Wind Turbine System with MPPT Algorithm

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Introduction

Renewable energy sources are becoming increasingly important as we strive to reduce carbon emissions and become more environmentally sustainable. Wind energy is one such source that has shown great potential in recent years. The focus of this project is to develop and implement a system for controlling the speed of a wind turbine to optimize its output power.

The project begins by plotting the power output of a turbine at different shaft speeds to establish its characteristics. The project involves analyzing the power output of a wind turbine at various shaft speeds using a permanent magnet synchronous motor to convert mechanical energy into electrical energy. The output power of a wind turbine is determined by the product of torque and rotational speed.

$$P = T * \omega \quad (1)$$

Torque is a measure of the twisting force that causes the shaft to rotate, and it is directly proportional to the force of the wind on the blades. Rotational speed, on the other hand, is the speed at which the shaft is rotating, and it is directly proportional to the speed of the wind. A diode bridge rectifies the AC signal to DC, which is then smoothed using a capacitor. The next step is to use a three-leg interleaved buck-boost converter for speed control, which can regulate power output to match desired output power quickly. Two controllers with optimized gain values are used in a Proportional-Integral (PI) loop to adjust the duty cycle of the converter, combining proportional and integral controls to minimize overshoot and provide a stable system. The input speed, measured by the shaft speed, is adjusted to match multiple input speeds, and the system is tested for performance. The flow of power through the circuit is represented in Figure 1.

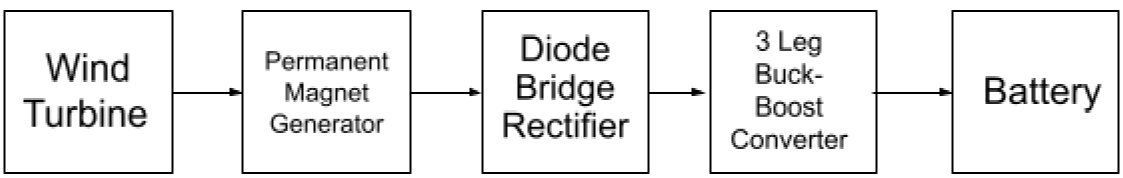

Figure 1: Block Diagram Showing Flow of Power Through System

The next task is to implement Maximum Power Point Tracking (MPPT) using Perturbation and Observation. The purpose of the MPPT is to adjust the speed of the wind turbine to maintain maximum power output. Different perturbation delta values are tested to fine-tune the system, and the wind turbine's speed is changed from 12m/s to 8m/s. Figure 2 shows the schematic the project is based around. The control diagram representing the scope of the project is shown in Figure 3.

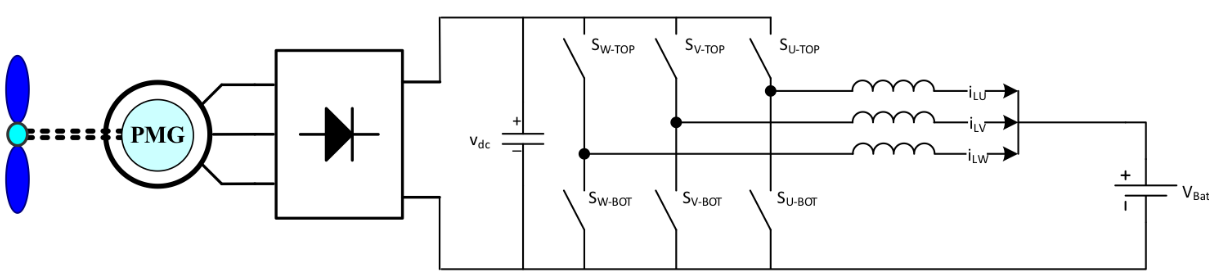

Figure 2: Wind Turbine System

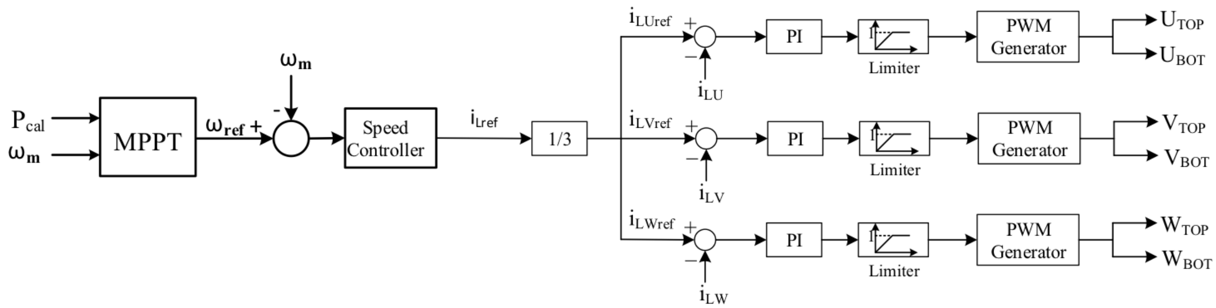

Figure 3: Control Block Diagram for MPPT Algorithm

This project is relevant because optimizing wind energy production is essential in our transition to renewable energy sources. By controlling the wind turbine's speed, its power output can be maximized, thereby increasing its efficiency and reducing our reliance on non-renewable energy sources.

Problem Definition

A system that measures both the torque and the rotational speed of the shaft can be used to find the output power of a wind turbine in relation to the shaft speed. This system can be designed to vary the input wind speed to the turbine, allowing to observe how the output power changes as the wind speed increases or decreases. By collecting data on the relationship between the shaft speed and the power output at different wind speeds, it can be determined the optimal operating conditions for the wind turbine. This information can be used to improve the efficiency of the turbine and maximize the amount of electricity generated.

Once the above results are found, the next step is to implement speed control. To implement speed control, a three leg interleaved buck-boost converter is to be developed as shown in Figure 4. A three leg interleaved buck-boost converter is a highly efficient DC-DC converter that can handle high power levels, making it suitable for use in power electronics applications such as wind turbine power output tracking systems. By controlling the duty cycle of the converter, it is possible to adjust the output voltage or current and regulate the power output of the wind turbine to match the desired output power. This enables the system to respond quickly to changes in the wind speed, optimizing energy production. The interleaved structure of the converter reduces the amount of current and voltage stress on each switch, resulting in lower switching losses and higher efficiency, which is important for minimizing energy losses and maximizing overall energy production. The use of a three leg interleaved buck-boost converter in a wind turbine power output tracking system can improve the efficiency and reliability of the system, while also allowing for precise control of the wind turbine's output power.

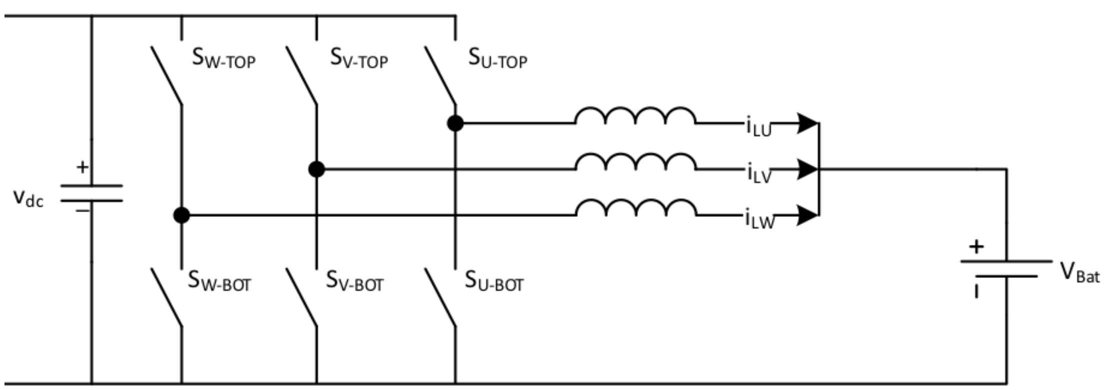

Figure 4: Three Leg Interleaved Buck-Boost Converter

In addition, the circuit is to have a three phase diode bridge, used at the input. This ensures that only one diode leg is on at a time, making it so that the most positive voltage is input at any given time. A permanent magnet synchronous motor is to be inputted into the three phase rectifier.

Once the circuit has been developed, the proper gain value for the circuit that allows for the generator speed to be tracked is to be found. This is done by trying different values for gain until a plot is seen where the measured speed stabilizes to the reference speed. Negative gain is to be used because there is an inverse relationship between speed and current. For example, if the reference speed is higher than the measured speed, the power pulled will be decreased as well as the current so that the speed can be increased. After this gain value has been found, the system must be used to verify the speed control for multiple input speeds.

Maximum Power Point Tracking is implemented using Perturbation and Observation. To implement MPPT, the schematic needs the following updates: change from constant reference speed input to C block on PSIM with the inputs speed and power, and change from constant torque input to wind turbine input with a speed of 12m/s.

A C block is used to program the logic for MPPT. Two two-layer nested conditional statements will be used to emulate a MUX-like system when it comes to changes in reference speed. Taking current power output and current speed as input, the MPPT will compare those against the previous power output and previous speed. With these comparisons, the system can deduce change in power (denoted as P(k)-P(k-1)) and change in speed (denoted as $\omega(k)-\omega(k-1)$) in Figure 5.

The MPPT is then to be tested with multiple delta values that change how much the speed is being perturbed each iteration. The MPPT method is represented by the flow chart diagram in Figure 5. Different perturbation delta values are to be tested for the speed (corresponding to “Decrease ω_{ref}” or “Increase ω_{ref}” in the flow chart diagram).

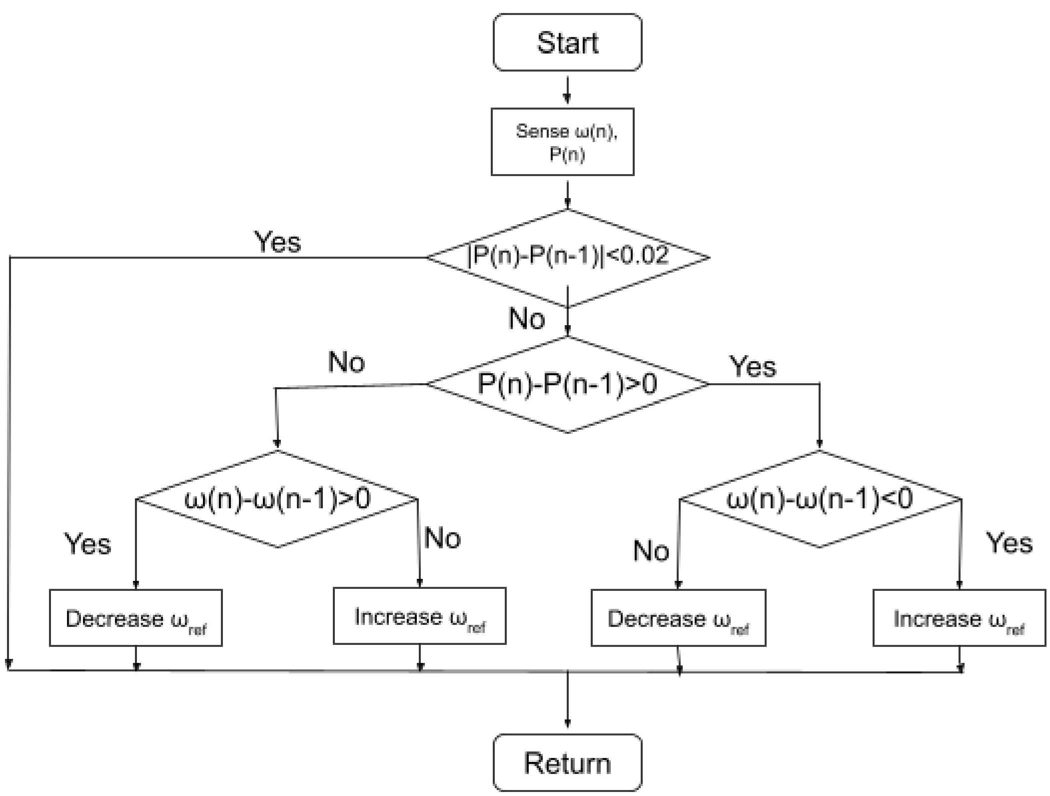

Figure 5: Perturbation and Observation Algorithm for Wind Turbine

Finally, the MPPT is to have a wind turbine change from a speed of 12m/s to a speed of 8m/s.

Solution

<u>Plotting output Power for Shaft Speeds of 8, 12, 16m/s</u>

To accurately measure the output power of a wind turbine in relation to the shaft speed, it is important to use a system that is specifically designed to measure both the torque and rotational speed of the shaft. The following system should be able to accurately detect and record any changes in the torque and rotational speed of the shaft that occur in response to changes in wind speed. By using such a system, it is possible to accurately measure the relationship between the shaft speed and the output power of the wind turbine.

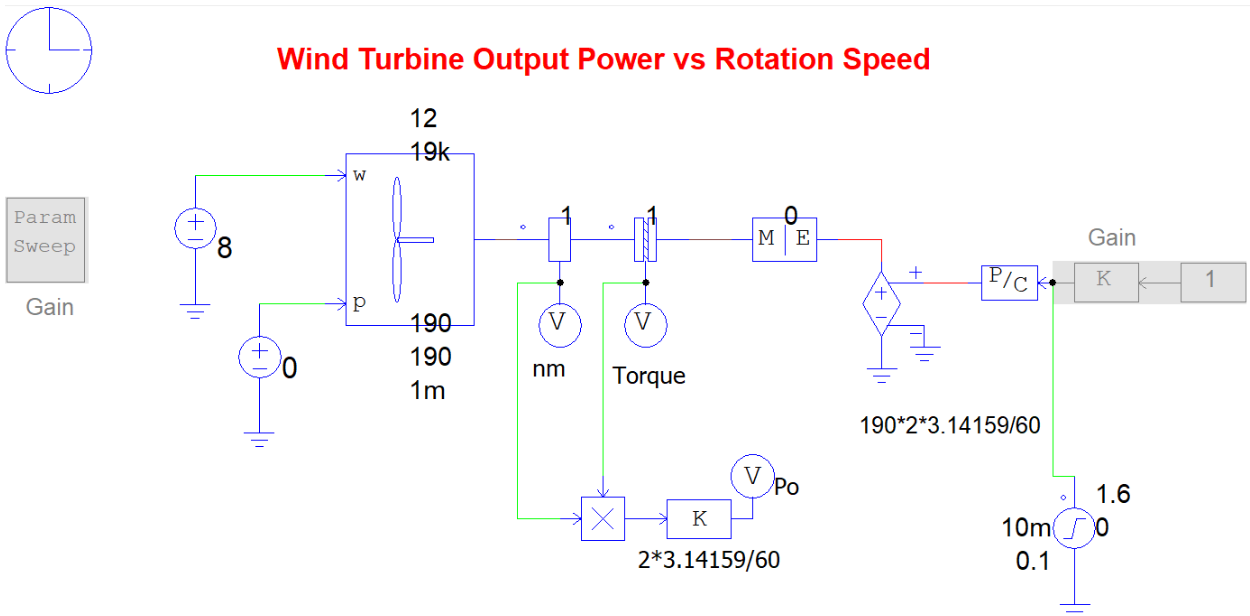

Figure 6: Wind power generator circuit.

The performance of a wind turbine is strongly influenced by the wind speed. At a wind speed of 8m/s, the output power of the wind turbine was measured to be approximately 5.7KW. This power output was achieved at a rotational speed of around 130 rad/sec, which indicates that the wind turbine was operating at an optimal speed for this wind speed.

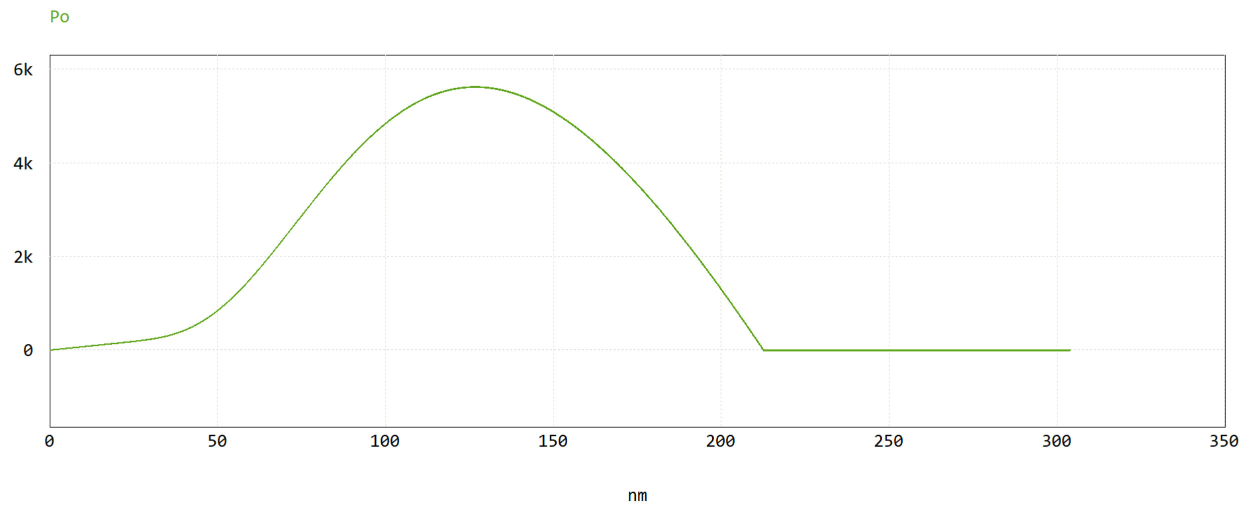

Figure 7: Output power for 8 m/s wind speed.

As the wind speed increases, the output power of the wind turbine also increases. At a wind speed of 12m/s, the output power of the wind turbine was measured to be approximately 18KW. This power output was achieved at a rotational speed of around 190 rad/sec, which indicates that the wind turbine was operating at an optimal speed for this wind speed.

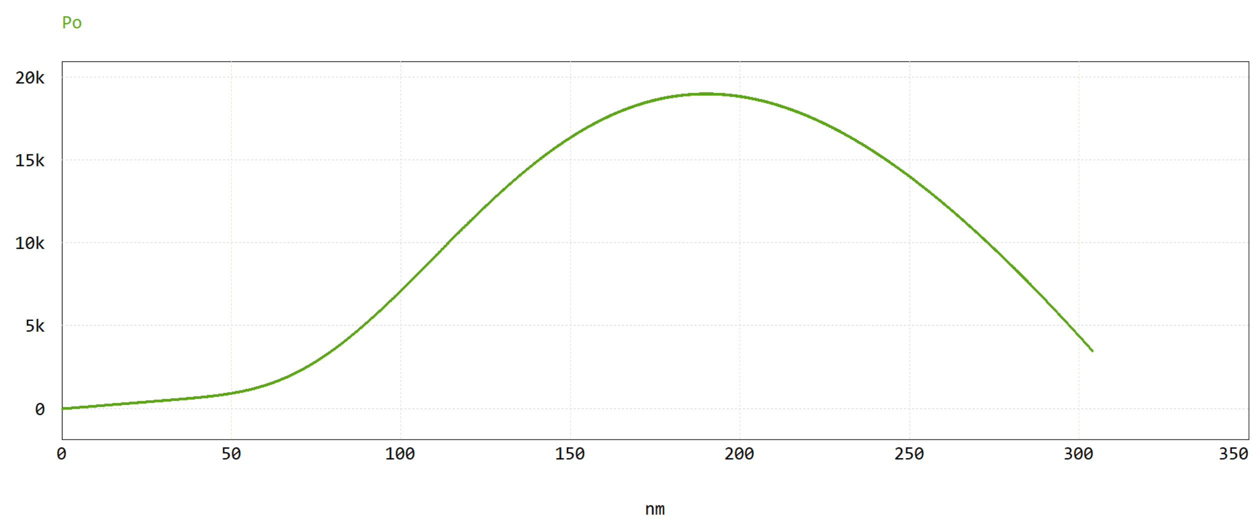

Figure 8: Output power for 12 m/s wind speed.

At high wind speeds, the wind turbine is able to generate a significant amount of power. At a wind speed of 16m/s, the output power of the wind turbine was measured to be approximately 45KW. This power output was achieved at a rotational speed of around 250 rad/sec, which indicates that the wind turbine was operating at an optimal speed for this wind speed.

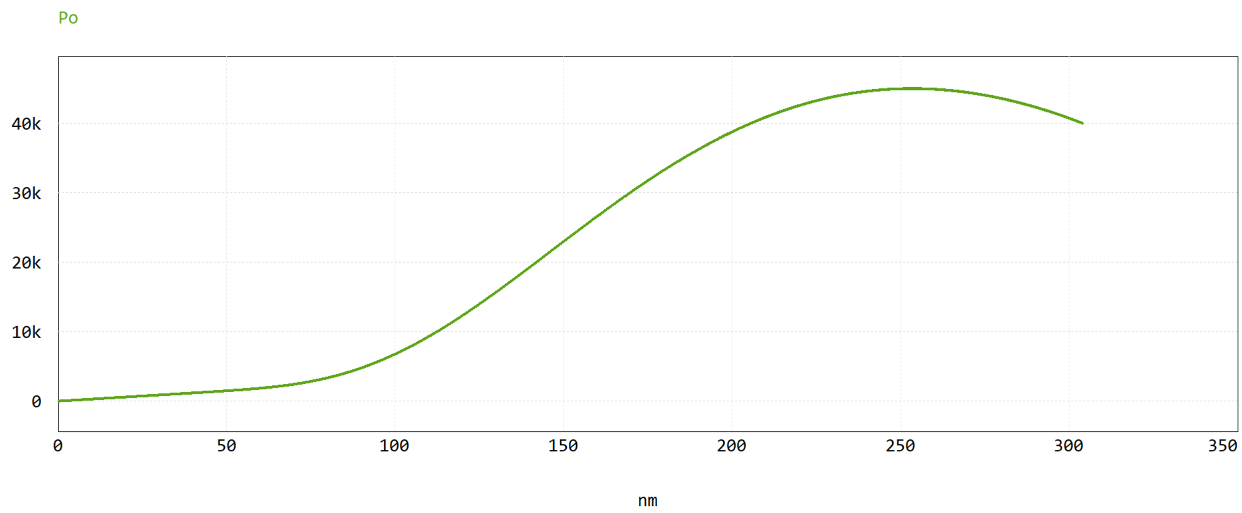

Figure 9: Output power for 16 m/s wind speed.

In order to convert the mechanical energy produced by the wind turbine into electrical energy, a system consisting of a 3-Phase Permanent Magnet Generator (PMG) and a full wave diode rectifier is used. The PMG is designed to produce a three-phase alternating voltage output, which is then fed into the full wave diode rectifier. The rectifier ensures that only the maximum positive gain of the turbine is kept, and any lower gain is filtered out by the diode rectifier system. This filtering process results in a more consistent and reliable output voltage from the wind turbine, which is necessary for efficient energy production.

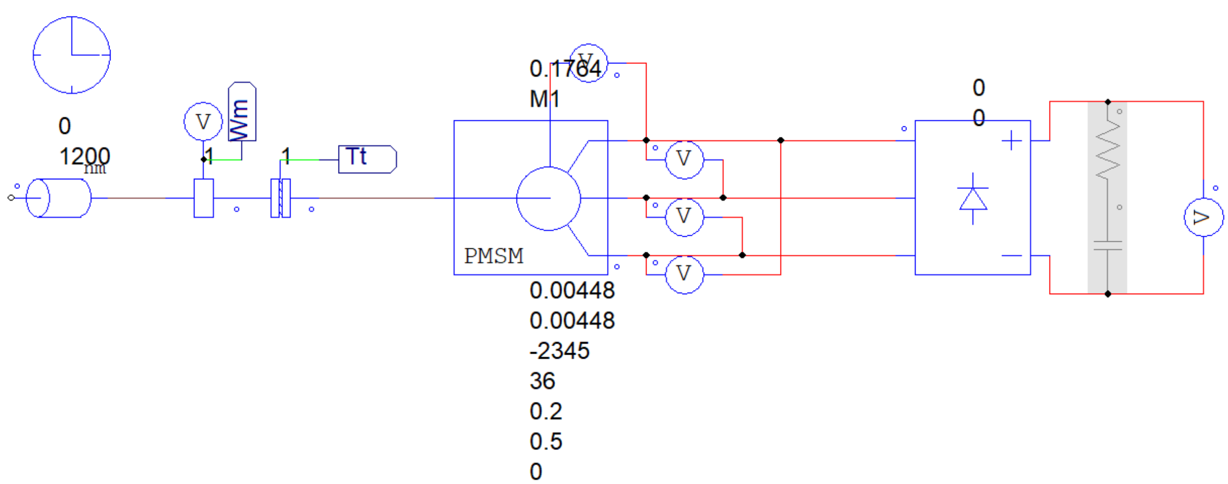

Figure 10: 3-Phase Permanent Magnet Generator connected to a full wave diode rectifier.

The performance of the full wave diode rectifier system can be seen in the plot provided. The plot shows how the designed full wave diode rectifier is able to detect and keep the crest of each of the three voltage waves of the PMG. Due to the high frequency of the system and the accuracy of the diode rectifier, the filtered voltage stays around 400V without much oscillation.

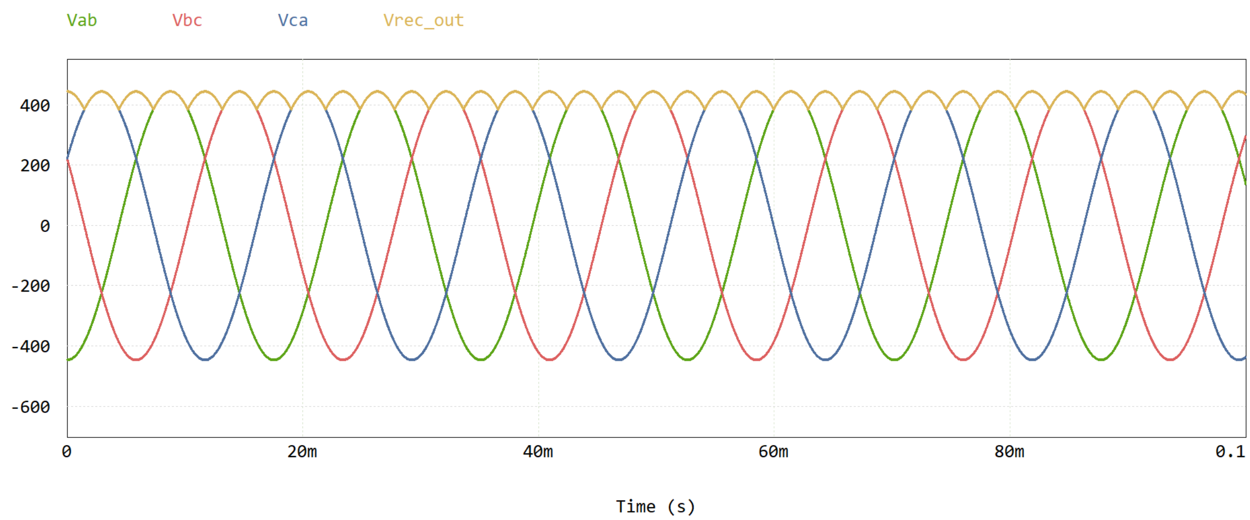

Figure 11: Voltage output of each phase of PMG and rectified voltage.

<u>Speed Control</u>

Once the shaft speeds were found for the wind turbine, the next step was to implement speed control into the 3 leg Buck-Boost Converter as described above. The schematic in Figure 12 was developed and used for the simulations for speed control implementation, with only the gain on the speed control PI being adjusted.

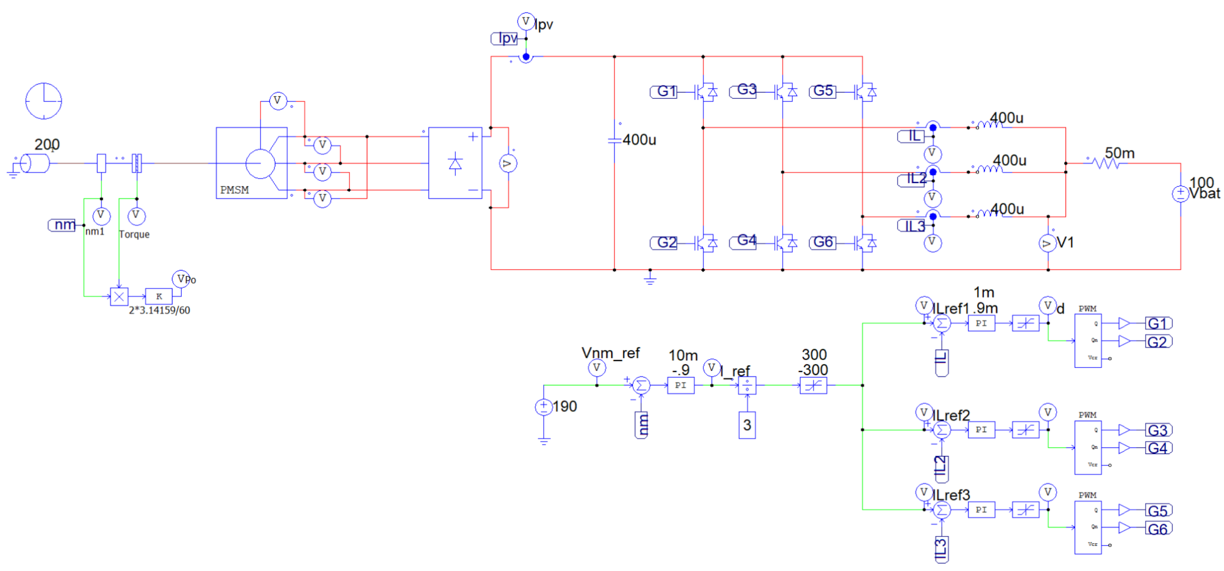

Figure 12: Schematic for Speed Control Implementation

The first gain used is -0.4 which produced the plot in Figure 13. The speed stabilizes, but a system that stabilizes quicker than ~0.6 seconds, as seen here, would be ideal. The reference speed in 190 rad/sec and input torque is 200 Nm.

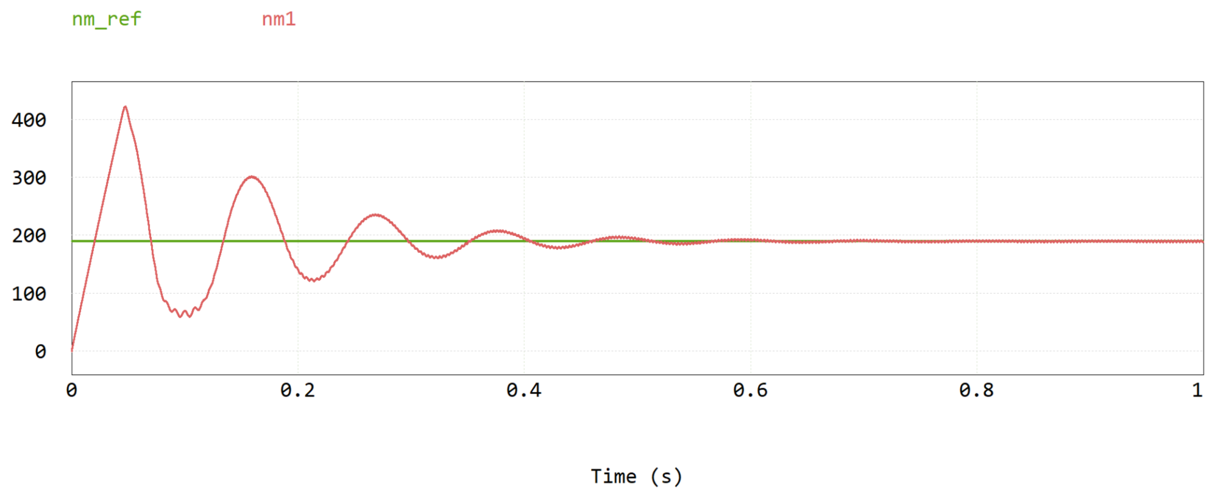

Figure 13: Speed Control Results for Gain = -0.4

The gain was changed from -0.4 to -0.9 with the goal of increasing the stabilization time. As seen in Figure 13 and Figure 14, the overshoot increased, but the second and subsequent peaks were reduced by about 25W and the total stabilization time was about 0.4s less.

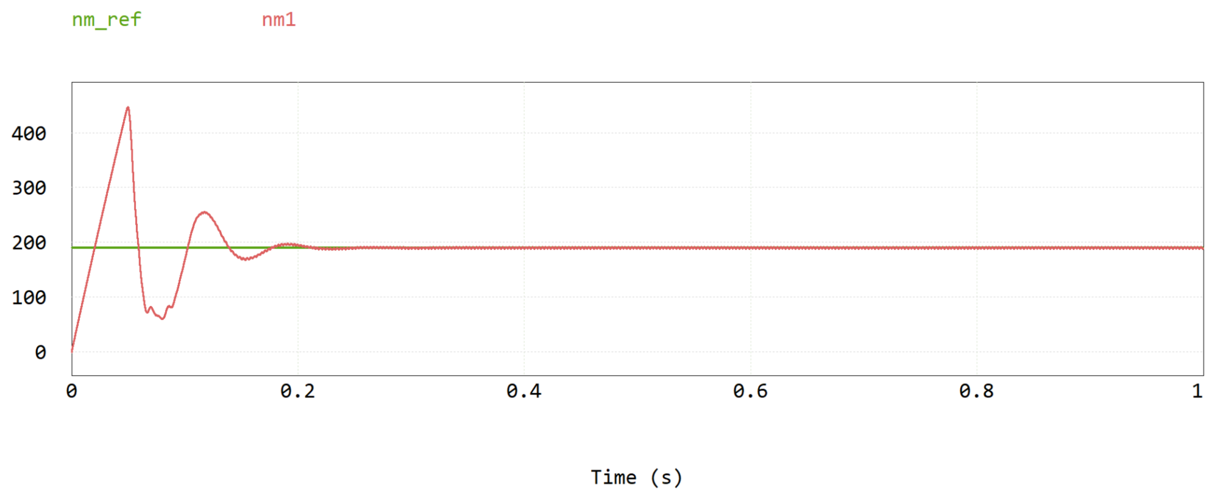

Figure 14: Speed Control Results for Gain = -0.9

To verify these results, the speed control was tested for a new torque of 150 and a reference speed of 250 rad/sec. The schematic is shown in Figure 15.

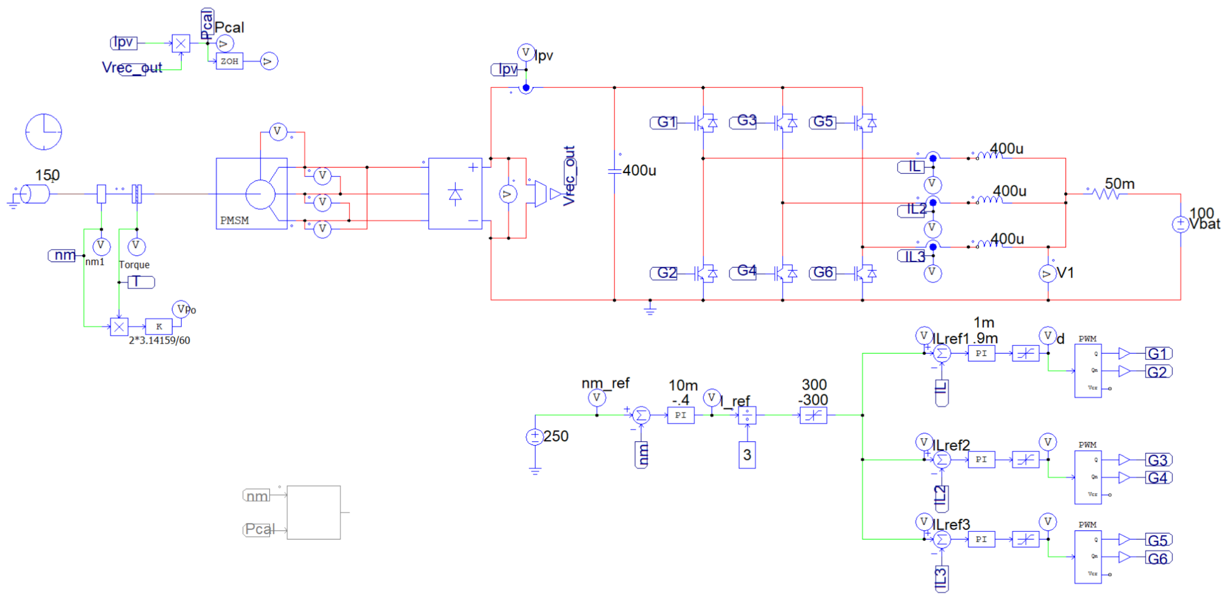

Figure 15: Schematic for Speed Control Implementation with Changed Reference Speed and Torque

As seen in Figure 16, the speed does stabilize, but not as quickly as for the previous input.

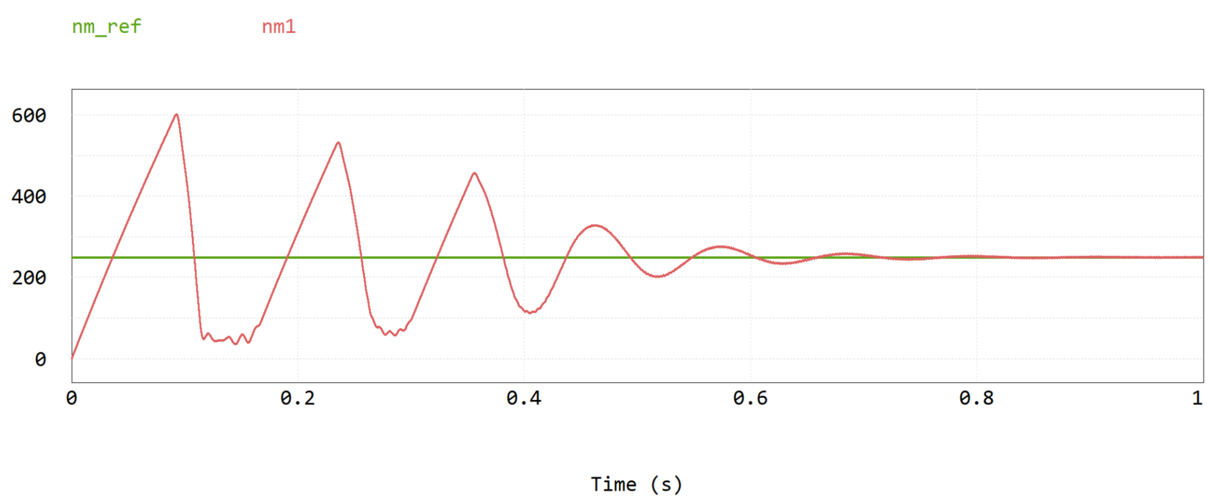

Figure 16: Speed Control Results for Gain = -0.9 for New Input Speed and Torque

<u>MPPT Implementation</u>

Once the speed control was implemented, the next step was implementing maximum power point tracking. The constant input is changed to a C block and the constant torque input is changed to a wind turbine. For this step, a wind speed of 12m/s is used for the wind turbine. Once the code was implemented in the C block as described above, the delta values that adjust how much the system is perturbed, need to be adjusted.

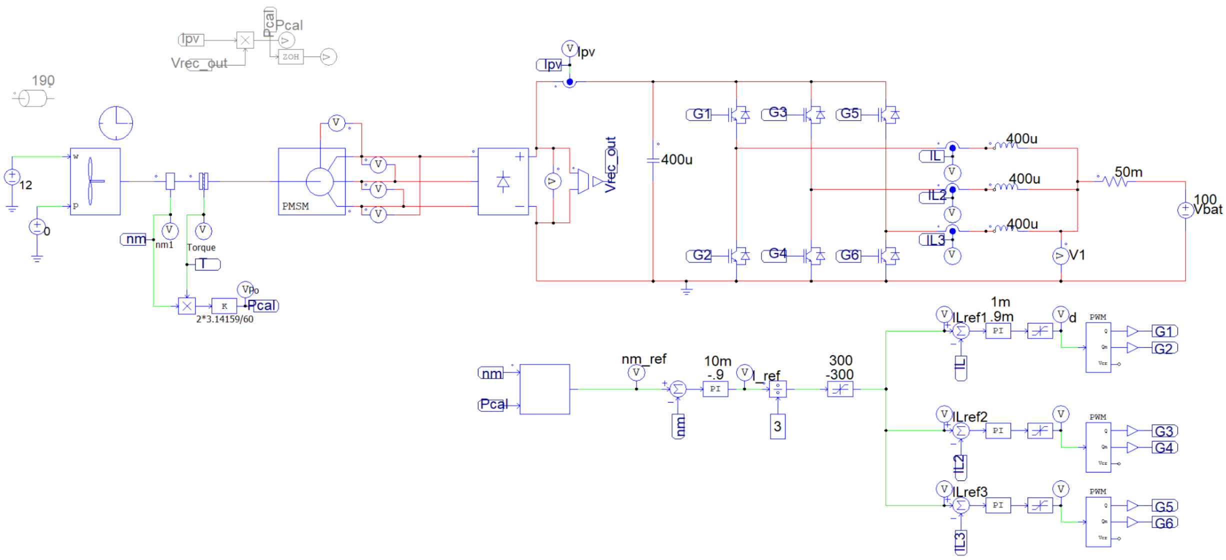

Figure 17: Schematic for MPPT Implementation

The plot in Figure 18 illustrates the result from using a delta value of 0.005. The power does not stabilize at the expected value of 19kW at all within 0.1s, so a new delta value was tried. It is also seen that the reference speed diverges, meaning the issue is likely with our code, rather than with our gain.

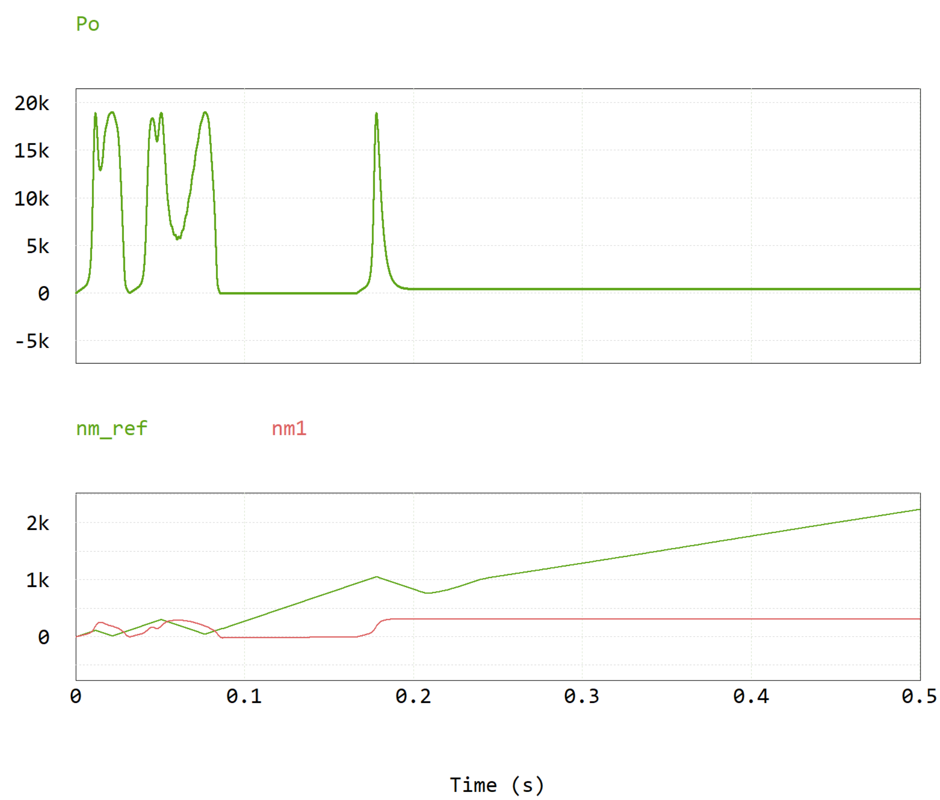

Figure 18: Output Power Results for Delta = 0.005

The negative delta value (corresponding to decreasing speed) is changed from 0.005 to -0.0005 and the positive delta value (corresponding to increasing speed) is kept at 0.005. The results from this simulation are displayed in Figure 19, which was initially run at 0.1s, so the running time would not take too long, but an improvement is already visible in that the power does not decrease to 0W.

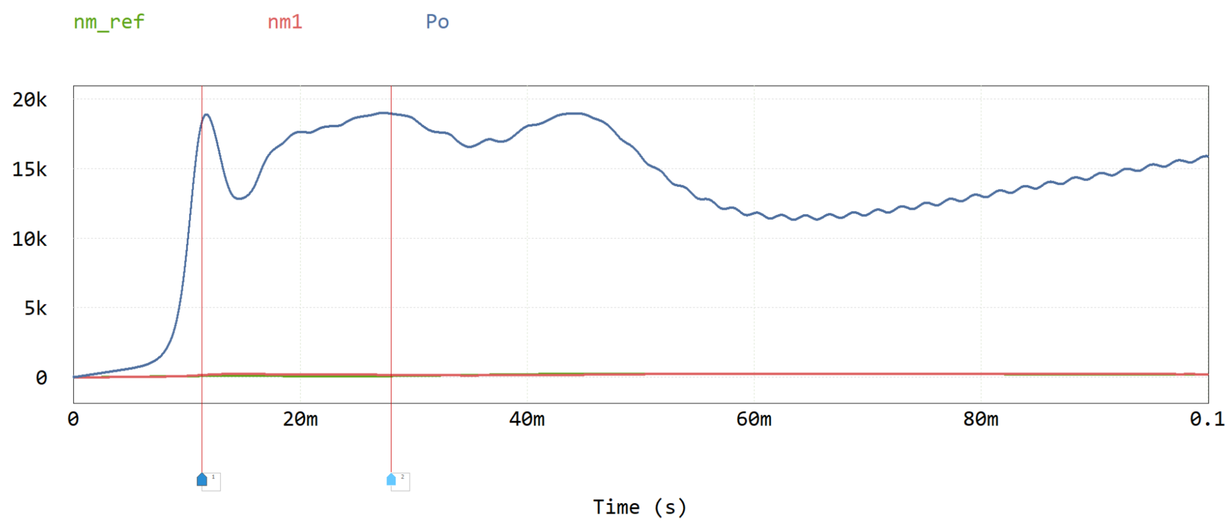

Figure 19: Output Power Results for Negative Delta: -0.0005, Positive Delta: 0.005

The plot in Figure 20 shows the same simulation run for 0.2s showing that these delta values do allow the system to stabilize at the goal power of 19kW. Aiming for a quicker stabilization time, more simulations were run.

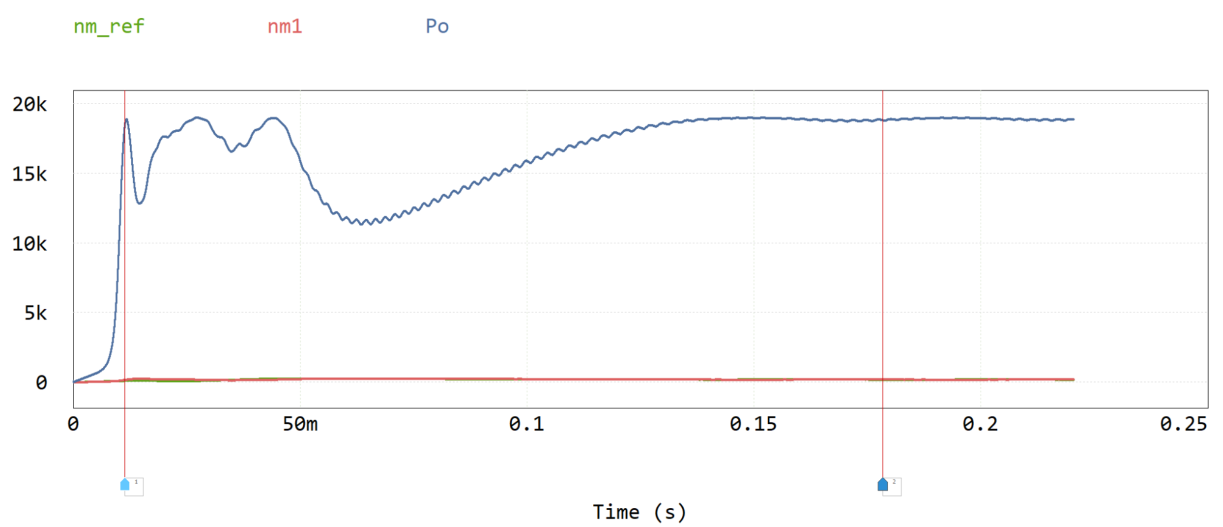

Figure 20: Output Power Results for Negative Delta: -0.0005, Positive Delta: 0.005 (Same as above, but run for more time to show longer term results)

Figure 21 shows the results for the next delta values used (Negative Delta: -0.00005, Positive Delta: 0.005). The negative delta was decreased with the goal removing the steep drop at around 50ms. As seen in the result, this did not work and the system does not stabilize at all in the given time and diverges from the intended value of 19kW. The reference speed is incorrect here as well and consistently increasing.

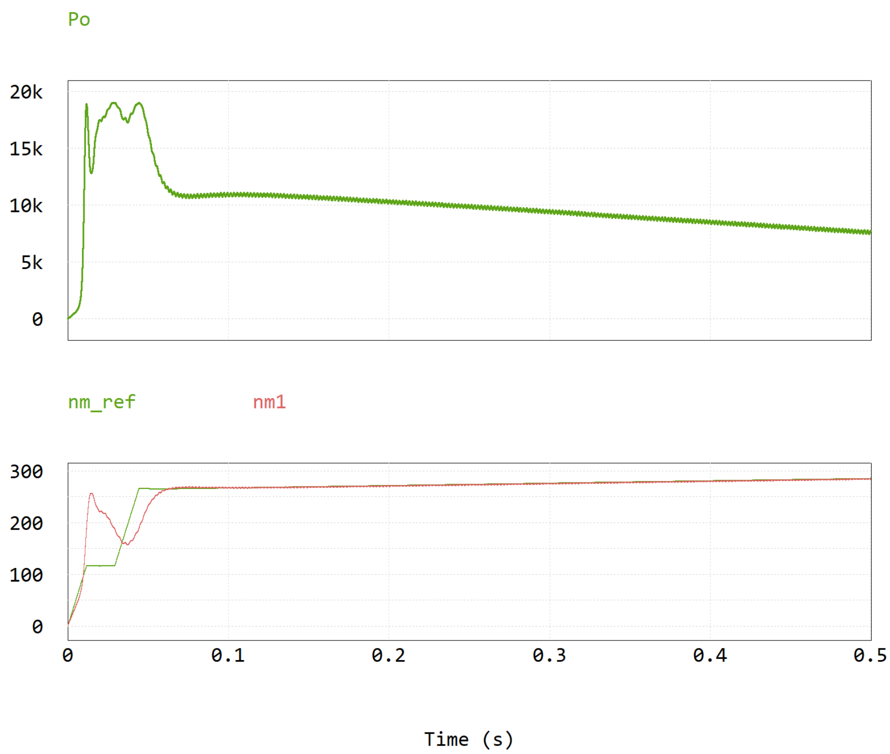

Figure 21: Output Power Results for Negative Delta: -0.00005, Positive Delta: 0.005

Following this, the decision was to have the negative delta (absolute value) decreased from 0.0005 and increased from 0.00005 to find a midway point. Using these new values (Negative Delta: -0.0002, Positive Delt: 0.005) the results shown in Figure 22 were found, where it is seen that the power stabilizes at 19kW and takes about 0.3s. This was an increase from the stabilization time in a previous result, so the previous result was retested to verify that it was the most efficient.

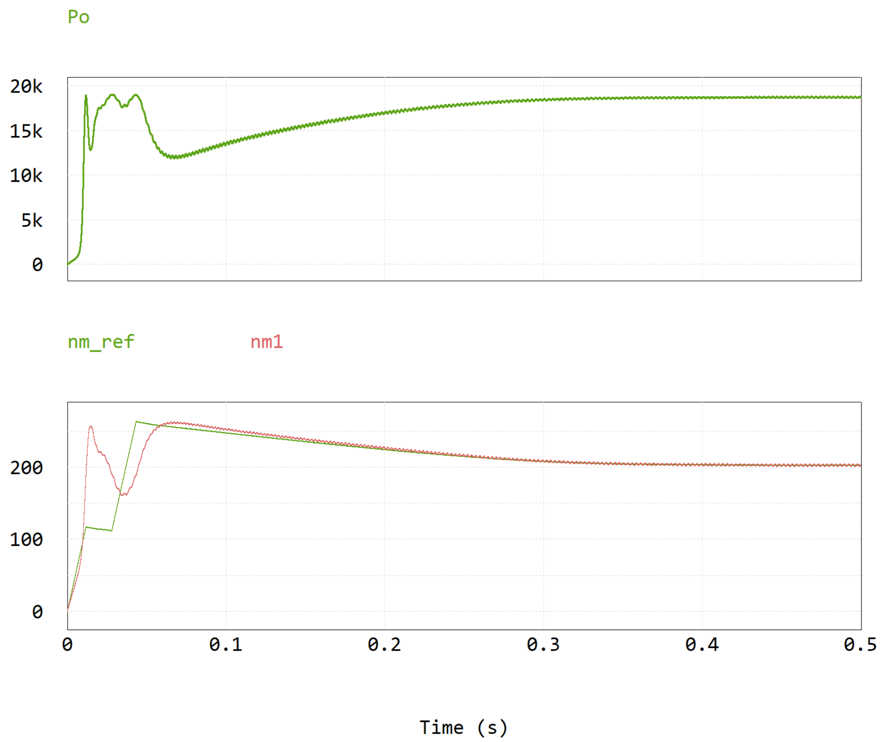

Figure 22: Output Power Results for Negative Delta: -0.0002, Positive Delta: 0.005

The results in Figure 23 show the retested results (Negative Delta: -0.0005, Positive Delta: 0.005) with the system stabilizing correctly at 19kW in about 0.15s. This resulted in the decision to keep these delta values for this stage and begin the next stage of changing the speed from 12m/s to 8m/s.

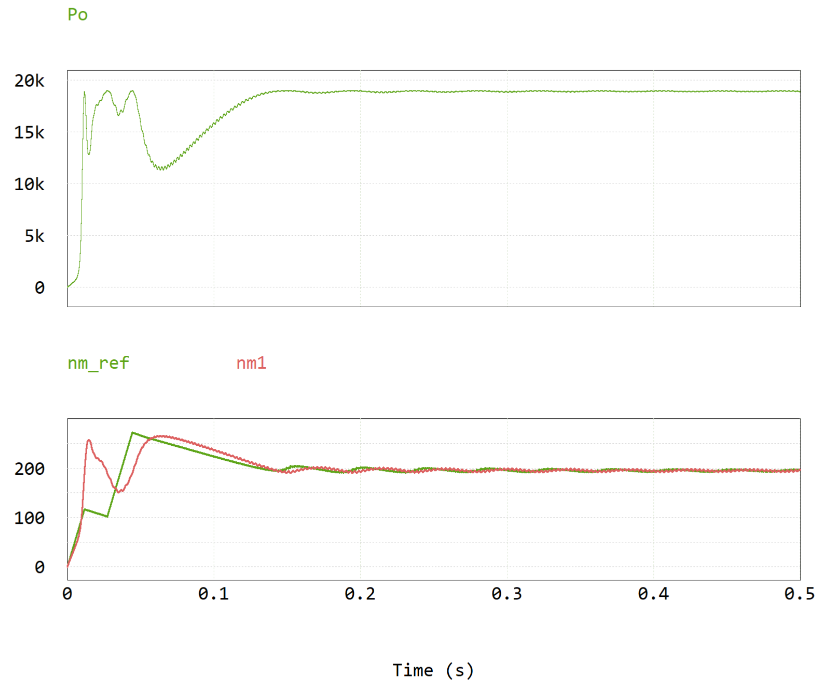

Figure 23: Output Power and Speed Results for Negative Delta: -0.0005, Positive Delta: 0.005

<u>Change speed from 12m/s to 8m/s:</u>

The next step was to test the MPPT when changing the wind speed from 12m/s to 8m/s. First, the MPPT that was used in the previous step was tested with the new step input. The PSIM schematic was changed to have a step input that changes the speed from 12m/s to 8m/s rather than the constant speed input. The schematic for this update circuit is shown in Figure 24.

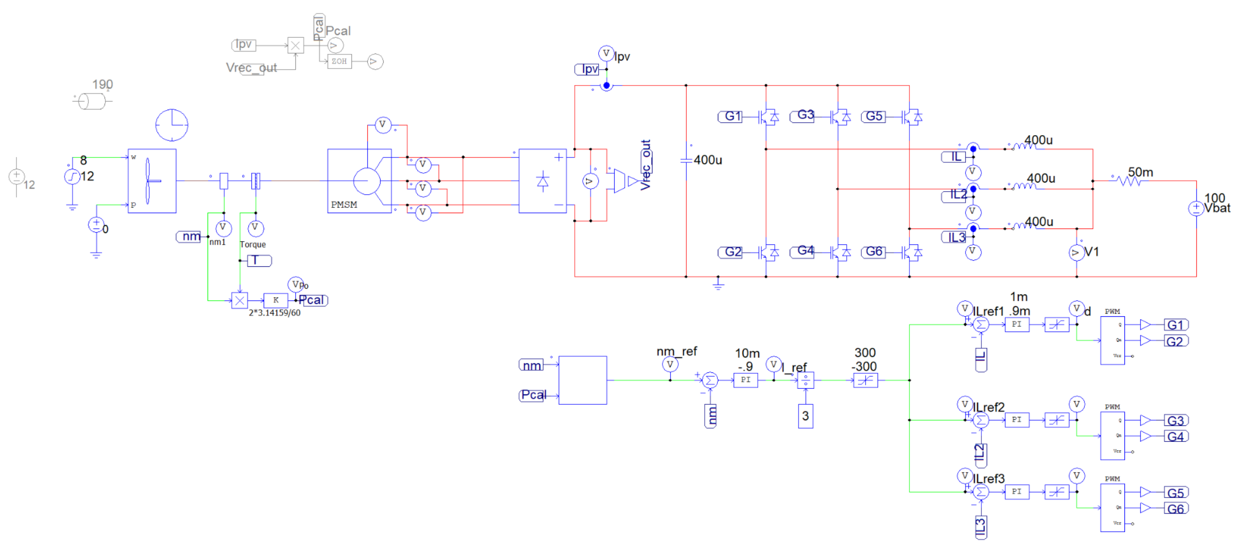

Figure 24: Schematic for MPPT Verification with Changing Input Speed from 12m/s to 8m/s

This resulted in the plot in Figure 25 where the power oscillates greatly around the goal speed of 5.6kW. This is not ideal because the aim is to have the system with less oscillations at the goal power. The speed was still being tracked relatively well, although the speed changed many times as shown in Figure 26.

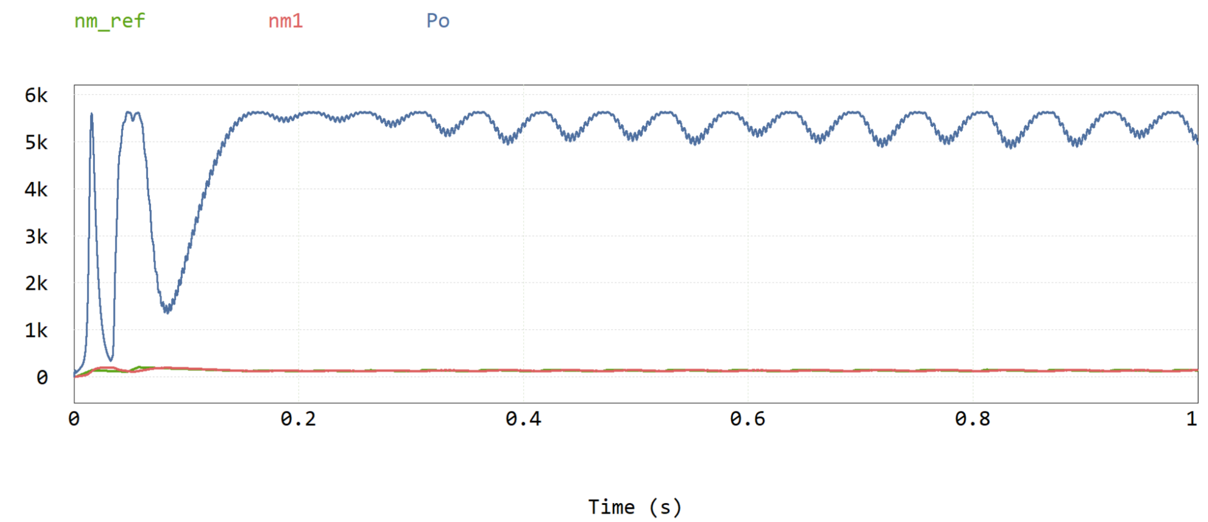

Figure 25: Power Output with Negative Delta: -0.0005, Positive Delta: 0.005

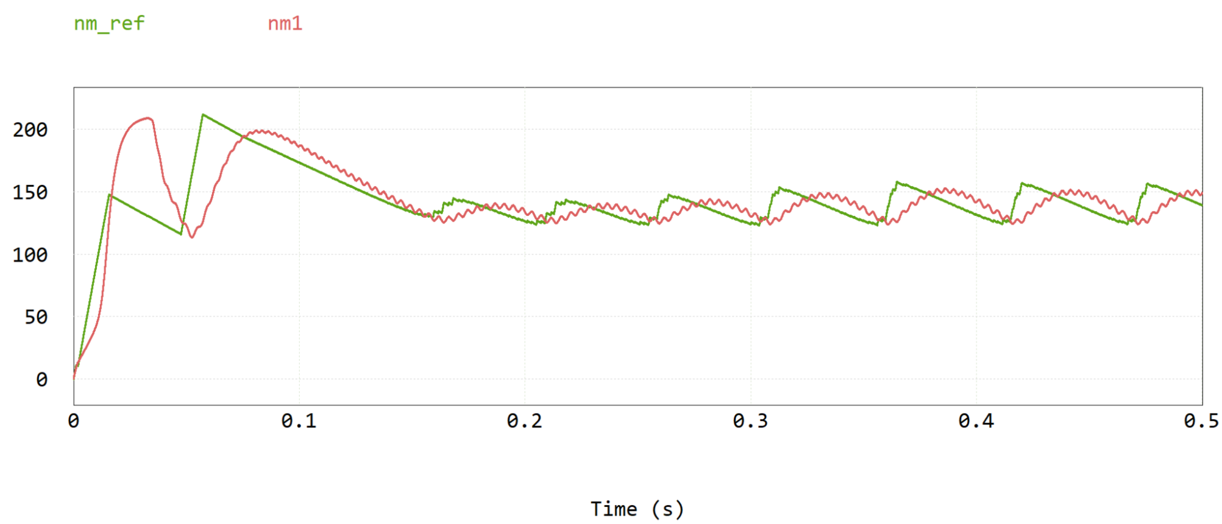

Figure 26: Measured Speed and Reference Speed with Negative Delta: -0.0005, Positive Delta: 0.005

The delta values were adjusted to attempt to get rid of the oscillations in power. The negative delta value was changed to -0.0002, so the decrease would not be as drastic and the result is displayed in Figure 27. The speed shows one step and then settles at around 130 rad/sec as expected from earlier simulations for turbine characteristics.

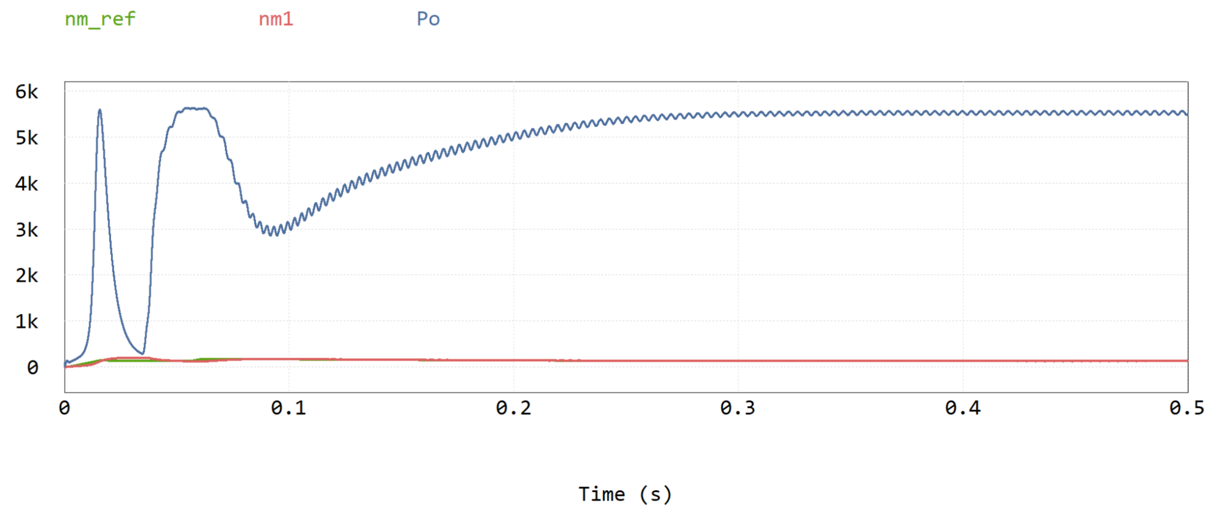

Figure 27: Power Output with Negative Delta: -0.0002, Positive Delta: 0.005

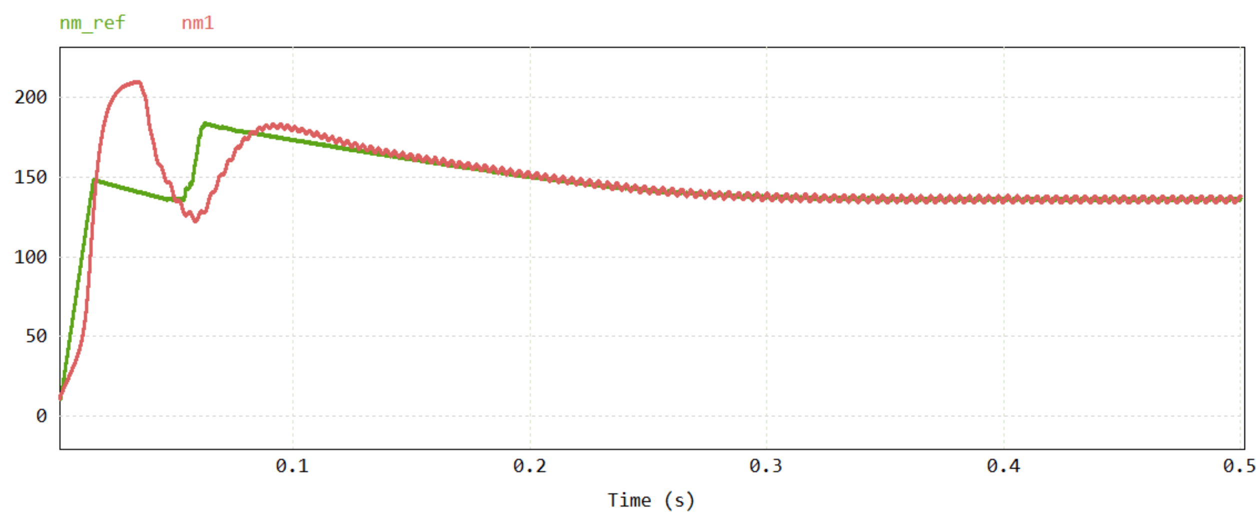

Figure 28: Measured Speed and Reference Speed with Negative Delta: -0.0002, Positive Delta: 0.005

Near Zero Implementation

In the C block logic for MPPT, a smart feature was added. In the previous logic, if change in power was equal to 0, no delta changes would be made. Now with the new smart logic, if the change in power is a value small enough, the MPPT will consider that to be 0 (Figure 37 CODE, Line 29). This was done in order to minimize pulsing at the peak power level. The "small enough" value chosen was **0.02** (Figure 37 CODE, Line 24). In order for the MPPT system to make positive and negative delta changes, the absolute value of the change in power must be greater than 0.02.

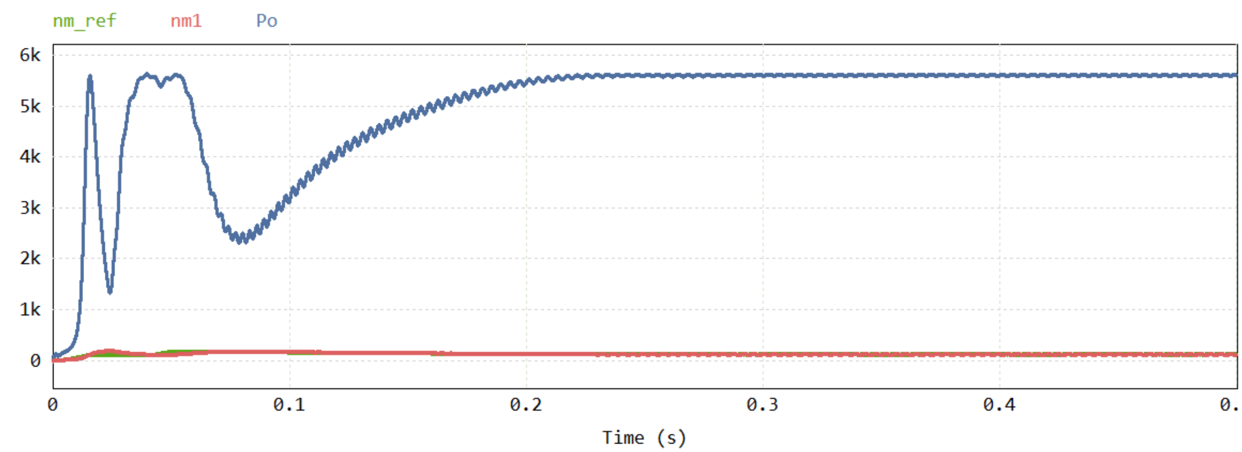

Figure 29: Measured Speed and Reference Speed with Negative Delta: -0.0002, Positive Delta: 0.005 (with Near-Zero Implementation)

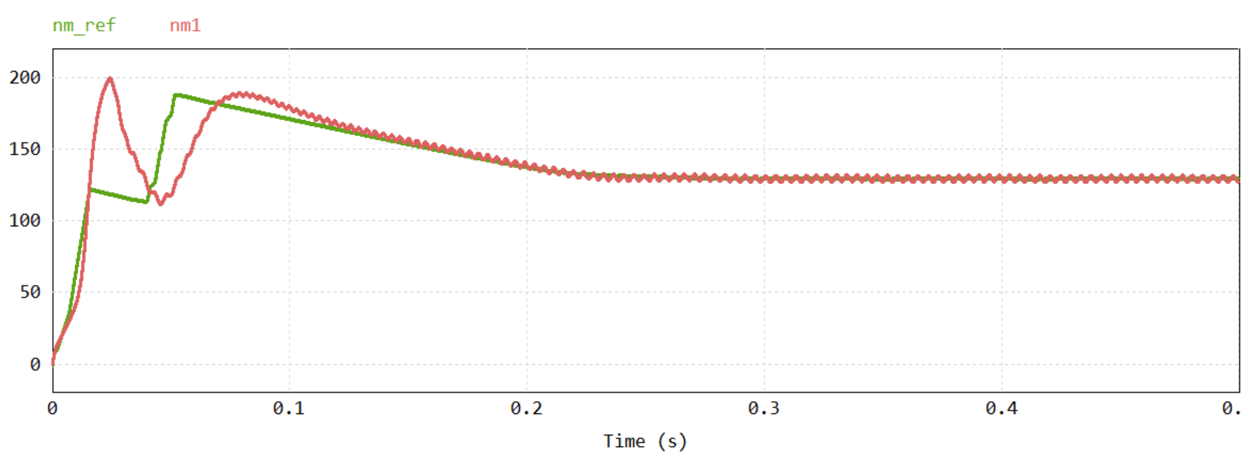

Figure 30: Measured Speed and Reference Speed with Negative Delta: -0.0002, Positive Delta: 0.005 (with Near-Zero Implementation)

With this extra feature, it is observed that power at peak is smoother with smaller ripples (Figure 29) than the larger ripples observed before (Figure 27).

It is also observed that the power output approaches peak power faster than before.

Table 1: Before and After Near Zero Implementation with Same Delta Values

	Before Near Zero Implementation	With Near Zero Implementation
Positive Delta Value	0.005	0.005
Negative Delta Value	-0.0002	-0.0002
Peak Power Approach	0.3 (Figure 27)	0.22 (Figure 29)
Peak Power Rippling	Larger and more jagged ripples	Smaller and smoother ripples

Continuing to optimize the MPPT system, additional delta changes were made. The goal was to remove the second power spike and allow the system to reach peak power and become stable in less time.

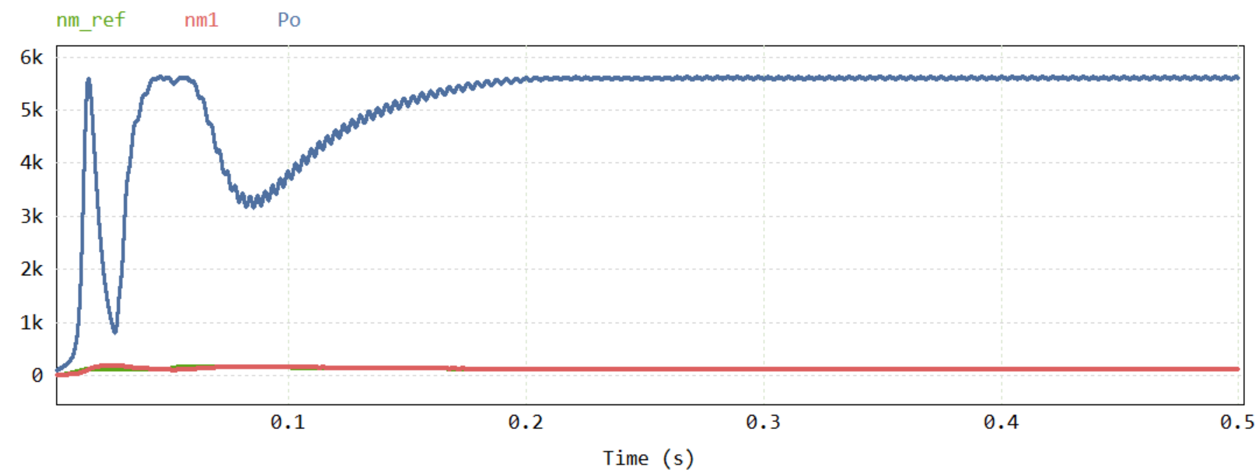

Figure 31: Power Output with Negative Delta: -0.0002, Positive Delta: 0.0055 (with Near-Zero Implementation)

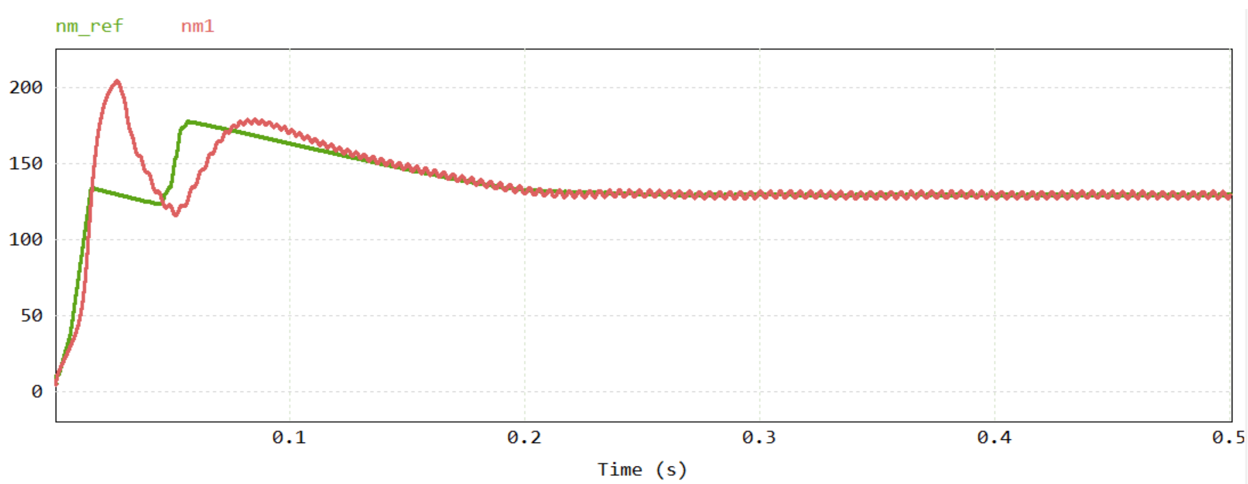

Figure 32: Measured Speed and Reference Speed with Negative Delta: -0.0002, Positive Delta: 0.0055 (with Near-Zero Implementation)

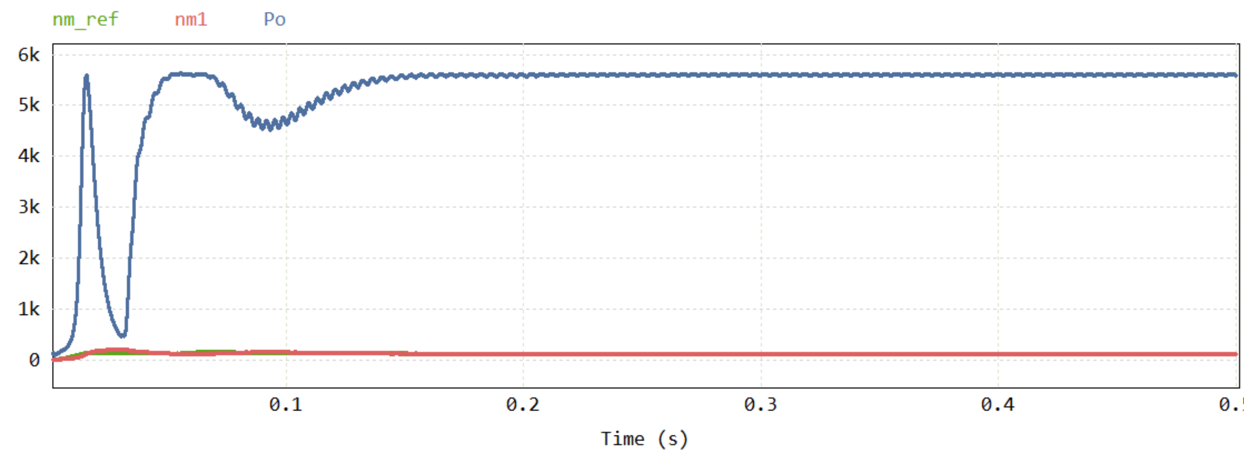

Figure 33: Power Output with Negative Delta: -0.0002, Positive Delta: 0.006 (with Near-Zero Implementation)

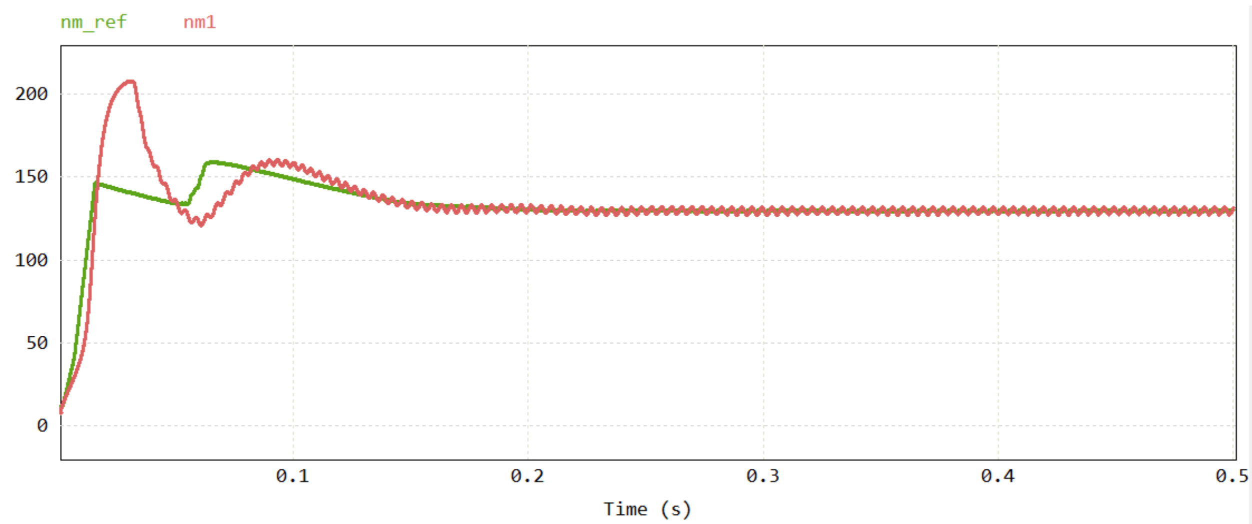

Figure 34: Measured Speed and Reference Speed with Negative Delta: -0.0002, Positive Delta: 0.006 (with Near-Zero Implementation)

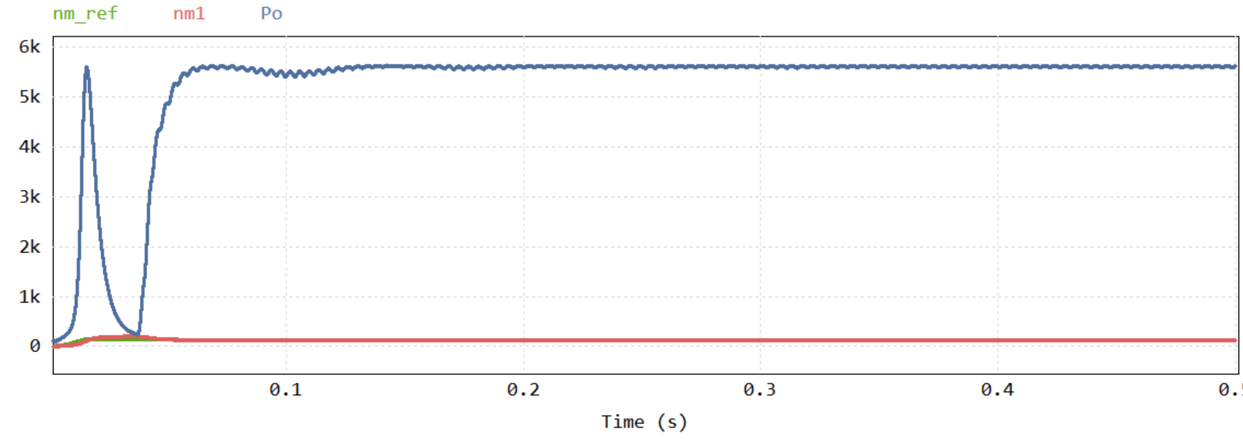

Figure 35: Power Output with Negative Delta: -0.0002, Positive Delta: 0.0065 (with Near-Zero Implementation)

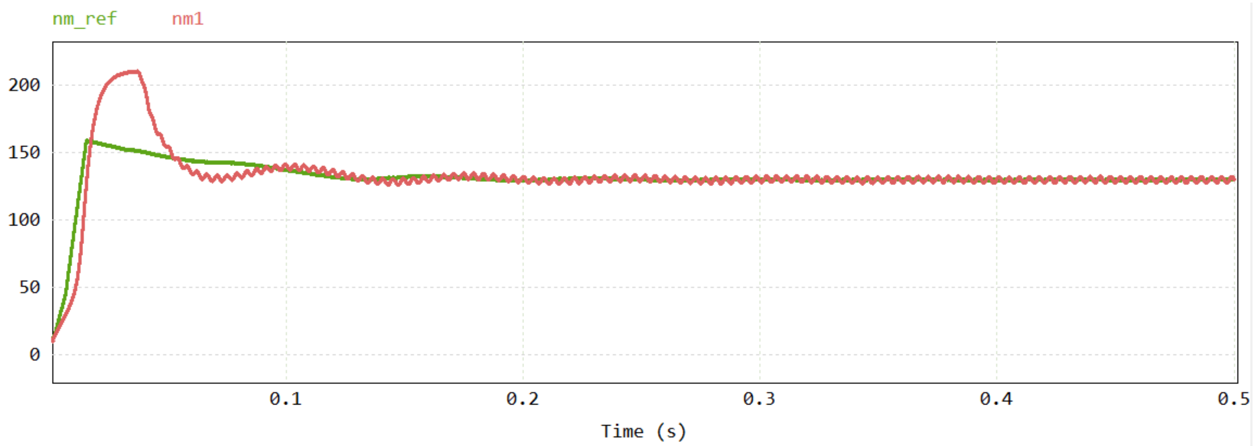

Figure 36: Measured Speed and Reference Speed with Negative Delta: -0.0002, Positive Delta: 0.0065 (with Near-Zero Implementation)

Results of MPPT optimization: After implementing the smart system (Near-Zero Implementation) and adjusting delta values, a few positive aspects are observed in system power output.

1. Faster Peak Power Approach:
    a. Previously, it took approximately 0.3 seconds to reach peak power (Figure 27)
    b. Now, it takes approximately only 0.06 seconds to reach peak power (Figure 35)
2. Less Power Spikes:
    a. Previously, two large power spikes were observed (Figure 27)
    b. Now, one large power spike is observed (Figure 35)
3. Less Peak Power Rippling:
    a. Previously, peak power had larger and more jagged/sharp ripples (Figure 27)
    b. Now, peak power has smaller and smoother ripples (Figure 35)

Table 2: Before and After Near Zero Implementation with Optimized Delta Values

	Before Near Zero Implementation	With Near Zero Implementation
Positive Delta Value	0.005	0.0065
Negative Delta Value	-0.0002	-0.0002
Peak Power Approach	0.3	0.06
Number of Power Spikes	2	1
Peak Power Rippling	Larger and more jagged ripples	Smaller and smoother ripples

It's worthy to note that the second power spike is still slightly apparent, as seen by the small dip at 0.1s in Figure 35. One of the goals of this optimization was to smoothen the power ramp-up enough, to the point of being able to consider it "removed."

Conclusion

The implementation of speed control and maximum power point tracking (MPPT) were successfully carried out for a wind turbine using a three leg interleaved buck-boost converter and a permanent magnet synchronous motor. The system was tested at different input speeds and perturbation delta values, and the results were analyzed to optimize the performance of the system. The simulation results for speed control implementation showed that a gain value of -0.9 was able to reduce the stabilization time to about 0.4 seconds while reducing the subsequent peaks by about 25W compared to a gain of -0.4. This indicates that the system can be optimized to reduce the stabilization time while maintaining a stable output. For MPPT implementation, the results showed that the initial delta value of 0.005 did not allow the system to stabilize at the expected power of 19 kW within 0.1 seconds. However, by changing the negative delta value to -0.0005, the system was able to stabilize at the goal power of 19 kW within 0.2 seconds. This suggests that the system can be further optimized by adjusting the delta values to achieve faster stabilization times. Overall, the successful implementation of speed control and MPPT for a wind turbine using a three leg interleaved buck-boost converter and a permanent magnet synchronous motor is a significant achievement. The system can be further optimized to achieve better performance and efficiency, making it a promising solution for wind power generation.

Appendix

```c
//MPPT algorithim
//Initialize values
static double nm;
static double nm_old;
static double nm_ref;
static double nm_delta;
static double Pcal;
static double Pcal_old;
static double Pdelta;
// Probe
nm = x1; // Input 0 = Vov
Pcal = x2; // input 1 = Ipv

//Ppv = Vpv * Ipv; // Calculate New power output
Pdelta = Pcal - Pcal_old; // Power Delta

// New Voltage Probed - Old Voltage Probed
nm_delta = nm - nm_old;

//MPPT Algorithm with Near-Zero implimentation
//if Pdelta is between range/threshold small enough to consider it 0 (to lessen zig zag at peak level)
// if Pdelta is between 'nearzero' and negative 'nearzero', then consider that closer enough to be 0

double nearzero = 0.02; // initialize neazero.
// A larger 'nearzero' means more range/threshold around 0 is considered to be 0.
// A smaller 'nearzero' means less range/threshold around 0 is considered to be 0.

// Cond 1: Change in power is 0 or extremely close to 0. No changes made.
if (Pdelta<nearzero && Pdelta >-1*nearzero){
    return;}

// Cond 2: Change in power is positive beyond near-zoro range/threshold. Changed will be made.
else if (Pdelta > 0){
    if(nm_delta > 0){ // Condition 2.1: Change in speed is positive
        nm_ref = nm_ref + 0.0065;}
    else // Condition 2.2: Change in speed is 0 or negative
        nm_ref = nm_ref - 0.0002;}

// Cond 3: Change in power is negative beyond near-zoro range/threshold. Changed will be made.
else if (Pdelta < 0){
    if(nm_delta < 0){ // Condition 3.1: Change in speed is negative
        nm_ref = nm_ref + 0.0065;}
    else // Condition 3.2: Change in speed is 0 or positive
        nm_ref = nm_ref - 0.0002;}

Pcal_old = Pcal; // Save current power for next step
nm_old = nm; // Save current speed for next step

y1=nm_ref; // Output
```

Figure 37: MPPT PSIM Code for C Block