ECE 128B Power Grid Modernization

Project Phase 2: Wind Turbine System with MPPT Algorithm

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Introduction

Wind power plays an important role in the development of scalable renewable energy. Specifically in the United States wind energy increased from (9 to 48 GW) according to “Energy Information Administration”. One of the biggest problems faced with wind power is the variance in the wind speed. The unpredictability of wind power limits optimal locations of where wind turbines can be built. This unpredictability makes it difficult to rely on as a reliable source on its own. Battery technologies are the key to maximizing wind power as it allows for the storing of wind power and then that power can be used when needed. The variance in wind speed leads to another problem: maximizing power. Capturing wind power builds on the Bernoulli’s Principle (velocity of a fluid is inversely proportional to pressure) to create a lift force. The formula for the amount of energy captured from wind power can be derived from the kinetic energy where A is the sweep area, δ is the air density and w is the wind speed:

$$P_{wind} = \frac{1}{2}A\delta w^3$$

Therefore, changing the sweep area of the wind allows for changing the amount of energy captured. This can be done by changing the angle of attack which affects the amount of lift. This will not be utilized in this project however it is a degree of control to consider. Additionally, this equation shows that it is much more economical to build wind power farms where high speed is common. Furthermore, the maximum amount of theoretical energy that can be extracted from a stream is 59% known as the Betz Limit. There are additional losses in the rotating blades, the gearbox, and the generator that converts mechanical to electric energy. The following equation relates the mechanical torque by the wind turbine and the electric torque by the generator with the moment of inertia J of the rotating blades and the angular speed of the blade's shaft.

$$T_m - T_e = J\frac{dw}{dt}$$

The reason why it's necessary to control the angular speed is because wind turbines have a cutoff speed at which the turbine must shut down to prevent mechanical damage. In this project, the speed of the turbine is controlled using MPPT that is captured by a generator. The generator provides a diode rectified DC signal to the Buck-boost converter discussed in project 1. The purpose of the Buck-boost converter is to step down the voltage while increasing the current provided to a battery. One of the challenges faced when developing a MPPT algorithm is that the control variable (in this case the speed in rad/s) needs to be changed by a large enough number to see a change in the power. If the step is too small, then the small oscillatory behavior of the system will make it difficult for the speed to converge at the maximum power point. Conversely, making too large a step leads to oscillations around the maximum power point while also making it take longer for the system to react to the previous input in time. For example, oscillations caused by the transient response of a time step needs to settle before deciding on how to change the control variable. Sampling frequency and step size both play an important role in how long it takes before it can be determined whether the previous step actually increased or decreased the power.

Problem Definition

In this phase of the project, the aim is to maximize the power of a wind turbine which is inputted to a permanent magnet generator for different wind speeds (specifically from 12m/s to 8m/s). Firstly, a wind turbine circuit should be built to measure and plot the power vs the angular speed for different wind speeds. The power of the wind turbine in this system can be calculated by multiplying the angular speed by the torque. It is important to keep in mind that the speed sensors in PSIM measure in rpm and should be converted to rad/s when generating the graphs. These plots can be used to see which value of angular speed, for each of the wind speeds, results in the highest power. When applying the MPPT, these values can be used as a reference to confirm it is working properly. Additionally, this information can be used to properly limit the speed within the speed controller. Before applying the MPPT block to the control system, the speed controller can be tested by using a constant torque and then by using a step voltage. The wind turbine system to be built includes a wind turbine connected to a 3-phase permanent magnet generator which has its output rectified and then captured by a buck-boost converter. The magnet generator is used to convert the mechanical output of the wind turbine into electrical power. After that, the 3-phase diode rectifier converts three AC waveforms into one DC waveform. This is fed to the buck-boost converter from phase 1 which can raise the current to the battery while stepping down the voltage. Once this wind turbine system is verified with the current control system, the MPPT block can be added. The MPPT algorithm is employed similarly to phase 1 but for angular speed as opposed to voltage. The MPPT algorithm from phase 1 can be used but the angular speed step, the increment that the speed gets changed every time, has to be picked properly. If it is chosen too small, the power of the wind turbine won't change enough to be noted. If it is chosen too large, an incorrect maximum power might be calculated.

Solution

First, the buck boost converter with the current and voltage control from phase 1 is used. The development of the buck boost converter started with controlling the current of a single leg. The reference current is fixed to constants (for example 20A but several different currents are tested to verify correctness) and then finds the difference between that reference current and the actual load current through the inductor. This value is then fed into a PI controller which is then sent through a limiter and then into PWM duty cycle. The limits of the duty cycle are 0 and 1. The next step is to experiment with different time constants and gains for the PI block. Gains that cause the output to hit the limits (values larger than 1 in this case), cause oscillation and are hard to control. Additionally, the time constant needs to be large enough for current to converge in a reasonable amount of time. Once the current controller is verified using variable current references, the same methodology is then applied to creating the voltage controller with constant voltage references. The main theme is that each base component is first tested and verified before adding new parts to the system. This allows for much easier debugging and realizing what part of the system actually needed to be adjusted. The voltage controller time constant is 10x that of the current controller. This is due to the voltage controller needing to wait for the current controller to reach steady state for that particular input. As explained in phase 1, the three current legs have a phase offset of 0, 120, and 240 degrees respectively to reduce oscillations. For phase 2, the buck boost converter and the current controllers are reused however the voltage controller is replaced with a speed controller.

The first step of developing the wind turbine system is to first find the characteristic curve of the power versus angular speed for wind speeds of 8m/s, 12m/s, and 16m/s respectively. The testing is done using a modified “Wind Turbine Output Power vs Rotation Speed” example from PSIM. The test is performed by using a step voltage source used as a load. This creates the varying angular speed values. The wind speed input is set to a constant. For 8m/s, the maximum achievable power is 5631W at an angular speed of 13.3 rad/s. For 12m/s, the maximum achievable power is 19004 at an angular speed of 19.9 rad/s. For 16m/s, the maximum achievable power is 45044W at an angular speed of 26.54 rad/s.

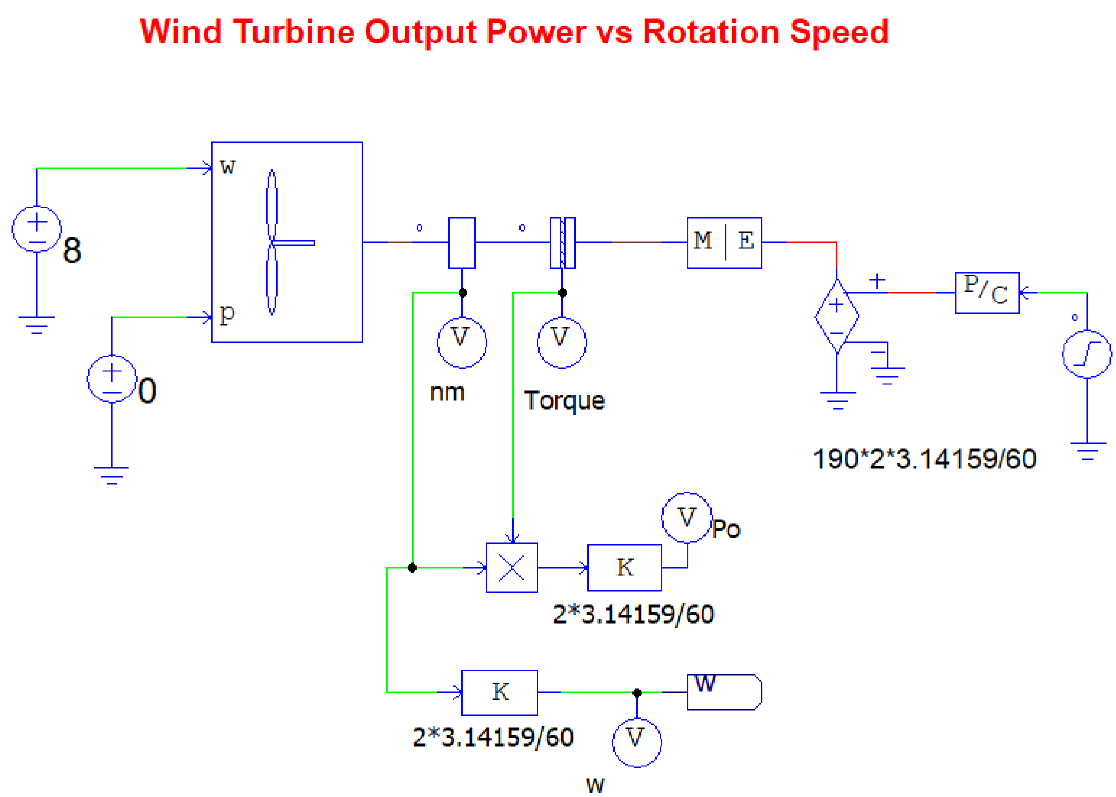

Figure 0: Wind Turbine Characteristic Test Circuit

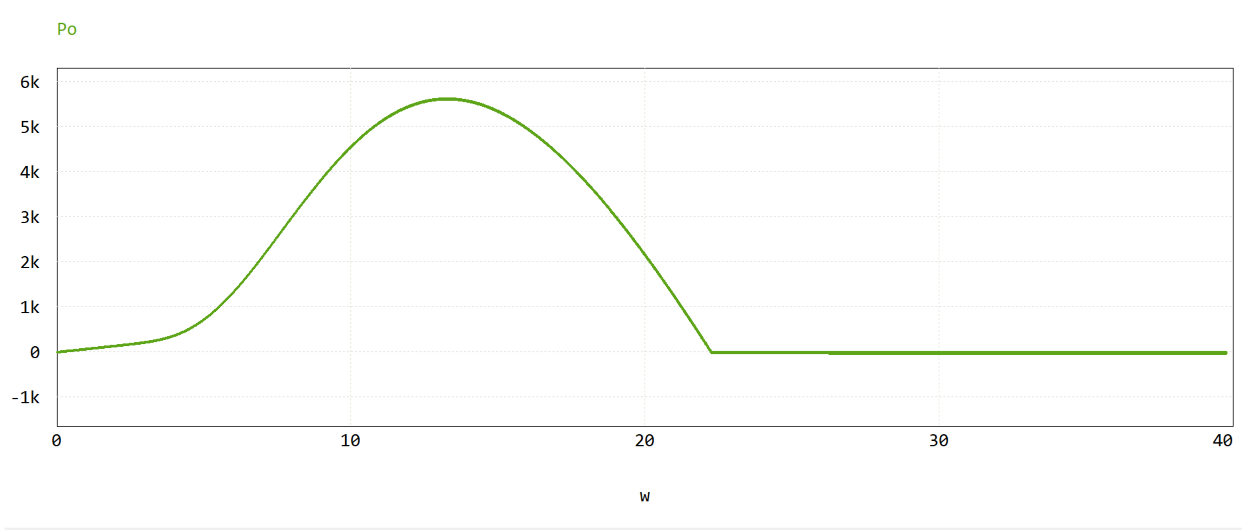

Figure 1: Wind Turbine Characteristic: Power (W) vs Angular Speed (rad/s), Wind Speed 8m/s

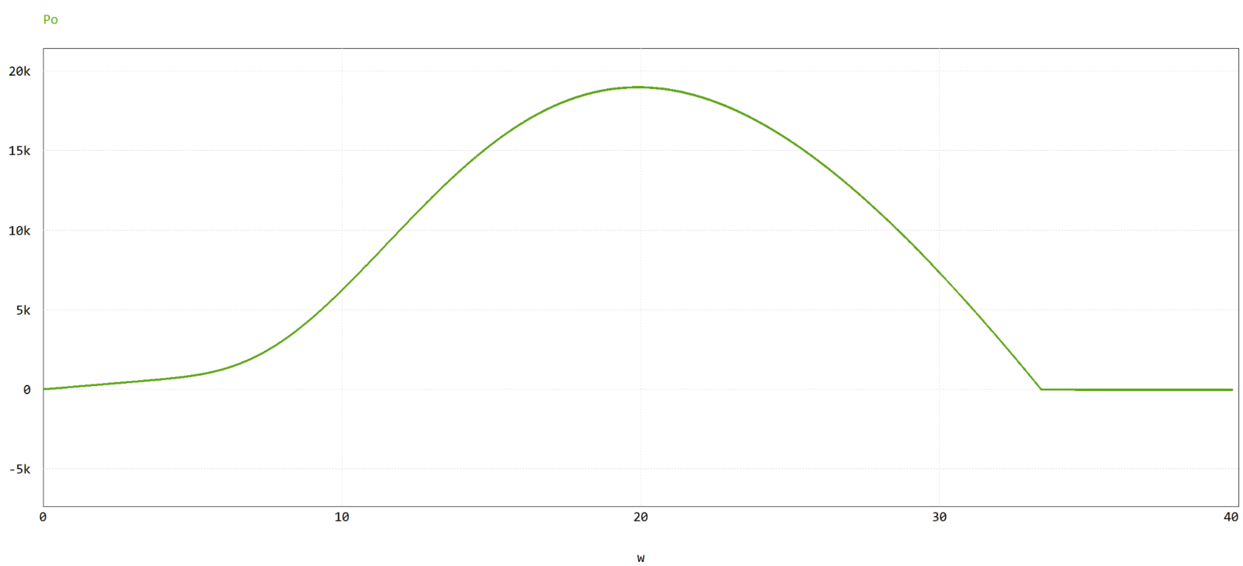

Figure 2: Wind Turbine Characteristic: Power (W) vs Angular Speed (rad/s), Wind Speed 12m/s

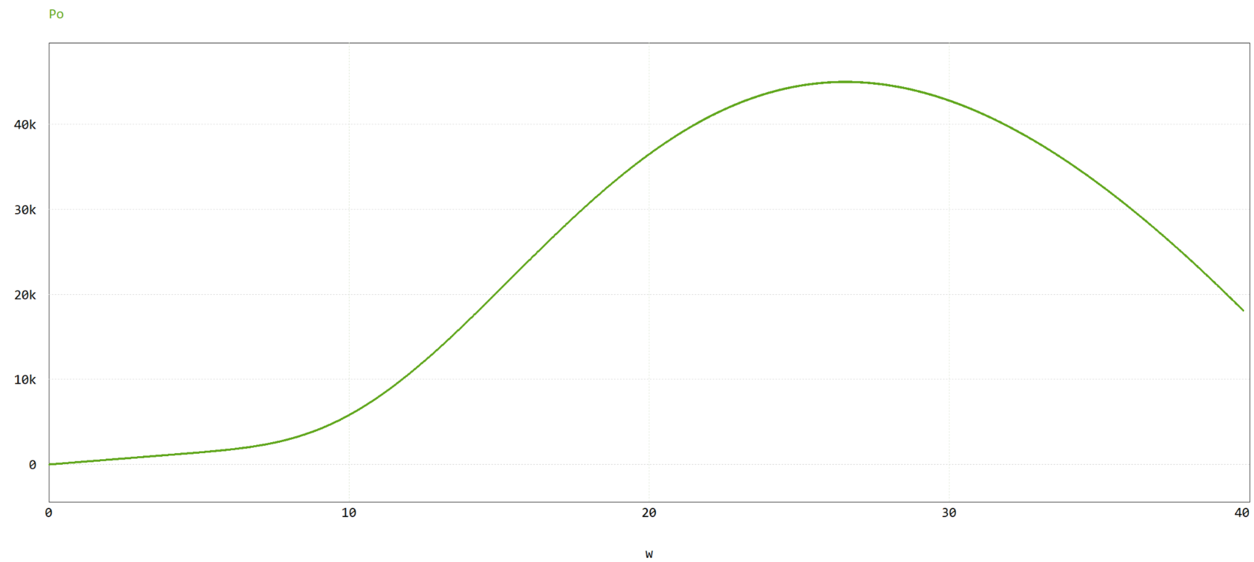

Figure 3: Wind Turbine Characteristic: Power (W) vs Angular Speed (rad/s), Wind Speed 16m/s

As mentioned in the introduction, power is proportional to w^3 which is consistent with the findings above. The reason why the power decreases as w increases is because of the cut-out speed of the wind turbine, causing the power to ramp down and eventually reach 0. Knowing the optimal power and working range of w values, it is possible to develop a speed controller. A requirement for the buck boost converter to work probably is the following equation where d is the duty cycle of S_{TOP}:

$$dV_{in} = I_o r_L + V_{out}$$

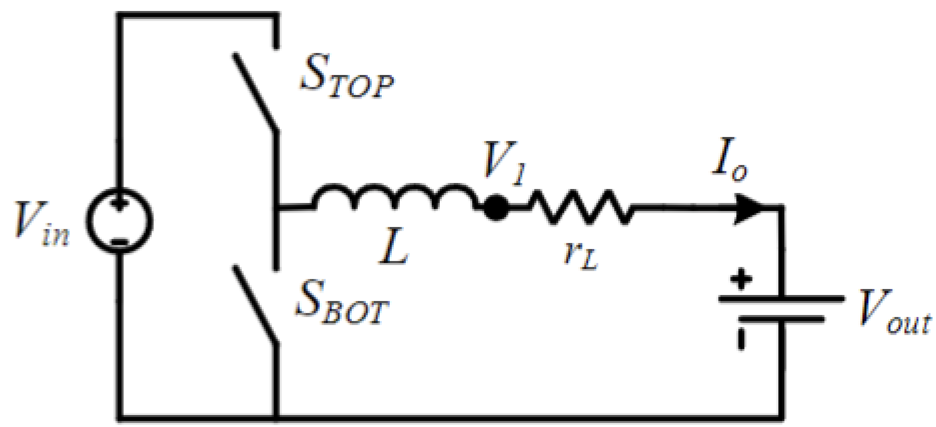

Figure 4: Buck-Boost Single-Leg

If dV_{in} drops below $I_o r_L + V_{out}$, then the buck-boost converter is no longer charging the battery of V_{out}. Found experimentally, if the V_{in} drops too low, the system becomes unstable and the speed of the turbine reaches 0. Then, the wind speed starts moving the turbine and the system reaches the reference w value. The output of the speed controller is limited between 175 and -250. The 175 value is critical for preventing the speed controller from overshooting the speed value which often causes the speed to drop to zero. The speed controller uses the same constant of 10x the current controller with a gain of -2.0. The reason why the speed is inversely proportional to the current is because of the torque equation described in the introduction. Increasing the current leads to an increase in electric torque. This then causes the turbine to decrease the angular speed. The speed controller first was tested with a constant torque generator. Once verified, the w_{ref} is driven by a step voltage that starts at 20 rad/s and ends at 13 rad/s. Additionally, the wind turbine in Figure 6 is driven by a step voltage that starts at 12m/s and ends at 8m/s. This is to simulate the behavior of power point tracking while isolating the speed controller from the actual MPPT block.

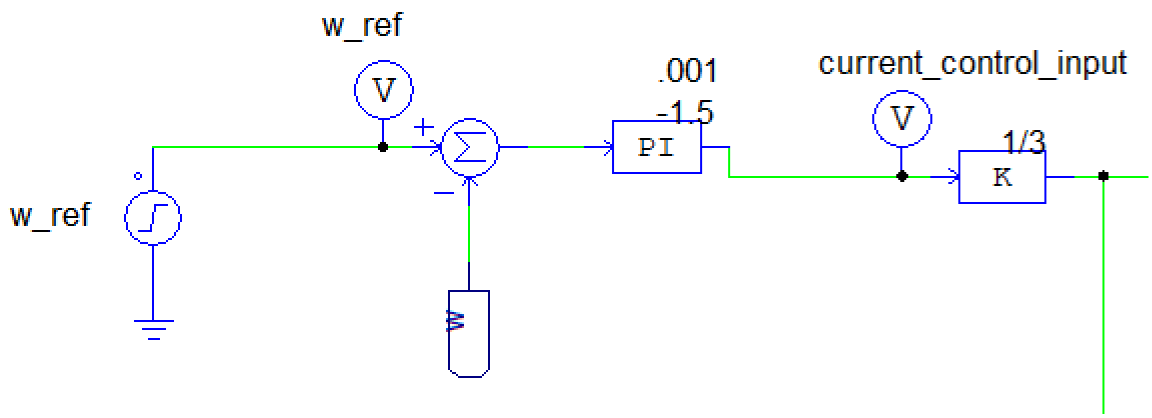

Figure 5: Speed Controller

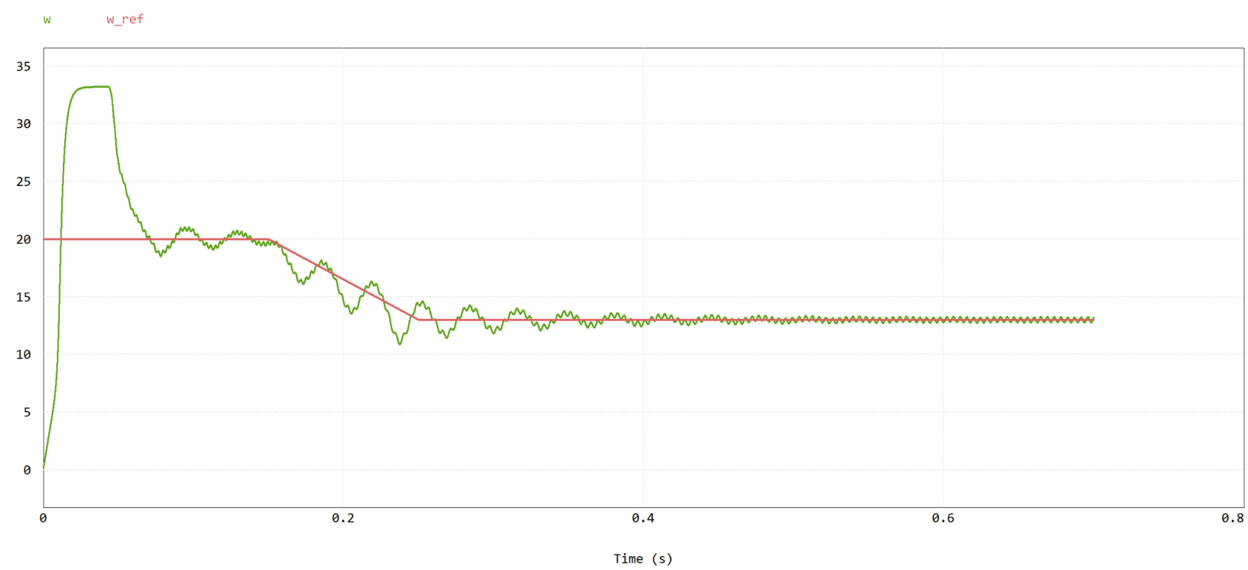

Figure 6: Verifying Control: W and W_{ref} versus Time

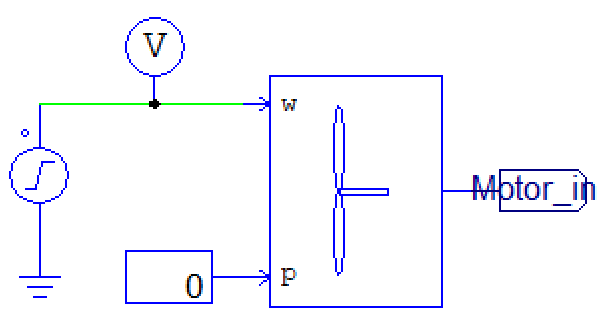

Figure 7: Wind Turbine

Next step is building a circuit that connects the wind turbine to the buck boost converter. The wind turbine is set as the master and the PMSM as the slave to mark the direction of positive torque. The output of the wind turbine is connected to a PMSM which is configured as a generator. The output of the PMSM is three AC signals which feed into a diode rectifier to create a clean DC signal seen in Figure 7. This voltage is then used to drive the boost-buck converter.

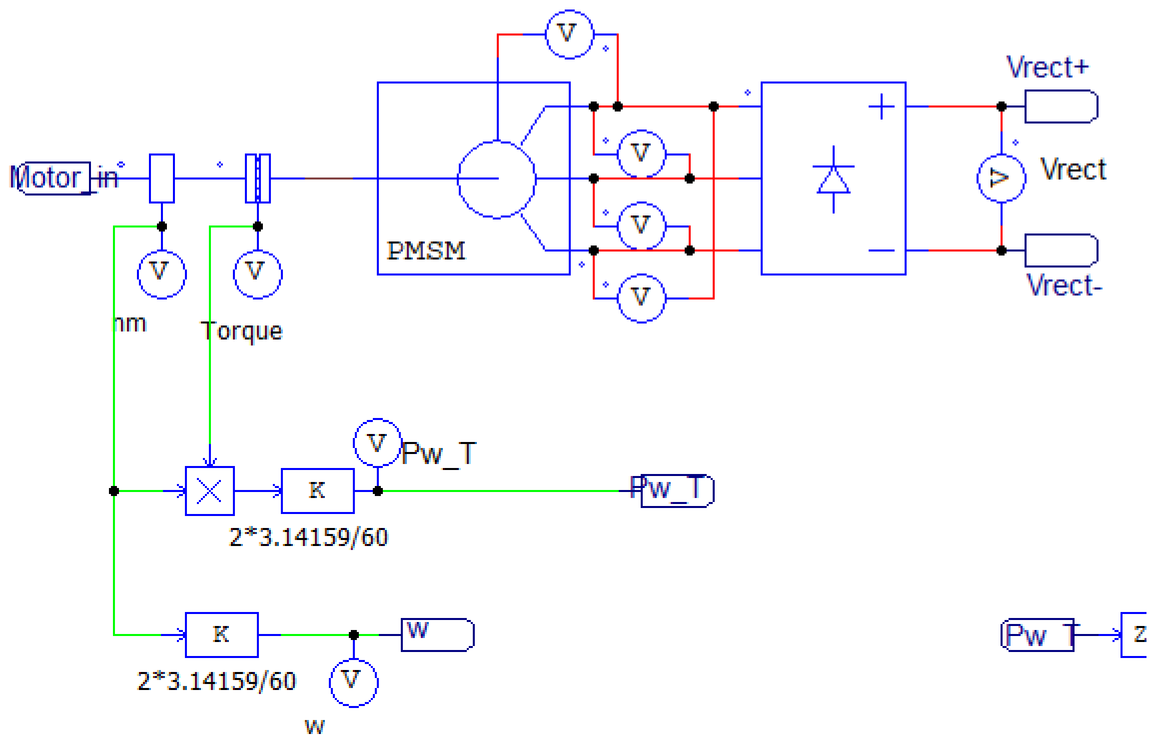

Figure 8: PMSM and 3-Phase Full Wave Diode Rectifier

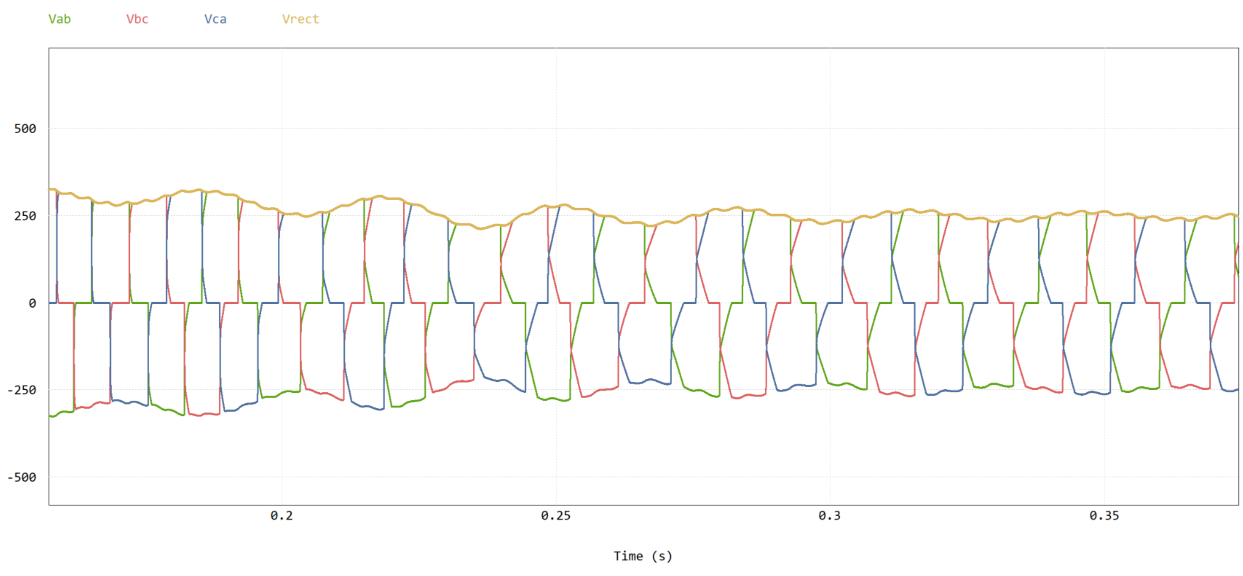

Figure 9: Diode Rectified Voltage

Finally once the speed controller is validated with the wind turbine the MPPT block drives w_{ref}. The MPPT block takes as inputs the power of the turbine and the current angular speed. Unlike phase 1, the power is obtained by measuring the torque and angular speed (converted to rad/s) from the output of the wind turbine. This power signal is much cleaner compared to using the input voltage and current of the buck boost converter, so it did not need to be filtered to be used by the MPPT. The MPPT algorithm used is the same one described in phase 1, with the voltage replaced with angular speed. The power and angular speed are sampled at a rate of 1000Hz. The step size of the angular speed is .25 rad/s. The output is then run through a running average sensor to clean up the oscillations. In practice, this increased the stability and helped the angular speed reach its maximum power point at steady state. In Figure 11, a test is run to confirm power point tracking of wind speed in steady state with a wind starting at 12 m/s and then decreasing to 8 m/s. The 12m/s wind reaches steady state after .3 seconds and 8 m/s after .35 seconds. It can be seen that the maximum power point converges to 19.994 rad/s with an oscillating range of .2 rad/s. The power measured at this point is 19007 W which is very close to the optimal 19004. The maximum power point for the 8 m/s wind converges to 5622 W (compared to the optimal 5631 W) at 13.4 rad/s with an oscillating range of .2 rad/s.

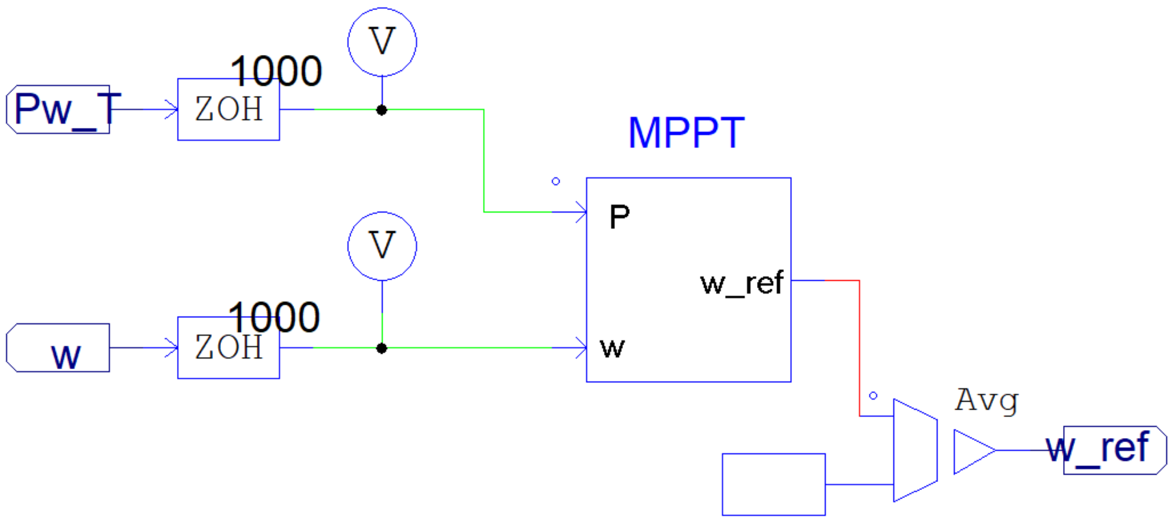

Figure 10: MPPT Unit

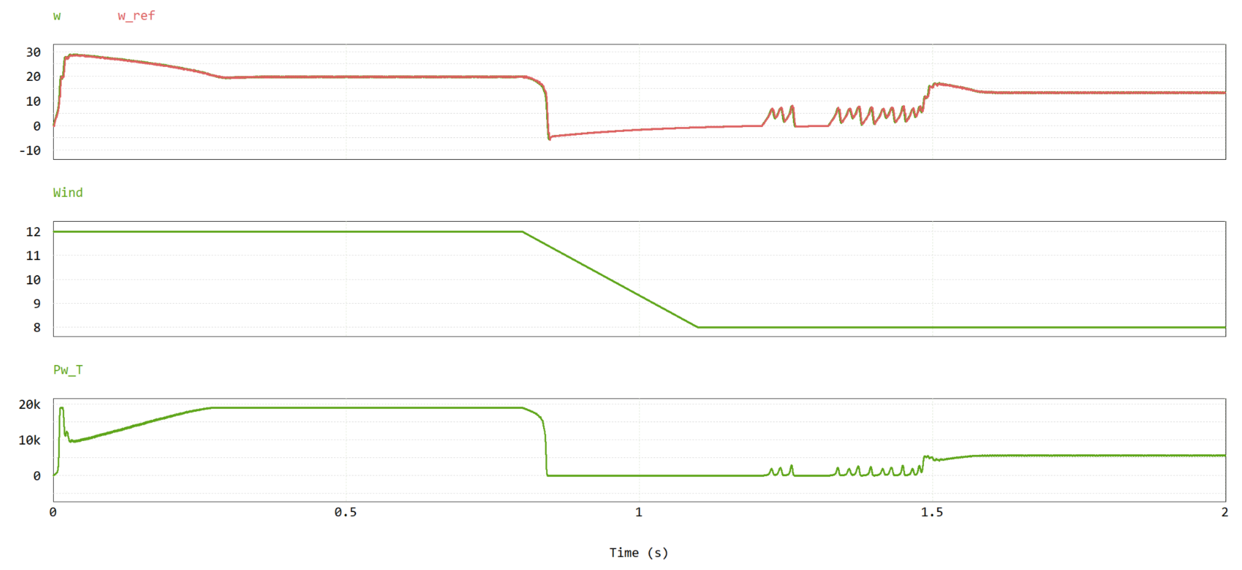

Figure 11: Power Point Tracking, Variable Wind

Conclusion

When plotting the relationship between power and angular speed, the maximum power and the angular speed at which it occurs were able to be determined. From Figures 1,2 and 3, the maximum power and its corresponding angular speed for wind speeds of 8, 12 and 16 m/s are shown. These angular speed values provided an indication later if the MPPT algorithm was working correctly. When applying a step voltage input to the speed control, the control system was adequately tested by simulating the behavior of the MPPT. As seen in Figure 6, the angular speed tracks the reference speed more accurately as time increases. The wind turbine system that is implemented has the wind turbine feed into a permanent magnet generator which has an output that gets rectified. This is shown in Figure 9. Finally, when applying the MPPT to the control system, the angular speed step size was chosen to be 0.25 seconds in order to achieve optimal tracking. In Figure 11, the wind speed changes from 12 m/s to 8 m/s and it can be seen that, for both speeds, steady state is reached in less than 0.4 seconds. Further, the maximum power values for 8 m/s and 12 m/s are relatively close to the expected values measured in the test circuit in Figure 0 (8 m/s: 19007 W compared to 19004 W, 12 m/s: 5622 W compared to 5631 W).