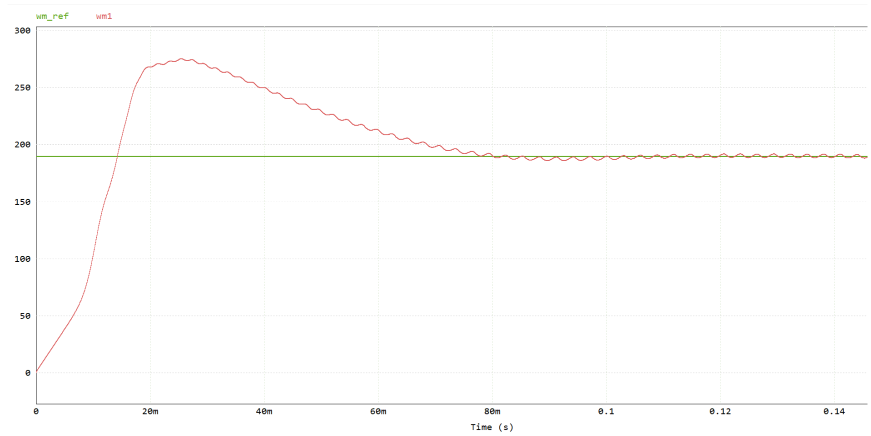

Figure 14: Gain of 0.9 and time constant of 0.1

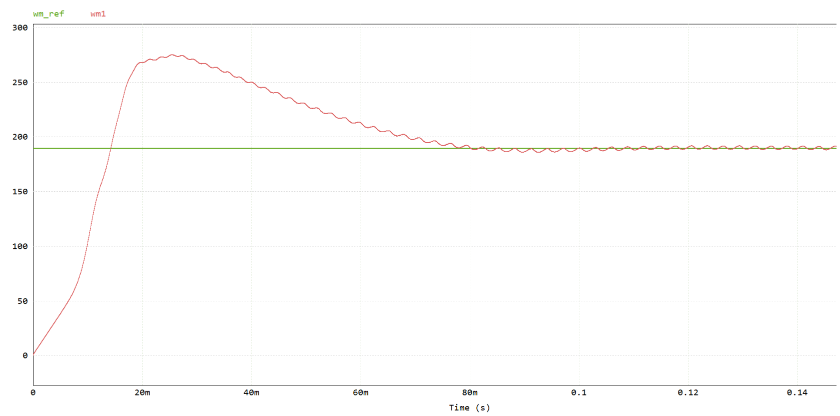

Figure 15: Gain of 0.9 and time constant of 0.1

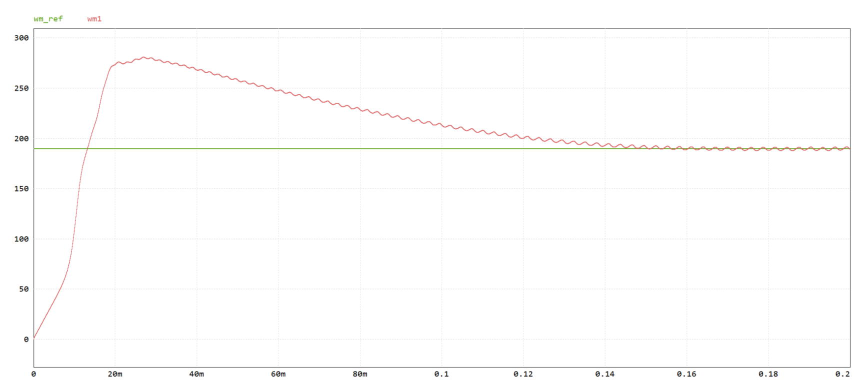

Figure 16: Gain of 0.4 and time constant of 0.2

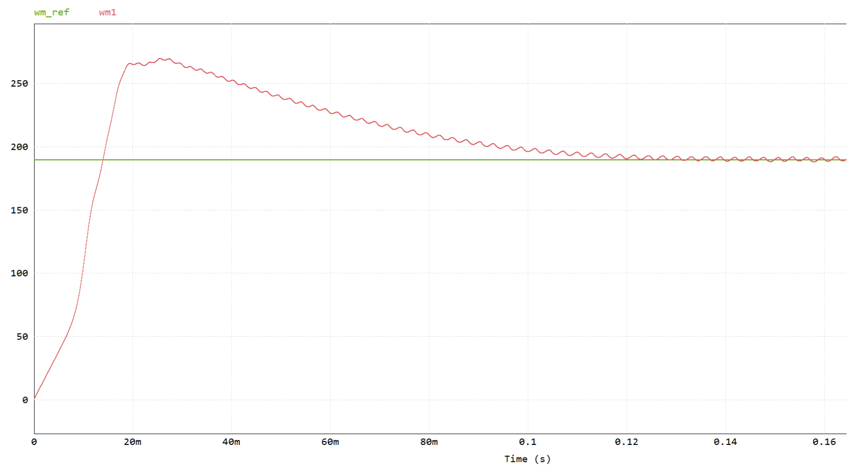

Figure 17: Gain of 0.6 and time constant of 0.2

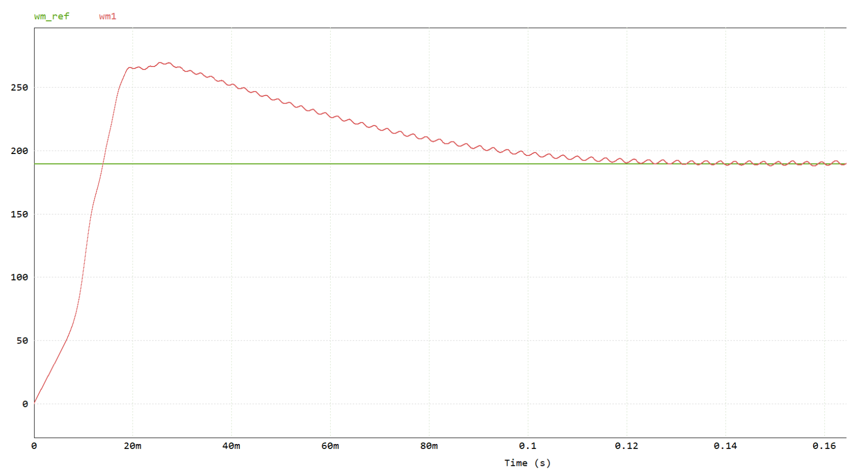

Figure 18: Gain of 0.9 and time constant of 0.2

Tabulated Values:

$Gain$	τ	$Overshoot$ %	$Settling\ Time$
0.4	0.01	50.2%	$0.1456s$
0.6	0.01	44.967%	$0.1078s$
0.9	0.01	44.967%	$0.10584s$
0.4	0.02	52.69%	$0.2024s$
0.6	0.02	47.95%	$0.16047s$
0.9	0.02	41.98%	$0.1418s$

<u>MPPT:</u>

This MPPT algorithm dynamically adjusts the turbine's shaft speed reference (ω_{ref}) to maximize power output in changing wind conditions. It takes in the turbine's shaft speed (ω_m), power output (P_{cal}), and wind speed (Speed), then calculates their differences from the previous cycle. The step size for adjusting ω_{ref} is adaptive, increasing when power changes significantly. If power increases, ω_{ref} is adjusted upward to track the optimal power point, while a decrease in power causes ω_{ref} to move downward. Large power fluctuations (Pdiff > 1000) trigger a reset of ω_{ref} to prevent instability. Additionally, wind speed changes (Sdiff) influence ω_{ref}, ensuring responsiveness to varying wind conditions. By continuously updating and refining the shaft speed reference, the system efficiently tracks the maximum power output in real time.

The Maximum Power Point Tracking (MPPT) algorithm was tested in two stages to evaluate its ability to dynamically adjust the turbine's shaft speed reference ω_{ref} and maintain maximum power output. The first stage involved simulating a constant wind speed of 12 m/s. In this test, the MPPT algorithm successfully converged on the optimal operating point, with the generator speed ω_m closely tracking ω_{ref}. The power output stabilized around 18 kW, with a settling time of approximately 0.126 seconds and an overshoot of about 40.09%.

To improve system responsiveness and reduce lag between ω_{ref} and ω_m, the sampling rate of the Zero Order Hold (ZOH) block was increased to 200 Hz, and the perturbation step size was carefully adjusted. These changes allowed the generator speed to more closely follow the reference speed without introducing instability.

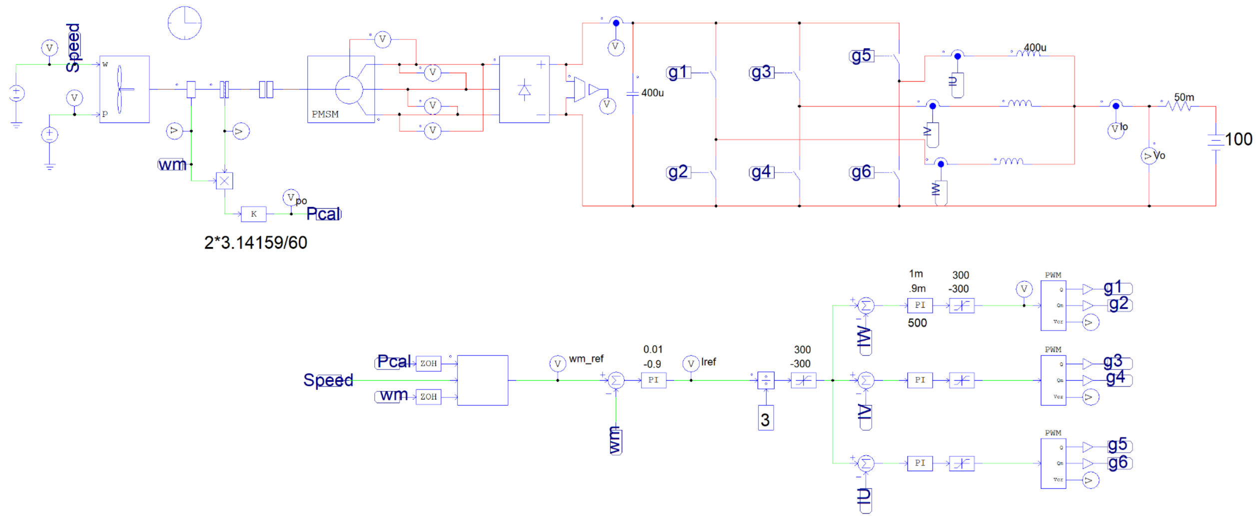

Figure 19: MPPT Schematic

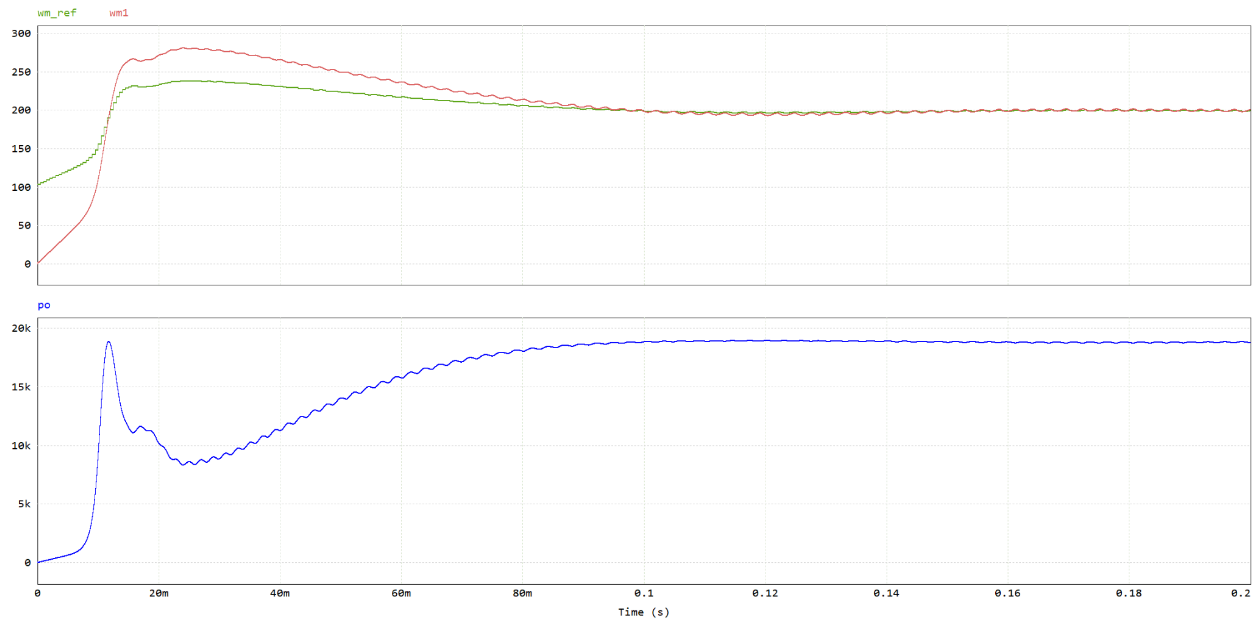

Figure 20: ω_{ref} vs ω and P_{MP} for constant windspeed 12m/s

Settling time ~0.126s
Overshoot ~ 40.09%

<u>Change speed from 12m/s to 8m/s:</u>
The next step involved testing the MPPT algorithm under varying wind conditions, specifically changing windspeed from 12 m/s to 8 m/s. To simulate this scenario, the PSIM schematic was modified by replacing the constant wind speed input with a step input that decreases the wind speed from 12 m/s to 8 m/s during the simulation. The same MPPT algorithm used in the previous constant-speed test was applied to evaluate its ability to adapt and track the new maximum power point. Power output dropped and oscillated around 2.2 kW, which is consistent with expected performance at 8 m/s. The system exhibited a 15% undershoot as ω_{ref} adjusted downward in response to the drop in wind speed, with a settling time of 0.134 seconds. These results confirm the algorithm's robustness and demonstrate its ability to adapt in real time to changing environmental conditions.

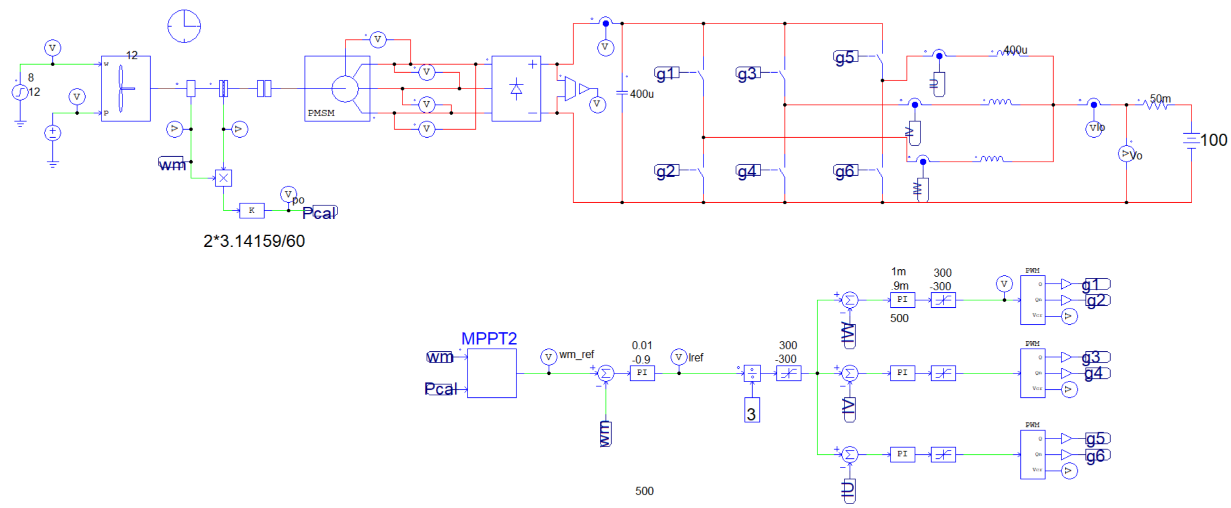

Figure 21: MPPT Schematic (changing windspeed from 12m/s to 8m/s)

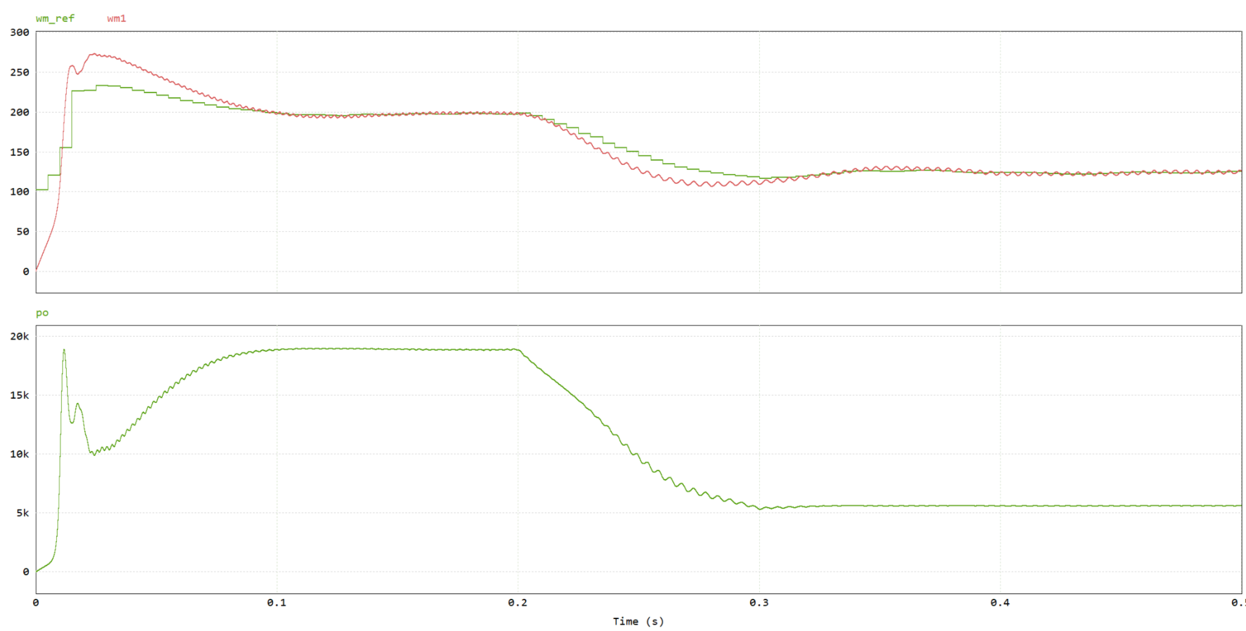

Figure 22: ω_{ref} vs ω and P_{MP} for changing winspeed from 12m/s to 8m/s

Tabulated Values:

$Wind$	$Gain$	τ	ZOH	$Overshoot\ \%$	$Settling\ Time$
12	0.9	0.01	200	43.74%	0.1489
8	0.9	0.01	200	−15%	0.134s

Code:

```
float wm = x1;
float Pcal = x2;
float Speed = x3;
static float wprev = 0.0;
static float Pprev = 0.0;
static float Sprev = 0.0;
static float wmref = 100;
const float base_step = 1.8;
float Pdiff = Pcal - Pprev;
float wdiff = wm - wprev;
float Sdiff = Speed - Sprev;
float step = base_step + 0.1 * fabs(Pdiff);
if (fabs(Pdiff) > 0.02) {
    if (Pdiff > 0) {
        wmref += step;
    } else {
        wmref -= step;
    }
}
if (Pdiff > 1000) {
            wmref = 100;
}
if(fabs(Pdiff) > 1000){
            wmref = 50;
}
wmref += 0.48 * Sdiff;
wprev = wm;
Pprev = Pcal;
Sprev = Speed;
y1 = wmref;
```

Figure 23: MPPT Code

Conclusion

This project successfully implemented speed control and Maximum Power Point Tracking (MPPT) for a wind energy conversion system using an interleaved buck-boost converter and a three-phase permanent magnet generator. The system was modeled and simulated in PSIM, integrating Proportional-Integral (PI) controllers for current and speed regulation, along with a Perturbation and Observation (P&O) based MPPT algorithm to maximize power output under varying wind conditions.

The speed control strategy was first tested with a constant torque load, and then with the wind turbine model. Multiple gain and time constant combinations were evaluated to determine their effect on system stability and responsiveness. A gain of 0.9 and time constant of 0.01 provided the most optimal performance, achieving a low settling time of approximately 0.1058 seconds with manageable overshoot. When the turbine was introduced, the system showed slightly increased transients due to its mechanical characteristics, but still maintained effective speed tracking, highlighting the reliability of the control system.

The MPPT algorithm was tested in two phases: first with a constant wind speed of 12 m/s, and then with a wind speed drop from 12 m/s to 8 m/s. In the constant-speed test, the MPPT controller effectively guided the system to the maximum power point, reaching a steady power output around 18 kW with minimal oscillation. For the variable-speed test, the same algorithm adjusted accordingly to the drop in wind speed, stabilizing the power output near 2.2 kW. To improve the tracking performance, the sampling rate of the Zero Order Hold block was increased to 200 Hz, and the step size was tuned to allow the generator speed ω_m to better follow the reference speed ω_{ref}.

Overall, the simulation results demonstrate that the system is capable of maintaining stable operation and efficiently extracting wind energy under both steady and changing environmental conditions. The project highlights the effectiveness of combining PI control with a P&O-based MPPT algorithm for small-scale wind energy systems, while also identifying opportunities for further optimization in real-time responsiveness and control precision.

Each team member played a significant role in the project's development, with contributions spanning circuit design, control system implementation, MPPT algorithm development, and performance analysis. The integration of these components ensured that the system met its objectives, providing a robust and efficient power management solution for solar energy systems. Jarett led the circuit analysis and schematic design, ensuring the electrical components and control systems were structured correctly. Additionally, he played a key role in developing the Maximum Power Point Tracking (MPPT) system, leading the computational aspects of the project, including implementing and analyzing MPPT performance. Spencer collaborated with Jarret in designing and implementing the MPPT algorithm, focusing on its optimization and integration within the overall system, as well as making sure the speed control for both with constant torque block and turbine. Sam assisted in the solutions part in general and he was responsible for writing and formatting most of the report, ensuring clarity, consistency, and adherence to the required format.