ECE 445 Design Document
Active AC-DC Converter for the Power Lab's Wind Turbine
Team #11
Fall 2018

By: Alec Biesterfeld (bstrfld2) , Tyler Rasmussen (trasmus2), Ben Scrementi (scremen2)
TA: Evan Widloski

October 4, 2018

1 Introduction

1.1 Objective

As the world races to reduce emissions and satisfy ever-increasing energy demands, one of the problems that continually persists is the challenge of storing renewable energy for times when the wind ceases to blow and the sun does not shine. Many solutions for storing excess energy on the current electric grid have been proposed and even tested such as compressed air storage, pumped storage dams, and giant batteries; yet, these technologies have failed to be adopted on a large scale[1]. With global energy demand expected to increase by nearly 30% in the next 12 years, many experts are anticipating that much of the world, especially in developing regions, must transition to a microgrid approach where energy is generated and stored in smaller spaces such as individual homes and offices [2] to meet anticipated demand while simultaneously reducing emissions. However, the main barrier to adopting a microgrid can be tied to the costs of implementation. While the price of photovoltaics and wind turbines continues to decrease or remain stable, the costs associated with maximizing power extraction and storage remains to be costly. If the cost barrier can be reduced, the world can accelerate its transition to a more distributed and sustainable electric grid.

In order to help remedy the issue of costly microgrids, our goal will be to produce a cost-effective maximum power point tracker (MPPT) that delivers the maximum amount of power to a DC load such as a battery pack for storage at wattages of 700W-800W while also remaining within the safe charging voltages for the battery pack. We will create a solution with a footprint suitable for use in a home or office setting where we intend a microgrid wind system to be employed. In addition to maximum power extraction at a lower cost, we will also strive to create a system with a mechanical to electric power efficiency that is comparable to current solutions on the market to reduce any unnecessary energy waste. Overall, our project will offer a comprehensive solution to convert 3-phase AC electricity from small-mid sized turbines into the a maximum power delivery at the load by actively tracking the point of maximum power extraction.

1.2 Background

Many experts agree that the deployment of microgrid systems is a key step towards incorporating more renewable energy generation while also meeting the growing demand for energy in both the industrialized and developing parts of the world. However, the main challenges to overcome are cost of deployment and ensuring reliability when the generating capacity is lower than the demand on the grid[3]. While the cost of photovoltaics and wind power systems has been reduced with increasing global investment in renewable technologies[4], we have still not seen the necessary cost reduction in smaller scale systems. In fact, the charge controller for a 1kW battery bank system often costs over $400, which decreases the incentive for deployment of off-grid or microgrid systems due to the high component costs associated with increasing reliability. Also, individuals may be discouraged from using existing solutions due to the complexity involved in creating an off-grid or small scale wind energy harvesting system.

To make a large impact in this space, our product must aim to reduce the cost of a battery charge controller while also maximizing power extraction so that energy is not wasted and can be made available for times when the wind does not blow. Our MPPT device must also aim to provide an accessible and comprehensive solution to ensure no additional components are need between the generator and energy storage such that cost can be minimized and our product is attractive to use among individuals without a particular knowledge base. Finally, we must deliver an output voltage suitable for charging batteries that are low cost and readily available to a consumer or community in the developing world in the drive to accelerate renewable wind power and microgrid adaptation.

1.3 High-Level Requirements

- Our solution must have a viable market cost of less than $200 to provide a significant reduction in the current market cost.
- The power electronics must be able to reliably operate at a power rating of 800W and amperage of 40A DC.
- At the load, the system must deliver between 22 and 29V to charge a low-cost and readily available battery bank.

2 Design

2.1 Block Diagram

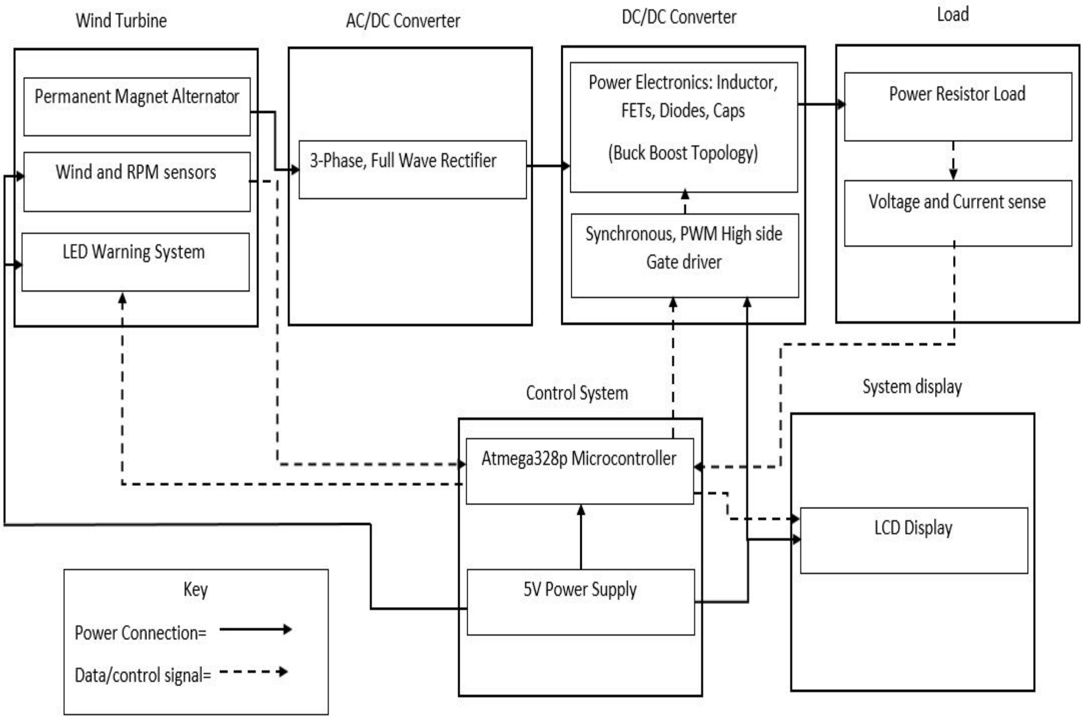

Figure 1: Proposed Sytems Level Block Diagram

Our systems level design illustrated in the block diagram indicates our proposed solution to creating a system capable of extracting maximum power from the windtura 750 wind turbine. In order to minimize costs, we elected to go with a simple systems level design with the core cost coming stemming from the power electronics needed to implement the AC/DC and DC/DC converters that are responsible for supplying power up to 800W to the load. For the control system, the cost is minimized by using a low-cost microcontroller to control the duty ratio of the DC/DC subsystem, which will in turn regulated the speed of the generator to maximize power extraction without the need for additional costs in implementing our control algorithm. The separation of the control subsystem from the power converters in the block diagram is indicative of our plan to create separate PCBs for the power and control circuits so that the board area on the AC/DC and DC/DC subsystems can be utilized to place large traces capable of sustaining 40A of current as stated in the high-level requirements. For the final requirement, the DC/DC converter topology and the switching frequency will be chosen such that the output voltage will remain at approximately 24 V so that the battery can charge safely while having the flexibility to track the point of maximum power to an extent. The buck-boost topology of the DC/DC converter was also chosen to ensure the output voltage at the load is sufficient in varying wind conditions that are expected in normal operation.

2.2 Physical Design

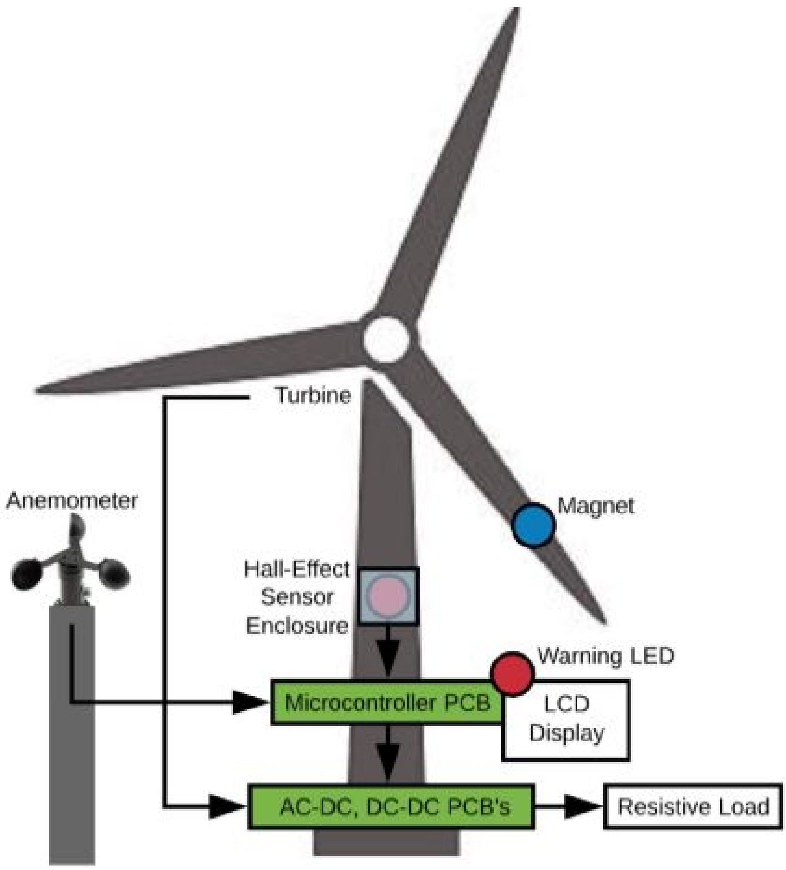

Figure 2: Proposed Physical Diagram

Our design requires us to use both a wind speed sensor, or anemometer, and a hall-effect sensor. The anemometer can simply be placed close to the turbine. The hall-effect sensor will be placed on the turbine's stand high enough that the blade will pass in front of it. There will be a small magnet attached to the blade at a point that will pass by the hall effect sensor so it will be triggered. The hall-effect sensor will be connected to the 5V rail that powers the microcontroller PCB, and its data output will be connected to the microcontroller. The turbine's 3-phase output will be connected to the power electronics required to convert the output to DC at the base of the turbine's stand. The AC/DC converter and DC-DC converter will be on separate PCB's for added modularity. Their output will then be connected to power resistors capable of dissipating up to 800W at 24V.

The microcontroller will be on a separate PCB than the power electronics for added modularity and because the microcontroller circuit won't require thick traces for high currents like the power converters. The LCD display will be mounted on or adjacent to the microcontroller PCB. The flashing LED warning system will be attached to the microcontroller PCB in a location that makes it easily visible to the user, especially if they are close to the power electronics.

2.3 Functional Overview, Requirements and Verification

2.3.1 Permanent Magnet Alternator (Provided Turbine)

Windynation Windtura 750, which is rated for a maximum of 800W. The turbine uses a permanent magnet alternator (PMA) attached to 3 35 in. blades to generate power. The tip speed ratio (TSR) is simply the ratio of the linear velocity of the tip of the blade over the wind speed. The optimal tip speed ratio (TSR) is between 5 and 6 for a 3-blade wind turbine, so our goal is control the turbine's speed to achieve that TSR [5]. The advantage of using a permanent magnet alternator is that no excitation circuit is required for the generator and therefore it can run without needing to be connected to a battery. The output voltage is 3-phase AC, with variable voltage and variable frequency. As the wind speed increases, both the amplitude of the output voltage and the frequency of the output voltage will increase. The 3-phase output will be connected to the 3-phase, full-wave rectifier. This has been provided to us, so there is no need to verify its design.

2.3.2 Wind and RPM Sensors

We plan on using two sensors to use as inputs for our maximum power point tracking control algorithm. The wind sensor, or anemometer, does not require a power rail, but the hall effect sensor requires a 5V rail. The anemometer has an analog output that ranges between 0V and 2.5V, so it can be directly connected to our microcontroller. It will allow us to calculate the available power at the input to the wind turbine for efficiency calculations. The hall effect sensor will determine the RPM of the turbine by sensing every time a blade with a magnet attached to it passes by. The sensor will be connected to the microcontroller, which can then determine the number of times the blade with the magnet attached to it passes by the sensor in a given time period, which will allow us to calculate the RPM of the turbine.

Requirements	Verification
1. Wind sensor accurate within 10%	1. (a) Setup the weather station with anemometer located in the power lab. Connect the purchased anemometer to our microcontroller or an arduino. (b) Use compressed air from a 1 meter distance aimed at both anemometers. Record the wind speed determined from each anemometer after 3 seconds of compressed air and compare.
2. RPM Sensor module accurate within 5%	2. (a) Attach the magnet to one blade attached to the permanent magnet alternator (PMA) and connect the hall effect sensor to the microcontroller (b) Attach the PMA to a dynamometer and run it at 200RPM. Calculate the frequency with the microcontroller based on the hall effect sensor output and compare it to 200RPM
3. Anemometer should be able to function in the rain	3. (a) Measure the anemometer output while using compressed air to spin it (b) Use a spray bottle from 6 inches away to shower the anemometer with water for 1 minute (c) Verify that the measurements are still received by the microcontroller by probing a test point with an oscilloscope on the microcontroller PCB analog input to verify a non-zero voltage is received.
4. Hall effect sensor enclosure should be IP65 water resistant	4. (a) Fill the hall effect sensor enclosure with a dyed anhydrous powder (b) Use a spray bottle from 6 inches away to shower the enclosure with water from all directions for 2 minutes (c) Check the enclosure for any dyed liquid.

2.3.3 Three-Phase Rectifier

In order to convert the DC signal to an AC signal, we need to rectify the AC waveform. Each phase of the AC waveform from the PMA ranges from a 10V amplitude to a 37V amplitude for 100RPM and 400RPM, respectively. The frequency ranges from 1.67Hz to 6.67Hz. We are using a full wave rectifier, which will allow us to use smaller capacitors for our filter. This reverses the sign of the negative components of the AC waveform so that the output iis all positive. It is important to note that because the input signal is three phase, we will need 6 diodes for our rectifier. The output of the rectifier is a single-phase DC signal with less than 15% ripple. It is important to note that in order to filter a signal with such a low frequency with a peak voltage of around 65V, we would need a capacitor in the Farad range with a high voltage rating. These capacitors are not stocked and have very high lead times through common electronic component retailers.

Requirements	Verification
1. Produces a DC output voltage with ripple below 20% of average voltage at 100RPM and 400RPM 2. Efficiency >92% by minimizing conduction loss of the diodes	1. (a) Connect the PMA outputs to our rectifier circuit, and the output of the rectifier to a power resistor. Connect oscilloscope probes to the power resistor. (b) Use the dynamometer to run the PMA at 100RPM and 400RPM 2. Connect power meters to the PMA output using the two wattmeter method and the load.Repeat the above test.

2.3.4 Gate Driver

The gate driver will be based around the LTC4442 Synchronous Gate Driver IC. This gate driver was chosen because it could provide enough charge to switch the MOSFET in our buck-boost converter. It is powered by a 5V rail, and should be able to output a PWM signal with the same duty ratio as the input PWM signal, which will come from the microcontroller.

Requirements	Verification
1. Capable of outputting a 5V PWM signal between 62 and 63kHz with a duty cycle and frequency matching the input signal	1. (a) Connect an oscilloscope to a test point of the DC/DC converter PCB located at the output of the gate driver (b) Use a function generator to generate a 62.5kHz, 5V PWM signal, and use it as the input to the gate driver circuit Power the DC/DC converter with 5V and observe the output to ensure the frequency and duty cycle match the input signal

2.3.5 Buck-Boost DC/DC Converter

The output voltage of our rectifier circuit will depend on the speed of the turbine. At faster speeds, we will have a higher voltage, requiring our DC/DC converter to step down the voltage. At lower speeds, we will have a lower voltage, requiring our DC/DC converter to step up the voltage. We will use a buck-boost topology in order to be able to adjust the voltage up or down to reach approximately 24V. Our rectified input will range from approximately 12 V_{rms} to 64 V_{rms} when the generator is at 100RPM and 400RPM, respectively. This will require our buck boost converter to operate with a duty ratio between 0.27 and 0.67. We selected a schottky diode and power mosfet with high voltage and current ratings in order to be able to work in a system that could output up to 800W. We chose a schottky diode to reduce the switching losses of our converter. Using the equations for sizing the inductor and capacitor for a 0.4V peak-to-peak ripple, we obtained values of L = 10μH and C = 3.3mF. The duty ratio of the converter will be controlled by the microcontroller, which will output a 5V PWM signal to our gate driver IC.

Requirements	**Verification**
1. Output RMS voltage between 23-29V 2. Output voltage ripple from DC/DC converter ±3% of the output voltage at 100W, ±10% at 800W 3. Efficiency of just the DC/DC converter >80% at 800W, >90% at 100W	Test the buck-boost converter in the buck mode of operation and the boost mode. <u>Buck Mode</u> With a 64V DC power supply as the input, set the duty ratio to be 0.27. Connect power meters to the input and output. Start with a higher resistance load and slowly decrease the resistance to increase the power at the load. 1. Use an oscilloscope to measure the output voltage ripple 2. Use an oscilloscope to measure the RMS output voltage 3. Use the power meters at the input and output to measure the efficiency. <u>Boost Mode</u> Repeat steps 1 - 3 with a 12V DC power supply as the input, set the duty ratio to be 0.67.

2.3.6 Microcontroller

We are planning on using the ATMEGA328 microcontroller to control the duty ratio sent to the DC/DC converter based on the frequency of the AC waveform coming from the PMA. It is capable of outputting a PWM signal of up to 8MHz, and we plan on using a 62.5kHz PWM signal. We can use the microcontroller to implement a control algorithm, which is shown in the supporting materials section, to adjust the duty ratio to achieve the maximum power output. It will be an iterative algorithm that will slightly increase or decrease the duty ratio, observe the change in the output power, and adjust accordingly. We want the output voltage to have upper and lower bands of approximately 22V and 29V to stay within an acceptable range for charging a 24V battery. The microcontroller will also be able to calculate the input power to the turbine based on the wind speed sensor and the turbine's power calculation.

Requirements	Verification
1. Capable of receiving data from the anemometer, hall-effect sensor, and output voltage and current sensors	1. (a) Connect the sensors to the microcontroller and program it to print data from each sensor using the serial connection with a PC at a baud rate of 9600. The analog information from the anemometer and voltage sensor will be referenced from 0 to 5V and the digital information from the hall effect sensor is binary and based off of 5V logic and will be printed out on the PC side.
2. Can calculate the efficiency of the overall system by using the output power read by the voltage and current sensors and the input power calculated from the wind speed	2. (a) Blow compressed air on the anemometer (b) Supply 10V to a simple resistor divider circuit with attached voltage and current sensors with the load dissipating approximately 20W of power. (c) Program the microcontroller to print out the efficiency computation based on the wind speed and measured voltage and current.
3. Uses an iterative algorithm to determine the optimal duty ratio for the DC/DC converter to achieve the optimal amount of output power, which is calculated from the current sense resistor and the voltage sensor at the load. The delay should be below 1 second.	3. (a) Add a test-point to the hall-effect sensor and a test point to the duty ratio output of the microcontroller. (b) Have the hall effect sensor triggered by a magnet passing by the sensor at 100RPM for 30 seconds using a dynamometer. (c) Change the speed of the magnet rotating to 150RPM and measure the time it takes between the hall effect sensor output changing to 150RPM and the duty ratio changing using an oscilloscope connected to both test points to ensure the control loop begins executing 10ms after a full rotation at the new speed.

2.3.7 5V Power Supply

To power the microcontroller, wind sensor, photo-interrupter sensor, voltmeter, and LCD display we will use a 5V, 1A power supply with electricity available from a wall outlet or 9V battery with a 5V linear regulator. In a practical implementation of this system in a permanent fixture, the power could be supply from the battery bank using a 12V-5V buck converter, so this design choice reflects the developmental nature of our project. Since we are using a commercially available power supply, there is not need to specify any of our own design requirements and verifications.

2.3.8 LCD Display

In order to display the efficiency of our system in real time, we plan on incorporating a simple, low cost LCD display, which will allow the user to view the output voltage and system efficiency in real time. The display will receive data from the microcontroller to indicate the output voltage using the voltmeter in the load module along with the system efficiency by calculating power at the load and dividing by the mechanical power available at the turbine. This element in our design will enable the user to verify the correct voltage at the load and serve a an indicator of our system's efficiency.

Requirements	Verification
1. Capable of displaying relevant data that is processed by the microcontroller, which includes efficiency and output voltage	1. (a) Test outputting data with an Arduino (b) Test outputting data with our microcontroller PCB calculated from the sensor input

2.3.9 LED Warning System

The warning LED will be flashing when the wind turbine is spinning, and thus providing power to the load. This is to warn the user that the electronics will be powered up at a potentially high voltage and that the blades of the turbine are spinning. The microcontroller will use the load voltage and current sensors in order to determine when the turbine is active.

Requirements	Verification
1. When the turbine blades are spinning, the LED will begin flashing within 3 seconds	1. (a) Connect the LED to the microcontroller and program it to detect current at the output (b) Spin the turbine by hand and measure the time elapsed with a stopwatch before the LED starts blinking

2.3.10 Power Resistors

The load for our system will be an array of parallel power resistors capable of absorbing up to 800W at around 27V. The resistance needed at this operating point is around 0.9 Ohms, and can achieve this by placing power resistors from the power lab in parallel. We will aim for a rating of 1kW to provide us with a margin for safety. The resistor bank is simulating another DC load, such as a DC battery, which would allow the user to store energy from the turbine.

Requirements	Verification
1. When the turbine blades are spinning, the LED will begin flashing within 3 seconds	1. (a) Measure the resistance of the resistor bank using a digital multimeter (b) See power ratings on each resistor or look at their datasheets. Determine the power dissipated by each resistor and verify that no power rating is violated

2.3.11 Voltage and Current Sensors

To measure the output voltage, we will use a resistor divider to step our output voltage down so that it's output is between 0 and 3V. The resistor values will be large enough that the amount of power they dissipate will be minimal. The data from the voltage sensor will be fed back to the microcontroller so we can calculate the output power, and therefore the efficiency of the overall system. We will use a 50A hall effect current sensor IC in order to measure the current at the load. It's output is an analog voltage between 0 and 5V, and it will be connected to the microcontroller. We can determine the RMS output voltage and current with these sensors and the microcontroller in order to calculate the total amount of power being delivered to the load.

Requirements	Verification
1. Voltmeter capable of measuring the output voltage level within 2% 2. Current sensor capable of measuring the output current within 2%	1. Measure the voltage of a simple series resistor divider circuit with our voltage sensor connected to our microcontroller. Compare to values determined by the voltage sensor with the value calculated by using the resistances and voltage. Difference should be less than 2% 2. Measure the current of a simple series resistor circuit with our current sensor connected to our microcontroller. Compare to values determined by the current sensor with the value calculated by using the resistance and voltage. Difference should be less than 2%

2.4 Risk Analysis

The biggest risk to our project working properly is the permanent magnet alternator (PMA) in the wind turbine itself. The documentation available for the PMA is limited, so we will have to characterize some of the parameters ourselves before being able to integrate the PMA into the rest of our system. Testing the PMA in the lab will require us to coordinate with the machine shop to create a connection for the PMA so that it can be connected to a dynamometer in the power lab. This connection will also be required if we want to drive the PMA with a dynamometer to simulate wind spinning it without taking it outside.

Additionally, if the turbine was ideal, then the coefficient of power - tip speed ratio curve that we need to maximize for our control algorithm will have no local maximums. The curve should have one point that is the only local and absolute maximum, so our control algorithm will need to find that point and adjust the duty-ratio of the converter accordingly for different wind speeds. If the turbine is not ideal, or the curve is not as smooth as it should be, then there may be multiple local maximums along the curve, which could mean that our control loop would treat the local maximum is the absolute maximum and get stuck at that point. In order to avoid this situation, our control algorithm will need to be able to look at a wide enough range of values to determine if a maximum is truly the absolute maximum or just a local maximum.

2.5 Supporting Material

2.5.1 Wind Turbine Specifications

Below are three curves regarding the electrical characteristics of the Windtura 750 Generator. The first two have data from tests of the generator done by the manufacturer of the wind turbine, Windy Nation. Using a gasoline engine pulley system, the generator was excited and began producing electricity. Its output was fed into a 3-phase bridge rectifier in order to The open circuit voltage and shorted current were measured simultaneously with the RPM of the generator to help visualize a relationship between the movement of the generator and the electricity it produced. The curves show the approximate RPM that must be reached to get the desired electrical output. The plot of the shorted current versus the RPM also illustrates why the generator RPM should not exceed 400 RPM, as the current at that speed is 40 A, which is the maximum rated current for our system. On the other hand, the voltage plot shows what the minimum RPM should be. The RPM should not go below 135 if the rectified DC output of the generator is 24V. The third set of curves is provided by Windynation, and shows the relationship between power output and wind speed based on the load, whether it is a 12V or 24V battery bank. The 24V battery bank reaches the goal of 750W faster than the 12V battery bank, hence why we are choosing to deliver 24V to our resistive load for the project.

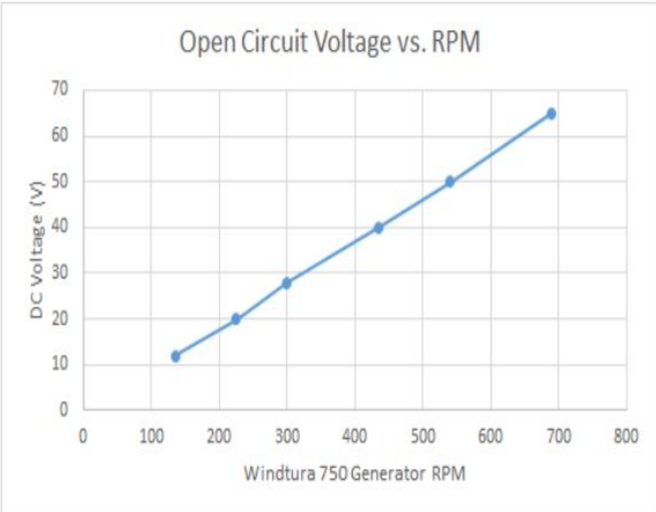

Figure 3: Open-Circuit Voltage vs RPM curve for the Windynation 750 PMA

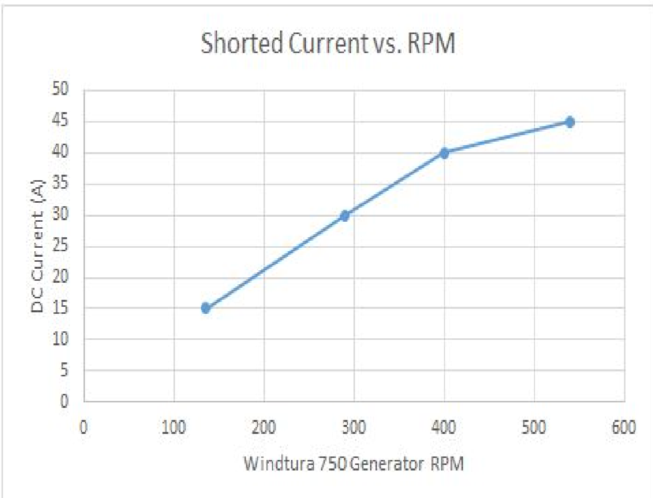

Figure 4: Short-Circuit Current vs RPM curve for the Windynation 750 PMA

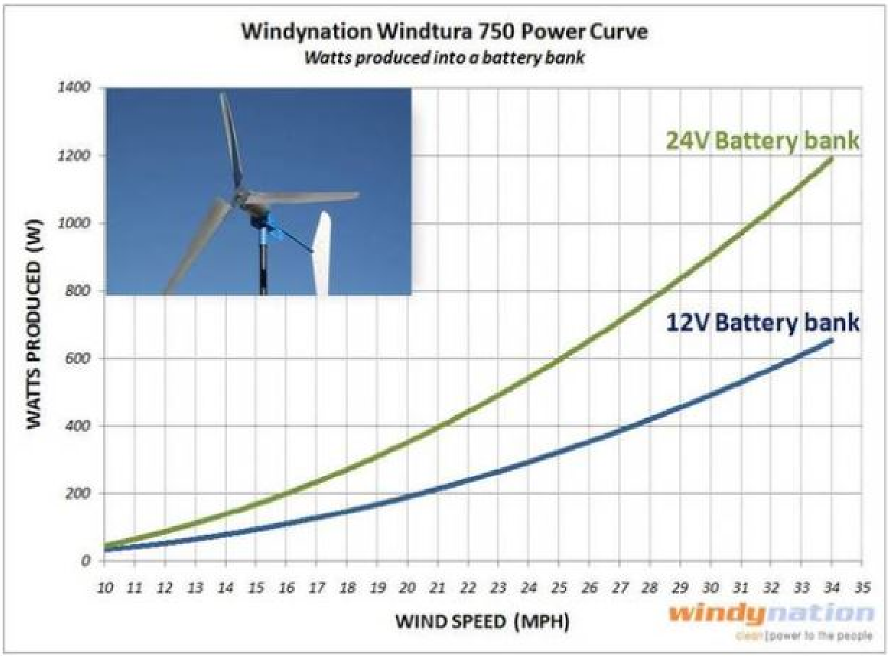

Figure 5: Power vs Wind Speed curve for the Windynation 750 PMA

2.5.2 Relevant Equations for the Buck-Boost Converter

$$V_{out} = \frac{-D}{1-D} V_{in}$$

The first equation indicates that the output voltage of the DC/DC converter is a function of the signals duty cycle. In our design we must set a duty cycle to ensure the output voltage is approximately 24V based on the variable input voltage to the DC/DC system, which stems from differences in the wind velocity.

$$L > \frac{V_{in}^2 (V_{out} - V_{in})}{K_{ind} f_{sw} I_{out} V_{out}^2} \; or \; L > \frac{V_{out}(V_{in,max} - V_{out})}{K_{ind} f_{sw} I_{out} V_{inmax}}$$

Calculating a minimum inductor size for DC/DC converters is a critical step in the design of power converters. The two equations above indicate that inductor size is primarily a function of input and output voltage, switching frequency, and output current. Given that our design proposes a variable input voltage with a less-variable output voltage and power, we can determine the necessary inductance by specifying upper and lower bounds on our system's capabilities at a switching frequency supported by the microcontroller's capabilities.

$$C > \frac{V_{in} I_{out}}{8 f_{sw} \Delta V_{out}} \; or \; C > \frac{I_{out} D_{boost}}{8 f_{sw} \Delta V_{out}}$$

Along with inductance, the output capacitance is another key component in the DC/DC converter design. In particular, once the minimum and maximum operating points are correctly identified, the output capacitance can be specified based on the fixed switching frequency alongside the range of input and output voltages.

2.5.3 Power Converter LTSpice Simulations

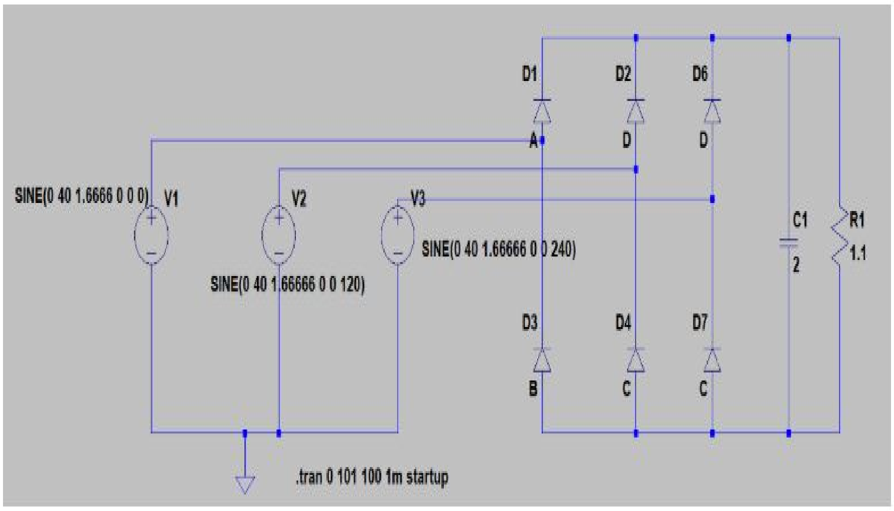

Figure 6: Schematic Used to Simulate the Operation of the AC/DC Converter

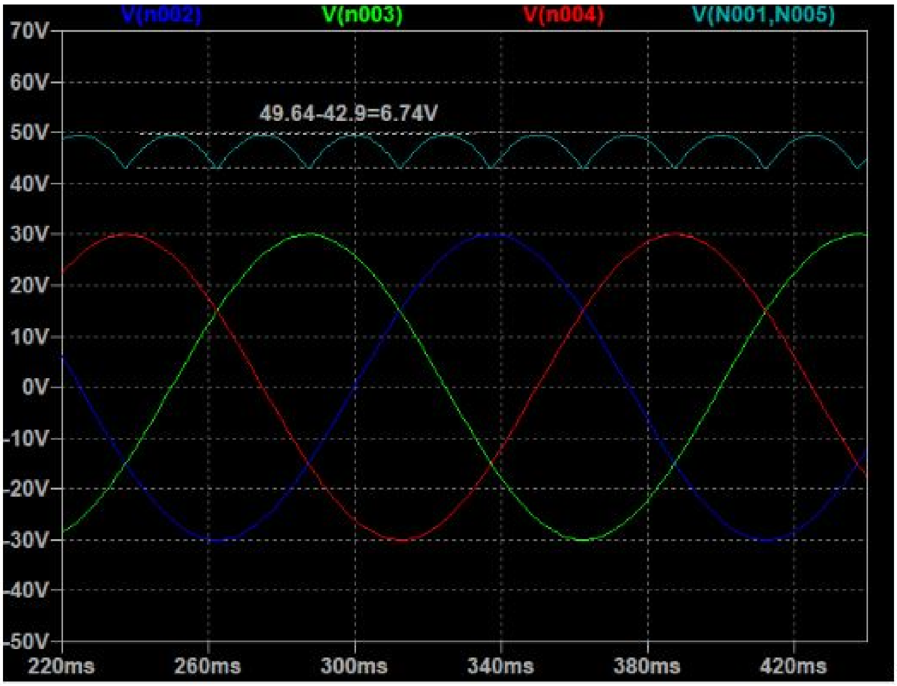

Figure 7: Results of the AC/DC Simulation

This is the simulation of the three-phase, full wave rectifier using LTSpice. According to the simulation results, the RMS voltage at the output of the rectifier is 3times the maximum voltage of the input AC signal as expected. With this in mind, the buck-boost topology makes sense for a varying amplitude AC signal coming from the wind turbine since the buck-boost topology will allow for the input voltage to be stepped up or down based on a duty cycle varying between 0 and 1.

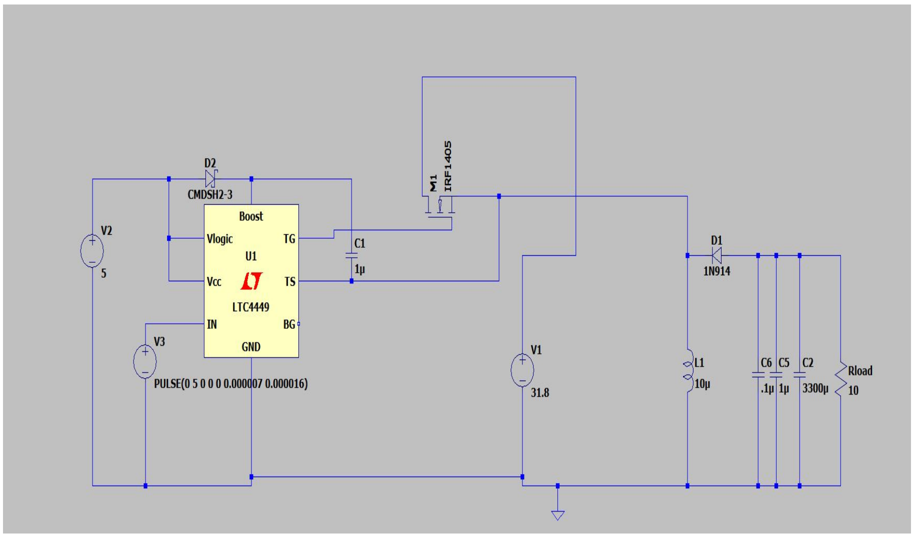

Figure 8: Schematic Used to Simulate the Operation of the DC/DC Converter

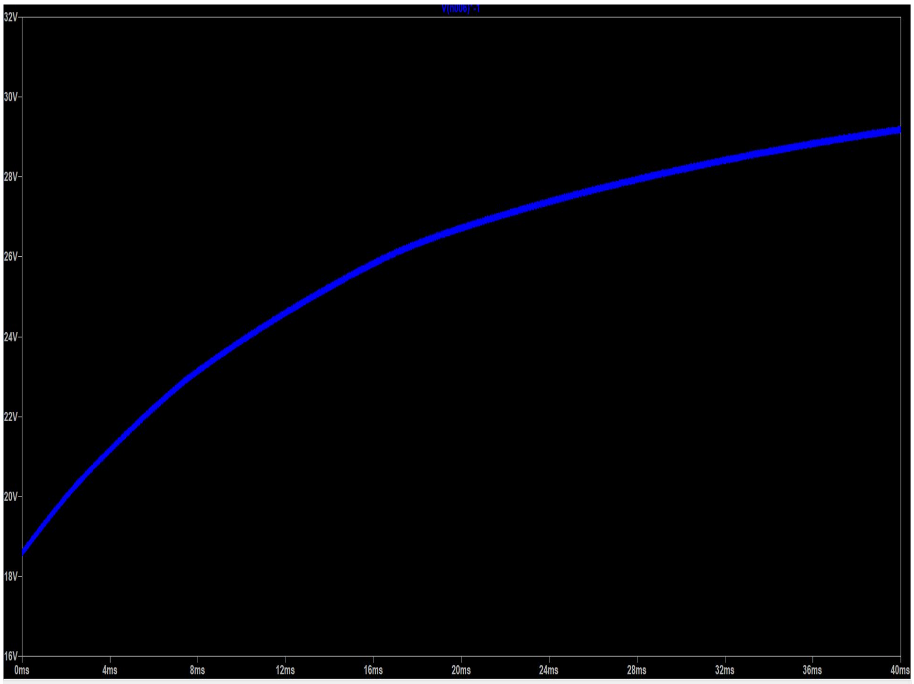

Figure 9: Results of the DC/DC Simulation

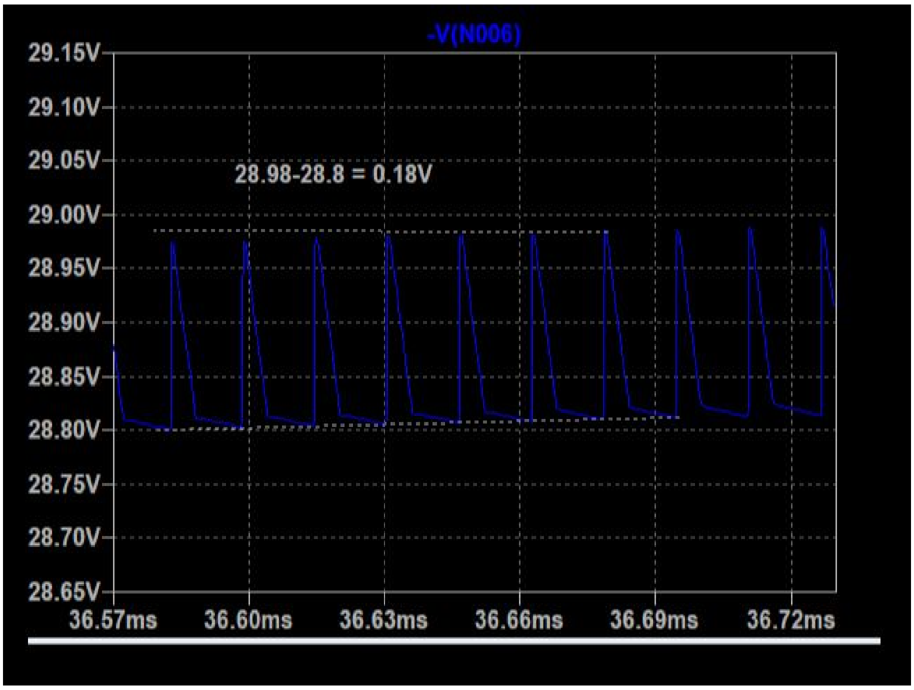

Figure 10: DC-DC Converter Ripple at 100W

After simulating the AC/DC converter, the next step was to simulate the buck-boost topology to ensure that a supply voltage, which we anticipate to be approximately 31V on average could be reliably regulated to a safe charging voltage for 24V battery bank. The above simulation indicates that a duty cycle of 0.4375 and a switching frequency of 62.5 kHz results an output that converges to 28V after 30ms. The simulation also utilizes the LTC4440 series gate driver IC as a means of demonstrating and testing a suitable high-side n-channel MOSFET driver in the buck-boost topology because an ideal switch cannot be implemented in a practical design. The need for a gate driver circuit stems from the fact that the source voltage of the MOSFET is susceptible to variations in the switching regulator, which requires feedback.

2.5.4 Flowchart for the Control Algorithm

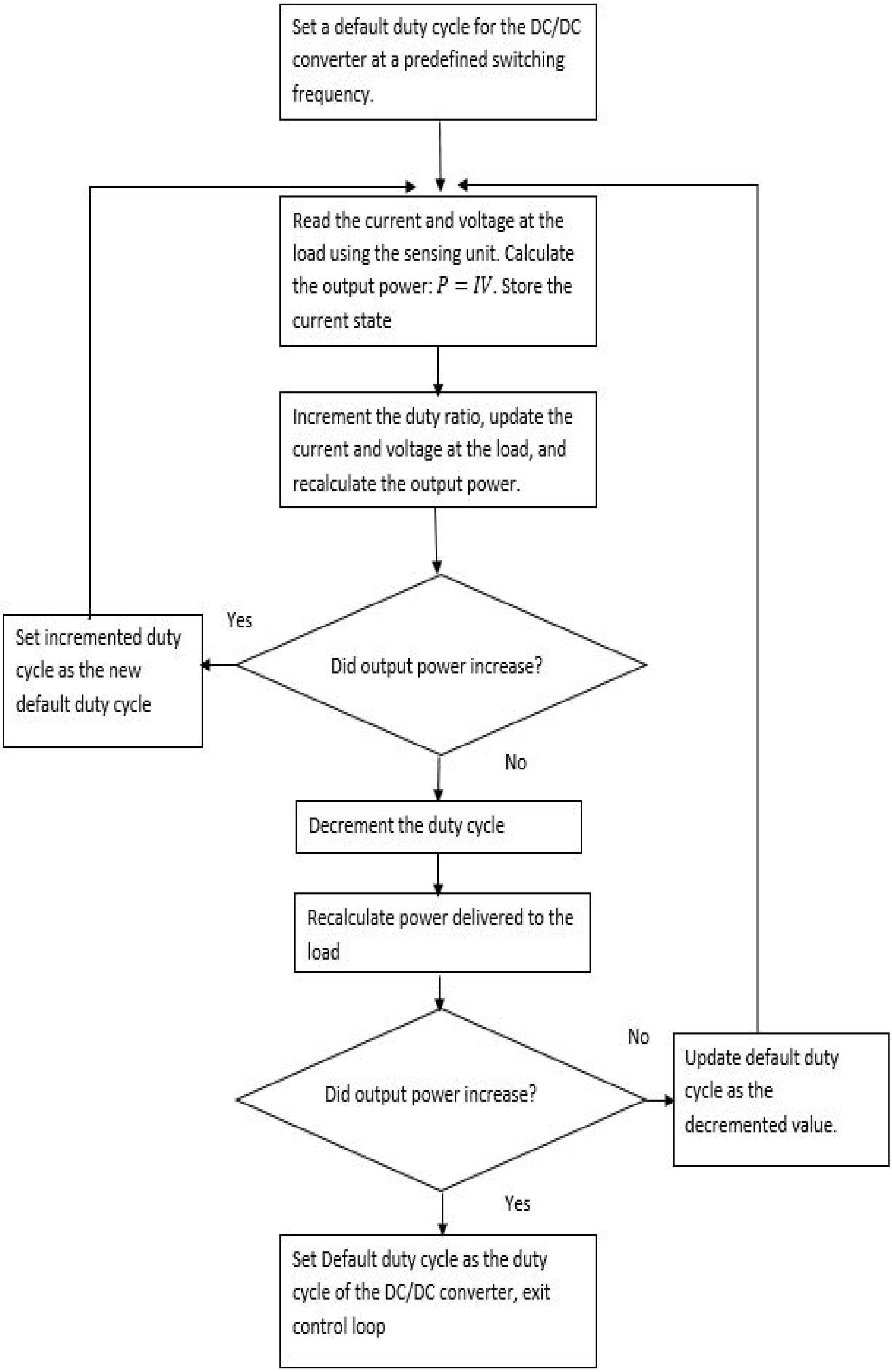

Figure 11: Control Algorithm Flowchart for the Software-based Control System

Our software control algorithm is designed to alter the output duty cycle in order to achieve maximum power delivery. In addition to the flowchart above, we also plan on incorporating upper and lower bounds to the acceptable output voltage range to ensure that the algorithm converges to a duty cycle that results in a battery safe voltage while providing maximum power within the specified range of operation.

2.5.5 Completed Subsystem Schematics

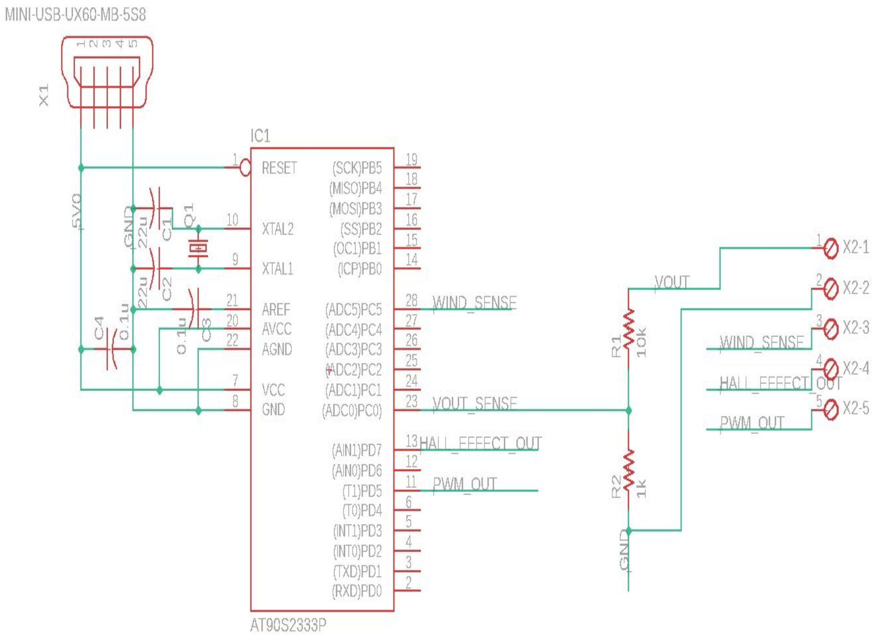

Figure 12: Current Schematic for our Microcontroller-based Control System

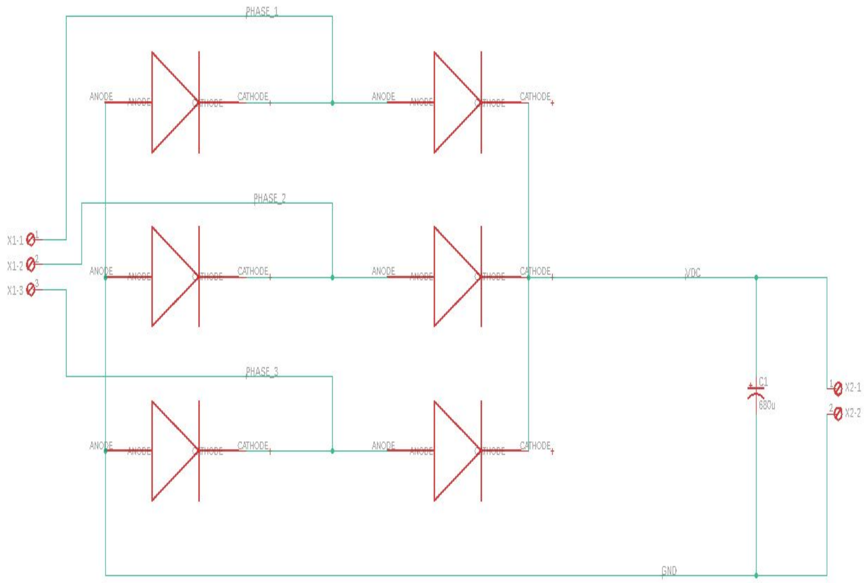

Figure 13: Current Schematic for the Three-phase AC-DC Converter

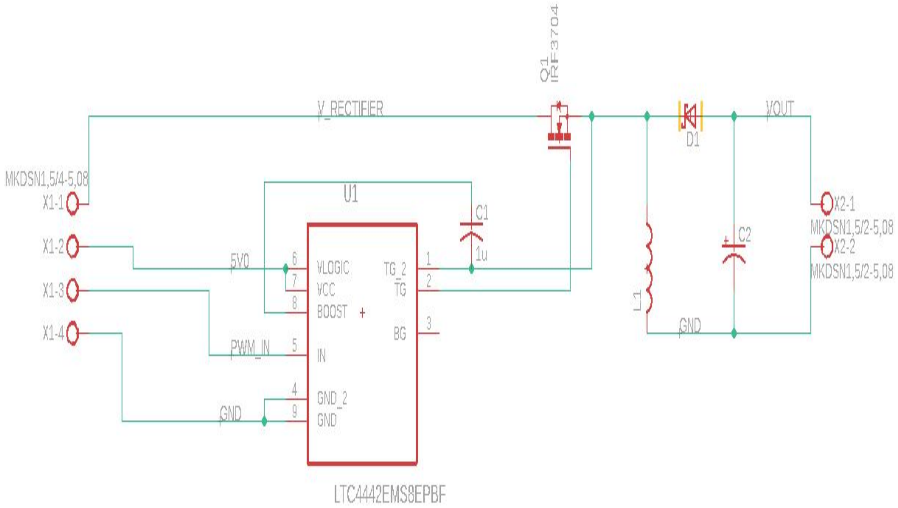

Figure 14: Current Schematic for the Buck-Boost DC-DC Converter

2.6 Tolerance Analysis

One element of our design where component tolerance can have an impact on the overall functionality of our system is the current and voltage sensing system in the load subsystem. Specifically, we plan on using a high-resistance voltage division circuit to step the voltage at the output down to the 0-5V range so that the analog input of the microcontroller can index the voltage reading to a value between 0 and 1023, which provides a resolution of 4.88 mV. Given that our project is also cost sensitive in the high level requirements, the resistors chosen to implement a voltage sensing circuitry are subject to a 1% tolerance.

These limitations will result in some degree of error in terms of measuring power delivered to the load. In the design requirements of the load subsystem, we had indicated that our system needs to accurately measure current to within 2% of the actual value while also measuring the output voltage to within 2% of the actual value. In order to analyze this effectively, we must consider the range of conditions at which our system is designed to operate and then calculate the effects of component tolerances on our ability to achieve the requirements we specify. In terms of our design, we intend on limiting the output voltage to a range of 19V-29V with an output current range of 3A-40A.

The effects of resistor tolerance can be mitigated using a larger ratio of the high side to the low side resistor in the voltage divider. In the worst case scenario with a resistor tolerance of 1% a 10:1 voltage divider is considered.With this arrangement, $R_1 = 10k\Omega, R_2 = 1k\Omega$ and $V_{microcontroller} = \frac{R_2}{R2+R1}Vout$. In the worst case scenario $R_1 = 10.1k\Omega, R_2 = 0.99k\Omega$. This edge case results in a 0.09% difference from the ideal case in which the resistor division was unaffected by the resistor tolerance, which shows that proper design of our sensor topology along with reasonable resistor tolerance results in minimal error. However, the error of the microcontroller must also be considered due to the low resolution of 4.88 mV. Specifically, at the lowest anticipated output voltage of 19V, $\frac{4.88mV}{19V} \times 100 = 0.0256\%$. Taking the resolution and resistor tolerances into account we expect the steady state accuracy of our voltage sensing system to have approximately 0.1156% error due to component tolerances.

In terms or the current sensor we plan on using a module with a resolution of 100 mV/A rated up to 50A. Considering the resolution of the microcontroller of 4.88 mV, the we can detect currents up to 48mA on the high current nets, which represents $\frac{48mV}{3000mV} \times 100 = 1.6\%$ uncertainty in the current measurement. This is within our specified limit of 2%, but is limited primarily by the resolution of the equipment, which is to be expected to some degree when cost plays is a major factor in the overall design. Another area of the design where we must remain vigilant is the power converters. The AC-DC converter must feed the DC-DC converter an input with little to no frequency The disadvantages of having a filter capacitor at the output of the AC-DC capacitor are the ability to find such a component and its effect on the power factor of the design. We will have to make sure that the frequency of the AC-DC output is low like what has come out of the simulations. The tolerance analysis would be to expect the component to have a +/-20% tolerance, so the voltage ripple would vary by -/+20%. According to the simulation, the ripple hovers at around 15% of the output voltage, so a 20% smaller capacitor would lead to ripple going up to 18%, which is still within the 20% requirement.

The DC-DC converter must supply an adequate voltage with little ripple to be able to charge a 24V battery bank. The tolerance analysis for the DC-DC converter will be based on the +/-20% tolerance on the inductor and capacitor values. The inductor size could vary from 8μH to 12μH and capacitor size could be as low as 2.7mF and as high as 3.9mF. Since the relationship between the output capacitor and the voltage ripple is inversely proportional, a 20% increase means 20% decrease in ripple, and vice versa. The same applies for the inductor and current ripple. Even if the output capacitance decreases by 20%, that puts the peak-to-peak ripple at 0.48V, which still puts the voltage ripple within +/-3% of the output voltage value, which at the lowest value of 22V, would be 1.34V peak-to-peak. The ripple current going up due to tolerance issues with the inductor could also affect voltage ripple if the equivalent series resistance of the capacitor is high enough, but since the output capacitance will be made up of more than one capacitor, the ESR should be negligible.

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor Costs

Using the data from the ECE Illinois website, the average yearly salary for ECE undergraduates upon entering the workforce is approximately \$75,625. This amount was determined by averaging the salary figures provided for electrical engineering (\$67,000) and computer engineering (\$84,250) students directly after graduation [8]. Taking this number into account with the standard 40 hour work week during a 52 week year, \$75,625 translates into an hourly rate of approximately \$36 per hour.

As a calculation of the estimated total labor cost, we use the following formula assuming each team member contributes an average of 10 hours per week to the project.

$$10\,\frac{hours}{week} \times \$36\,per\ hour \times 2.5 \times 3\,team\ members \times 16\,weeks = \$43,200$$

3.1.2 Parts

Part	QTY	Cost (Prototyping Scale)	Cost in Bulk
LTC4442 Synchronous Gate Driver	1	$2.56	$1.40
IRF1404 Power MOSFETs	1	$1.78	$1.40
ATMEGA328P Microcontroller	1	$1.96	$1.63
Anemometer	1	$13.50	$10.00
LCD Display	1	$2.46	$1.98
Rectifier Diodes	6	$15.78	$6.60
Misc. Capacitors and Resistors	1	$2.78	$1.98
$10\mu H$ inductor	1	$3.93	$2.78
Schottky Diodes	2	$2.34	$1.17
Aluminum Electrolytic Capacitors (3300 μF)	1	$1.24	$0.50
Crystal Oscillator	1	$0.74	$0.57
Hall Effect Sensor	1	$0.95	$0.48
DC Current Sensor	1	$13.49	$8.28
PCBs (PCBway est.)	3	$13.00	$5.00
5V Power Supply	1	$5.00	$ 2.00
Total:		$65.73	$40.16

Table 1: Cost of System Components at Individual and Bulk Pricing Levels

3.1.3 Grand Total

The total cost is the sum of the labor cost and the costs of the parts.

$$Grand\ Total = Parts + Labor = \$60.73 + \$43,200 = \$43,265.73$$

Given that the cost of our components bought both individually and in bulk is well below $100, it is reasonable to assume that successful development of this project could result in a product with a viable market cost of under $200 as we had stated in the high-level requirements.

3.2 Schedule

Week	Tyler	Ben	Alec
10/8/18	Order AC/DC and load parts. Design load resistor bank for 800W.	Finalize calculations for components. Order parts for DC/DC.	Compile a list of parts to meet our design specification. Order parts for low voltage and control system components.
10/15/18	Design AC/DC PCB. Test AC/DC on perfboard with Variac. Build load resistor bank.	Design DC/DC PCB	Design Microcontroller PCB schematic and layout. Pass audit for PCBway.
10/22/18	Test AC/DC with PMA connected to dynamometer.	Test DC/DC converter with DC source, waveform generator, and resistive load.	Work on software design. Test convergence times of the control algorithm.
10/29/18	Integrate AC/DC and DC/DC Converters. Test AC/DC PCB with variac and PMA.	Integrate subsystems	Test 1st pass control PCBs. Rework as needed.
11/5/18	Make revisions to AC/DC PCB. Order additional/new parts if needed. Testing AC/DC and DC/DC integration	Make revisions to calculations and DC/DC PCB if needed	Finish design of second pass PCBs for the control subsystem. Order any additional parts for the second pass..
11/12/18	Integration Testing - PMA to AC/DC to DC/DC converter	Second round of integration testing	Work on systems integration. Test and debug our design for a variety of test conditions.
11/19/18	Work on final demo presentation	Work on final demo presentation	Work on final demo presentation
11/26/18	Final Integration Testing and preparing for demo presentation	Preparation for Demo/presentation	Prepare for final demo and presentation. Perform final tests of the system
12/3/18	Revise demo presentation and final demo	Demo	Refine presentation following the mock presentation
12/10/18	Presentation	Presentation	Presentation

Table 2: Outline of the Project Schedule for the Remainder of the Semester

4 Ethics and Safety

Since the wind turbine does have spinning blades, safety precautions must be put in place to ensure that no one is injured while testing the turbine, in accordance with IEEE Code of Ethics, #9 [6]. While the turbine is active, it is pertinent that no one is within reach of the blades. Where we test the turbine also matters, as we need access to instruments but a way to spin to the blades, so if we are using a lab, then we need to alert others to the fact that we will be testing the wind turbine so they are safe and their work is not disturbed. We will also have to give adequate time for the blades to come to a rest after testing before normal activities can resume to be certain that no one is ever harmed by the wind turbine. As an additional precaution, we intend to include a flashing LED light to indicate that the turbine and power converters are operational so that any potential users can have a visual warning. This measure will be taken in light of the statement #1 in the IEEE code of ethics because the warning light will serve as a measure to warn the user of the fact that the turbine blades and power electronics may cause harm if not handled with caution [6].

Due to the high amperage and large transfer of energy, our components must be carefully selected so that they are rated for the conditions in which they will be used and that the integrity of the system is not affected by using subpar components. Attentiveness when picking parts for the power electronics and the load is key. If anything does go wrong, our diodes will breakdown and no one will be harmed. Our project also does not qualify as high voltage based on OSHA standards since at no point does any system of our design operate at 50V.

Since the wind turbine will ultimately have to be outside to be useful, it is vital that our design be waterproof. We plan on encasing our power converters and peripheral electronics so that it may never be exposed to water. The case will need to adhere to strict IP67 guidelines, which keeps the internals dry in up to 1m of water.

The projects fits the spirit of IEEE Code of Ethics, #5, as we are striving "to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies." [6] If successful, our project can accelerate the growth of microgrid systems and promote the use of green energy. Making microgrid solutions more accessible can drastically change the lives of people around the world, as more than 1 billion people still live without electricity [7]. We hope that our project's success causes not only improvements in microgrid technology, but also the lives of people worldwide.

References

[1] M. Froese, “An overview of 6 energy storage methods,” Windpower Engineering & Development, 26-Feb-2018. [Online]. Available: https://www.windpowerengineering.com/business-news-projects/uncategorized/an-overview-of-6-energy-storage-methods/. [Accessed: 15-Sep-2018].

[2] V. Boutin, M. Feasal, K. Cunic, and J. Wild, “How Microgrids Contribute to the Energy Transition,” *Schneider Electric.*

[3] O. Malik, “Micro-Grid: Concepts and Challenges in Practical Implementation,” *IEEE Canadian Review*, 2015.

[4] D. Milborrow, “At the tipping point: 2017 wind cost analysis,” *Windpower Monthly*, 01-Feb-2018. [Online]. Available: https://www.windpowermonthly.com/article/1455361/tipping-point-2017-wind-cost-analysis. [Accessed: 19-Sep-2018].

[5] Windynation.com, Tip Speed Ratio: How to Calculate and Apply TSR to Blade Selection. [online] Available at: https://www.windynation.com/jzv/inf/tip-speed-ratio-how-calculate-and-apply-tsr-blade-selection [Accessed 17 Sep. 2018].

[6] Ieee.org,"IEEE IEEE Code of Ethics", 2018. [Online]. Available: http://www.ieee.org/about/corporate [Accessed: 16- Sept- 2018]

[7] GE.com, “More Than 1 Billion People Live Without Electricity. Here’s How We Turn Their Lights On”, 2016. [Online]. Available: https://www.ge.com/reports/more-than-a-lightbulb/ [Accessed: 16-Sept-2018]

[8] ece.illinois.edu, “Salary Averages,” Salary Averages :: ECE ILLINOIS. [Online]. Available: https://ece.illinois.edu/admissions/why-ece/salary-averages.asp. [Accessed: 29-Sep-2018].

[9] Watanabe, Tomonori, et al. “Buck-Boost Converter Controlled by Hysteretic PWM Method with Input Voltage Feedforward.” 2011 IEEE 33rd International Telecommunications Energy Conference (INTELEC), 2011, doi:10.1109/intlec.2011.6099768

[10] R. Esmaili, L. Xu, and D. Nichols, “A new control method of permanent magnet generator for maximum power tracking in wind turbine application,” IEEE Power Engineering Society General Meeting, 2005.