Memorandum

To: Dr. Winfree

From: Nigel Grey, Humoud Abdulmalek, Mohammed Almutairi

Subject: Feasibility Report

Date: December 11, 2019

The document that follows is an aggregation of our team's Capstone project work throughout the Fall 2019 semester. Beginning with selected reviews of current and prior art and standards for wind turbine systems, we developed a strong conceptual framework to aid in the subsequent DC-DC converter design–the central role of our team. Next, a system overview is provided to encapsulate the bigger picture of the project. We provide an in-depth summary of our prototyping experience; with the successes and challenges of our converter design thus far, and resulting insight to guide us in the next phase of design and testing. Finally, a Work Breakdown Structure and Gantt Chart are provided to organize our completed and remaining tasks, as well as the expected timeline.

DC-DC Converter Project Plan

December 11, 2019

BOOSTER
PACK

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1 Introduction

In response to the Department of Energy (DOE) and National Renewable Energy Laboratory's (NREL) annual Collegiate Wind Competition, our Capstone project is to design a DC-DC converter system within a micro-scale wind turbine. Specifically, we have decided to explore the superiority of a synchronous boost converter topology for the DC-DC converter. Thus far, the project has manifested itself with three prototypes: A synchronous boost converter Simulink model, a boost converter with proportional-integral (PI) control Simulink model, and a boost converter circuit breadboard prototype. Our final product will be a model of effective and reliable wind power generation. Which is an extremely relevant technology, given the projected increase in reliance on wind energy in the near future. Renewable energy sources are leading the way into a less fossil fuel dependent, and more environmentally conscious world. Wind energy systems are one of the most appealing renewable energy technologies, which are currently reaching 760GW of global power capacity [1]. The key driver behind the increase in wind energy are due to a combination of government incentives, and improved technology.

Wind turbines have been converting the kinetic energy of the wind into electrical energy since 1887 [1]. There is a long lineage of prior art leading up to our task of designing the power converter component of this year's micro-scale wind turbine. This project promotes an optimization of current wind energy turbine systems by reducing the overall voltage drop and subsequent power loss over the system as a whole. This is accomplished by utilizing the synchronous converter configuration, where two MOSFETs are used, rather than a MOSFET and a diode. In addition, our design includes two boost converters in series, to increase power generation at very low cut-in wind speed. Apart from NREL aiming to ensure the availability of reliable energy in the country, its aspiration is to guarantee a clean environment by promoting the adoption of renewable energy. Our Capstone project aligns with NREL's goal, with the potential of developing new optimization strategies to advance the technology one the most appealing renewable energy source–wind power.

Our initial research on the the prior art of our Collegiate Wind Competition Capstone project, as well as current standards in wind energy technology more generally, is outlined in the **Literature Summaries** section below.

2 Literature Summaries

2.1 Introduction

2.2 High-Power Wind Energy Conversion Systems: State-of-the-Art and Emerging Technologies [1]

The current state-of-the-art wind energy technologies are presented in this paper, along with an informed analysis of where the technology is heading in the future. Though our turbine is not connected to the grid like the wind energy systems in this paper, the section on *Passive Generator-Side Converters* outlines the relevant jumping-off point for our design.

Historically, after the initial mechanics and circuitry of the turbine have transformed wind energy into a three-phase signal, the power converter topology consists of a diode rectifier circuit in series with a DC-DC boost converter, followed by a two-level voltage source inverter (2L-VSI), and a transformer to integrate the DC power output back into the AC grid. This standard topology is the basis of our project, in a non-grid connected format. It is a low-cost, high-reliability, high-efficiency configuration. However, our topology can be improved upon in the same way outlined by Yaramasu et al. In order to obtain a higher efficiency of wind energy conversion, adding a second DC-DC converter, a two-level (2-L) boost converter topology, has been shown to be a simple, yet significant improvement, particularly in low wind speeds.

In full-scale commercial wind energy systems there are numerous improvements, including three-level boost converter topology, six-phase generator/rectifier circuitry, cascaded and parallel configurations, all with specific applications, advantages, and drawbacks. These improvements comprise the current trends in wind turbine electrical technology as defined by Yaramasu et al.

2.3 Complete Digital Control Method for PWM DCDC Boost Converter [2]

This paper outlines a robust and comprehensive algorithm for digital control of a DC-DC converter. Beginning with some instruction on how to measure the output error signal, the content quickly dives into the central steps of digital control. The central goal is to create a seamless transition cycle from continuous conduction mode (CCM) to discontinuous conduction mode (DCM) and back. These two modes are essentially when the inductor current never reaches 0A (continuous), or when the inductor current can reach 0A (discontinuous). The pulse width modulation (PWM) signal is the driver of switching between modes, via the gate of an n-channel field-effect transistor (FET). Once the CCM and DCM power stage transfers have been modeled, the ideal period can be calculated for the PWM signal.

All equations and derivations for each step above are outlined in the paper, along with the method to find the proper output capacitance value to limit output voltage ripple; another key concern for our converter topology. The control algorithm was first implemented with a field-programmable gate array (FPGA), then made into a printed circuit board (PCB) with all peripheral circuitry integrated together with the DC-DC converter.

Kranz's DC-DC boost converter digital control algorithm results were verified with Bluetooth headsets, though the constraints he faced were similar to our project. Other than the small-size constraint he faced, the requirement of low input voltage (0.9V - 1.7V), and a boosted output voltage of 3.0V in his case (3.3V in our case) are nearly identical for the first DC-DC converter in our two-level topology.

2.4 Design of the DC-DC Converter for Aerodynamic Characteristics Testing of Wind Turbine [3]

The design of the DC-DC converter in this paper was particularly applicable to ours because it addresses a non-grid-connected system. The grid-connected wind turbine was previously the only way to create a large wind farm. Since battery technology is improving and becoming a more cost-effective option than it used to be, non-grid-connected wind power systems are growing in popularity. The design of the DC-DC converter for the non-grid-connected turbine in this paper is similar to the two-level topology we plan to use. The main exception, is that the first converter is a boost, and the second is a buck. In addition, each phase consists of four interleaved converters, to further reduce ripple output current.

Chen et al. take into consideration the wind turbines aerodynamic aspects to propose a DC-DC converter made up of two DC transformers: one at the front-end and the other at the back-end. For the proposed system to function, the two transformers are combined by four buck converters interleaved with a 90-degree phase shift relative to each other [3]. Chen et al. assert that the front-end DC transformer has to have two secondary windings to generate a medium level output range while guaranteeing an optimized output voltage [3]. Further, they suggest the suitability of buck-type topographic anatomy for the back-end converter because of its responsive and silent nature. The higher the number of phases in the device, the more complex it becomes. Thus, Chen et al. propose that three phases are used for the back-end converter. This non-grid model sorts out wind power's variable nature, guaranteeing a stable and high-quality voltage output.

The leading factor for this particular DC-DC converter design was the ability to perform within a wide working power range, 0.5A to 100A. To verify the design worked as needed, transient simulations with a wide variety of output loads, over the entire current range above were produced. After the simulations of the front-end and back-end converters were analyzed, along with the corresponding control circuits, the design was found to be significantly more optimal than previous iterations of non-grid-connected wind turbine DC-DC converter circuits. The objective of creating a converter with a high-precision of output current control over a large range of wind speed and power delivery was very successful, and will be implemented in future non-grid-connected wind energy systems.

2.5 High Power Medium Frequency DC-DC Power Converters For Wind Application [4]

In an attempt to deduce a feasible and effective DC-DC converter topology, Zhou et al. investigated three topologies [4]. Of the three topologies, one of them was based on phase shift, another one was based on series load resonance and the other ones main component was the thyristor. Zhou et al.s Series Load Resonant Converter use variable frequency as a control mechanism, a phenomenon that puts forth a constraint in the designing of magnetic components [4]. The Thyristor Based Resonant Convertors key components are a thyristor: its switching device because of its non-self-turn-off nature, and a capacitor.

The three scholars put into consideration the fact that the most effective topology would be the one that can handle the wide range of input power and voltage while maintaining a constant output. This is because wind turbines produce a range of voltage and power outputs depending on the wind speed. Thus, according to them, the Phase Shift (PS) DC-DC converter proved to be the most superior of the three since it can handle a widest input voltage range while presenting high-quality voltage outputs [4]. To ensure a soft switching, the PS DC-DC converter utilizes the transformers leakage inductance.

2.6 A Multiple-Input Cascaded DC-DC Converter For Very Small Wind Turbines [5]

It is worth noting that recently, micro-turbines have been adopted thanks to their flexibility, ease of maintenance, and their cost-efficiency nature. Although these kinds of wind turbines (WT) are effective, the fact that they have low power generation presents the need for stepping up by connecting the individual micro-turbines to a single robust system. Majeed et al. propose a multi-input non-secluded DC-DC converter that amasses the output power from micro-turbines connected in series [5]. Their proposed system is made up of two key stages: a Multi-Input Cascaded Converter (MCC), and a controller section as illustrated in Figure 1.

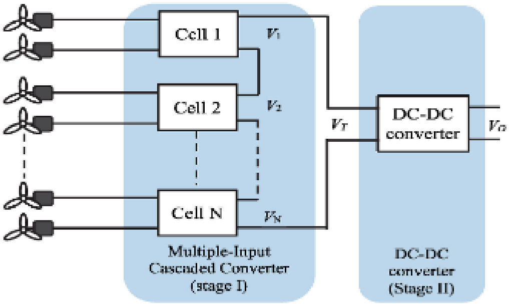


Figure 1: Majeed et al. Proposed Topography

The MCC combines voltage from individual micro-turbines connected in series thus increasing the voltage. The second stage is the output DC voltage management stage and is composed of a DC-DC converter whose input is the output of the combined cells. Majeed et al.s proposal portrayed and 80% efficiency level as tested in their lab thus validating the credibility of amplifying output voltages of individual small WTs [5].

2.7 Literature Survey Conclusion

We have kept this survey focused on the previous and current art related to our specific role in the 2020 Collegiate Wind Competition. The next step is to continue testing the DC-DC 2-L boost topology outlined in [1], and verify that the results will work in our micro-scale turbine.

We have identified digital control (microcontroller based) as the key component of our project's success. As [2] outlines, DC-DC converter output voltage control is typically done with analog control loops and a digital switch signal, though it can be done entirely digitally. Usually there will need to be an additional circuit for conversion of analog to digital, in order for digital control to be implemented, which is built-in to the Arduino microcontroller we are using in our tests and final design. This extra component allows for a digitally-controlled circuit with significantly less power consumption, which is a central concern for the DC-DC converter circuit.

The non-grid-connected design in [3] was impressive, though substantially more complex than what is necessary for our application. However, the focus of the converter design in [3]–reliably perform over a wide power range, with a non-grid-connected output load–is the objective of our DC-DC converter design, so this paper did provide insight into our specific role in this wind turbine project.

The references [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], and [18] were also studied to provide background research on wind turbine technology, though they have not been included in our summaries above. In reading an analysing the papers cited above, we developed a strong foundation for the work to follow. The results of which are outlined in the *System Organization Overview* and *Prototype Development* sections below.

3 System Organization Overview

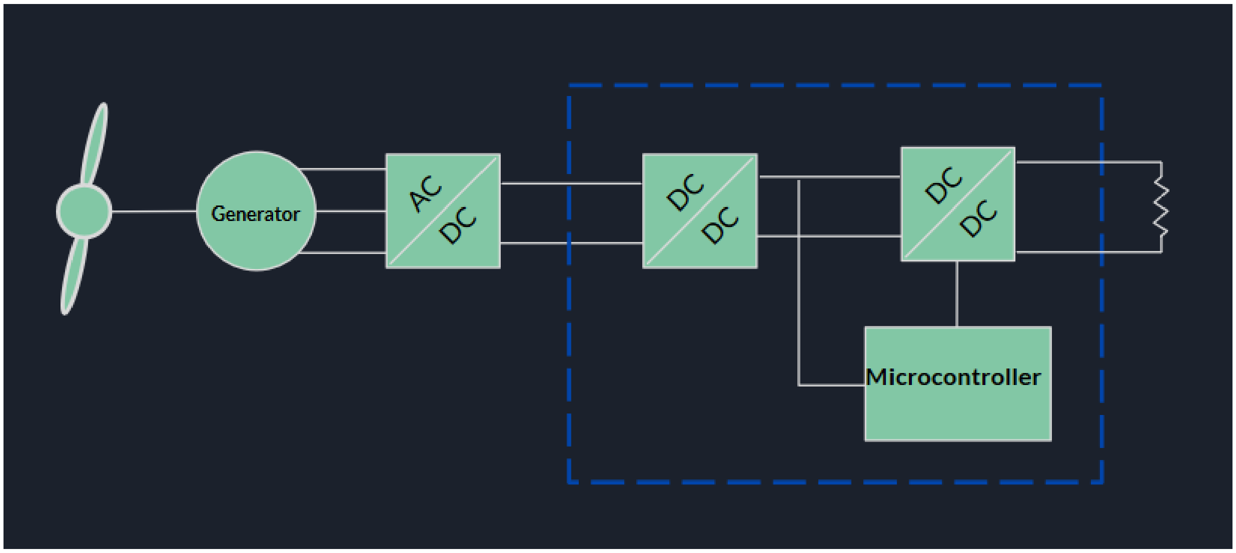


Figure 2: Simplified Turbine System Overview

In Figure 2 above, a simple block model of the wind turbine system as a whole is illustrated. From left to right, wind energy turns the turbine blades, which is converted into potential energy by the generator. The easiest way to conceptualize a generator is to think of a motor in reverse; where kinetic energy becomes potential energy (voltage) rather than the other way around. These first two phases of the model were designed by the Mechanical Engineering team. Next the potential energy is converted from alternating current (AC) to direct current (DC). This AC-DC converter, or more specifically AC-DC *rectifier*, was chosen by the Auxiliary Electrical Engineering sub-team. At this point, our team is responsible to convert the DC to a higher value, using an application-specific boost converter topology. For this phase, we designed a two-stage process to expose the load (represented by the resistor symbol in the far right of Figure 2). In grid-connected wind turbines the load would be represented by the power grid, and a conversion from DC back to AC would be required.

Our basic boost converter system is highlighted with the blue dashed line in Figure 2.

Though the block model abstracts much of the circuitry detail, the basic working principle can be observed. The first DC-DC converter will step-up the voltage from the AC-DC rectifier at a fixed scale–for example, the goal is to convert $0.1V$ to $3.3V$, $1V$ to $33V$, etc. This initial boost in voltage will allow our Arduino microcontroller to turn on, and begin the second stage of conversion. The second DC-DC converter will be controlled by the Arduino to adjust the output voltage exposed to the load, based on the input voltage, with the end goal of keeping the output voltage as constant as possible. We cannot exceed $48V$ on the output, so when the turbine is generating a high amount of voltage, the first converter will essentially turn off, to allow the second to take full control.

Once the DC-DC converter system is integrated with the AC-DC rectifier, our team will work in full collaboration with the Auxiliary team to complete the remaining electrical integration of the turbine.

4 Prototype Development

4.1 Prototypes Chosen

1. Synchronous boost converter Simulink model

2. Boost converter with proportional-integral (PI) control Simulink model

3. Boost converter circuit physical prototype

4.2 Why Were These Prototypes Chosen

The synchronous boost converter was chosen because this is the topology we plan to use on the project, for both DC-DC converters. A synchronous topology uses two MOSFETS instead of a MOSFET and a diode, which decreases the overall voltage drop delta throughout the circuit.

The boost converter with PI control used to regulate the duty cycle and subsequent output voltage was chosen because PI control is the industry standard for creating closed loop control of a converter. This simulation will also allow us to simply export the PI MATLAB code to our chosen microprocessor. So creating this prototype enabled us to learn, while at the same time make progress on a necessary project task.

The boost converter circuit was created because there is always a disconnect between the physical manifestation of a circuit, and the software simulation. Since we are tasked to build DC-DC converters in our Capstone project, we assumed that building one as a prototype would be a great learning experience.

4.3 How Do These Fit Into The Big Picture

Essentially these prototypes represent three different aspects of the big picture: PI control, boost converter topology, and specifically a synchronous boost configuration. Our team needs to do two things well: step up the voltage coming out of the AC-DC rectifier and keep that output voltage as consistent as possible. Creating these three prototypes was a big step in accomplishing our end goal.

4.4 Expected Outcome

The main goal driving the prototype choices and instantiation, was to assess the strengths and weaknesses of our DC-DC converter topology research. We wanted to build a physical boost converter to test our theoretical understanding of power converters. In addition, we needed to observe what factors vary when transitioning from the simulated circuit to the physical.

The synchronous boost simulation provided a foundation for understanding the differences between a traditional boost converter circuit (with a MOSFET adjacent to a diode), and the synchronous (two adjacent MOSFETs).

In the PI-controlled simulation, we expected to gain insight into how PI control is used to keep the output voltage of the converter constant, with a varying input voltage as well as a dynamically-changing load–two key problems to solve in our project.

4.5 Expected Challenges

Learning something new is always a challenge; these prototypes were no different. Not only did we anticipate a challenge on an individual level, maintaining productive teamwork was an expected challenge as well.

4.6 What Unknowns Did The Prototypes Include

- Synchronous boost simulation:
  - How are the gates of the two MOSFETs controlled to ensure proper functionality

  - What are the optimal inductor and capacitor values
  - What is the resistance value of the load
  - What is the lowest voltage input value that is still effective
  - How much noise does the output signal have compared to the non-synchronous configuration

- PI-controlled boost simulation:
  - What P and I values produce the best output
  - How will the controller respond to changing input voltage
  - How will the controller respond to changing the output load resistance
  - What are the optimal inductor and capacitor values
  - What is the resistance value of the load

- Boost converter circuit
  - Will our circuit work
  - What are the optimal inductor and capacitor values
  - What is the resistance value of the load
  - What is the minimum input voltage required to start boosting

4.7 Prototype Outcome

Certain aspects of our prototypes went as planned, considering we planned for a challenge. The boost converter simulation with PI control went smoothly once we invested time into learning Simulink and tuning the controller. The synchronous converter was less straightforward in implementation. Our stretch goal was to introduce PI control to the synchronous converter, however the output signal was terribly noisy, and it was not able to step up the input voltage in a significant way. The physical circuit presented many unexpected challenges. Initially we were unable to use a transistor in the circuit as planned, and had to settle on a simple switch-based circuit. Though looking back, we used a load resistor value that was too small, so it is possible that our transistor circuit was working as expected.

4.8 Deviation From The Original Plan

The only major change that was made was the decision to use a switch instead of a transistor to control the duty cycle of the boost converter circuit. As noted above, our circuit was most likely working properly with the transistor and our issue was the load resistor, but we realized this oversight when the switch circuit was built. Originally we planned to present a physical PI controller circuit, which we did build. Another stretch goal was to build a physical PI-controlled boost converter circuit, but considering the transistor implementation was not working properly, we settled on presenting the boost converter without PI control. These changes were due to our novice understanding of power electronics, rather than lack of time.

4.9 Prototyping Approach

A divide and conquer approach was used to complete the prototypes. Mohammed primarily worked on the physical circuit, Humoud created numerous simulations, resulting in the synchronous boost converter Simulink model. Nigel worked on PI control, both physical and simulated. As the team leader, Nigel also focused on making sure the team was progressing well and enjoying the process. As far as algorithmic approaches are concerned, these prototypes involved more brute force trial and error than we had hoped. But we suppose some trial and error was to be expected when learning how to use new software/tools.

Our team meets six hours a week in addition to lab time, so we worked together throughout the prototype development phase. This way we could see how we were progressing and help each other navigate challenges. We all put in extra time independently as well to ensure the success of the team. The prototype demonstration was certainly successful. We would have liked to have accomplished our team's stretch goals, but at this early stage, our presentation was a great representation of our collective knowledge and tenacity.

4.10 Major Challenges Addressed

- Synchronous boost simulation:
  - Noisy output signal
  - Did not initially know what component to use to invert the signal from one MOSFET gate to the other
- PI-controlled boost simulation:
  - Noisy output signal
  - P and I values needed to be changed independently, rather than in tandem, to ensure proper tuning
  - Once the input signal was varied, P and I values needed to change
  - Once the load resistance was varied, P and I values needed to change
- Boost converter circuit
  - Circuit did not boost the input voltage initially
  - Capacitor was too large
  - Arduino was not able to control the transistor gate

4.11 Key takeaways

Through writing about the prototyping experience, we have realized that this project is going to be more challenging than originally imagined in some areas, and easier in others. For example, we thought the physical circuit would be very easy to build; it was simple to follow a schematic, but the reality of how all the components come together, provided a larger delta of unpredictability than what was expected. On the positive side, PI control was relatively simple and predictable. Our model can even be exported to our microcontroller, so that component of the project is surprisingly nearly done.

Moving forward into next semester, we need to schedule in more time than expected to build working models of the synchronous DC-DC boost converters, before the printed circuit board is made. The discrepancies when moving from the simulated realm to the physical was a key takeaway in this prototyping experience.

The prototyping experience directly influenced the remaining project steps outlined in the *Work Breakdown Structure* below. We have built in extra time for testing into the *Gantt Chart* in Figure 3 that follows.

5 Work Breakdown Structure

1. DC-DC Converter System for Micro-scale Wind Turbine
    1.1. Research DC-DC Converter Topology and Wind Energy Systems
    1.2. Prototype Boost Converter Circuit and Controller
    1.3. Build and Test Boost Converter Circuit
        1.3.1. *Build Timer-Controlled Breadboard Circuit:* Involves using an LM555 Timer Integrated Circuit to generate a fixed square wave signal to control the duty cycle of the boost converter circuit. This circuit builds off of the simple boost converter circuit prototype from the previous stage of the project. This circuit does not incorporate any aspects of closed loop control, rather a fixed increase of the voltage provided by the AC-DC rectifier on the input, V_{in}. The deliverable for this task is the physical, fully-functioning circuit. "Fully-functioning" in this case will be verified by measuring the output voltage across a resistive load and observing $V_{out} \gg V_{in}$. The configuration of this circuit will be integrated on a single PCB in WBS task 1.4.
        1.3.2. *Build Arduino-Controlled Breadboard Circuit:* The only physical difference between this circuit and the circuit outlined in 1.3.1 is the controller. Instead of having a fixed square pulse signal on the MOSFET gate, the Arduino will implement proportional-integral (PI) control (see 1.3.3) to create a closed loop boost converter circuit, with a fixed output voltage V_{out}. The deliverable for this task is also the physical, fully-functioning circuit. "Fully-functioning" in this case will be verified by measuring the output voltage across a resistive load and observing $V_{out} \gg V_{in}$, where V_{in} is the voltage leaving the timer-controlled boost converter from task 1.3.1. The configuration of this circuit will be integrated on a single PCB in task 1.4.

1.3.3. *Export and Tune PI Controller from Simulink:* Simulink models can be compiled to executable C++ code to be run on the Arduino microcontroller. Since the simulated PI controller was successfully created and modeled in the prototyping phase of this project, we will be able to flash the controller implementation directly from Simulink to the Arduino. However, this deliverable will be verified with thorough testing of the PI-controlled boost converter circuit. Since the P and I terms are sensitive to all variables in the circuit, we will need to tune these parameters based on the physical circuit behavior. The simulation will help with the calculations, but the physical circuit will inevitably require further analysis and tuning. The deliverable of this task will be in the form of error-free C++ code that compares the boost converter V_{out} to a fixed reference parameter, V_{ref}, and adjusts the duty cycle accordingly to keep $V_{out} \cong V_{ref}$.

1.4. Integrate DC-DC Converter System with Auxiliary Electrical System

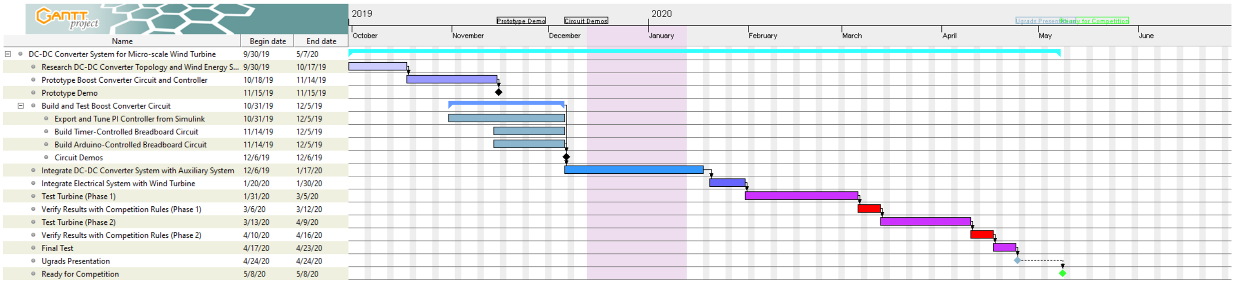
1.5. Integrate Electrical System with Wind Turbine

1.6. Test Turbine

1.7. Verify Results with Competition Rules

1.8. Final Test

6 Gantt Chart



Name	Begin date	End date
DC-DC Converter System for Micro-scale Wind Turbine	9/30/19	5/7/20
Research DC-DC Converter Topology and Wind Energy S...	9/30/19	10/17/19
Prototype Boost Converter Circuit and Controller	10/18/19	11/14/19
Prototype Demo	11/15/19	11/15/19
Build and Test Boost Converter Circuit	10/31/19	12/5/19
Export and Tune PI Controller from Simulink	10/31/19	12/5/19
Build Timer-Controlled Breadboard Circuit	11/14/19	12/5/19
Build Arduino-Controlled Breadboard Circuit	11/14/19	12/5/19
Circuit Demos	12/6/19	12/6/19
Integrate DC-DC Converter System with Auxiliary System	12/6/19	1/17/20
Integrate Electrical System with Wind Turbine	1/20/20	1/30/20
Test Turbine (Phase 1)	1/31/20	3/5/20
Verify Results with Competition Rules (Phase 1)	3/6/20	3/12/20
Test Turbine (Phase 2)	3/13/20	4/9/20
Verify Results with Competition Rules (Phase 2)	4/10/20	4/16/20
Final Test	4/17/20	4/23/20
Ugrads Presentation	4/24/20	4/24/20
Ready for Competition	5/8/20	5/8/20

Figure 3: Project Timeline

The Gantt Chart in Figure 3 above outlines our DC-DC converter project timeline. Dependencies are noted with arrows from one task row to another; the dependency linking the *UGRADS Presentation* to *Ready for Competition* includes some padding time to denote that there may be some final work to be done between the two milestones. The columns of winter break from December 13th through January 12th are highlighted in red. Work will be done on the project during the break, though in a less structured manner than during the semester. Fixed milestones without flexibility are noted with the diamond symbol, others will be added as needed. At this time all testing tasks after December 6th account for 5 days of padding, due to the possibility, though not likely, of finishing tests early. Currently there are no floating tasks.

7 Conclusion

In closing, we have created a strong foundation of conceptual and applied knowledge to embark on the remaining project milestones ahead. Our Work Breakdown Structure (WBS) provided a complete and clear organization for the remaining tasks. The project timeline illustrated in Figure 3 incorporates extra time that may be necessary due to unforeseen testing challenges, like those uncovered during prototyping (see section *4.11*).

We are honored to take part in this year's Collegiate Wind Competition and are looking forward to the collaboration with the Auxiliary and Mechanical teams in the semester ahead.

8 Appendix

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