User Manual

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Sponsors:

Mr. David Willy
Dr. Venkata Yaramasu

Mentor:

Jason Foster
jf727@nau.edu

Team Members:

Humoud Abdulmalek
ha434@nau.edu
Mohammed Almutairi
mma559@nau.edu
Calum Eikenberry
cje223@nau.edu
Nigel Grey
ng474@nau.edu
Carlos Najera
crn82@nau.edu
Nicholas Wurtz
naw94@nau.edu

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User Manual

Introduction

The motivation for this capstone project was to research, design, and build a turbine for the eastern Colorado environment. Fig. 12 below shows the high-level design of the CWC. The DC-DC Team was responsible for implementing an effective, safe, and reliable DC-DC converter system within the *turbine electrical system* block in Fig. 12. The Auxiliary Team was responsible for supporting the DC-DC Team, as well as designing and assembling an enclosure for the electronics, load selection, and all external wiring. The “product” in our case is not only a turbine (in collaboration with the mechanical engineering teams), but a successful design that follows the CWC rules, and ideally wins the in-person competition. Though the CWC is quite different this year than the previous years, the approach of our teams remained focused on this original goal throughout the project.

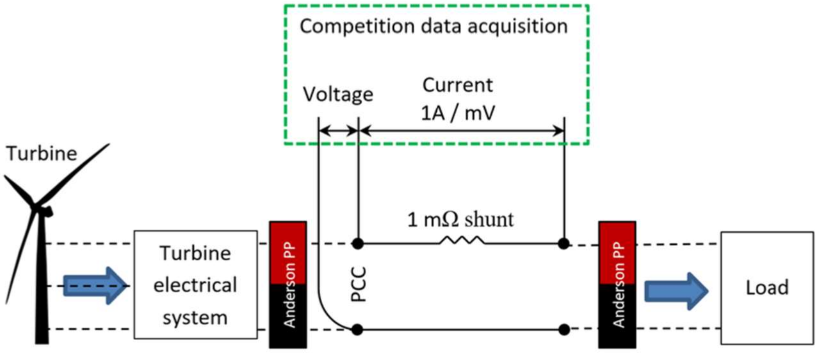


Figure 12: Competition Block Diagram

The key to understanding the project at hand, is to first define the rules of the competition. Until mid-March of 2020, they were as follows:

- Voltage must be direct current (DC) and less than 48V at any point in the system
- The turbine base plate must be tied to ground with a 100 kΩ or less resistor
- Capacitors and inductors may not be used as bulk energy storage on turbine side of point of common coupling (PCC)
- No capacitors rated greater than 10J of energy storage may be used on the turbine side of the system
- Turbine components (capacitors and inductors) must start from a zero-charge energy state
- All external wired connections must be optically isolated
- Turbine electronics must be separately enclosed
- PCC interfacing wires must be terminated with Anderson Powerpole Connectors

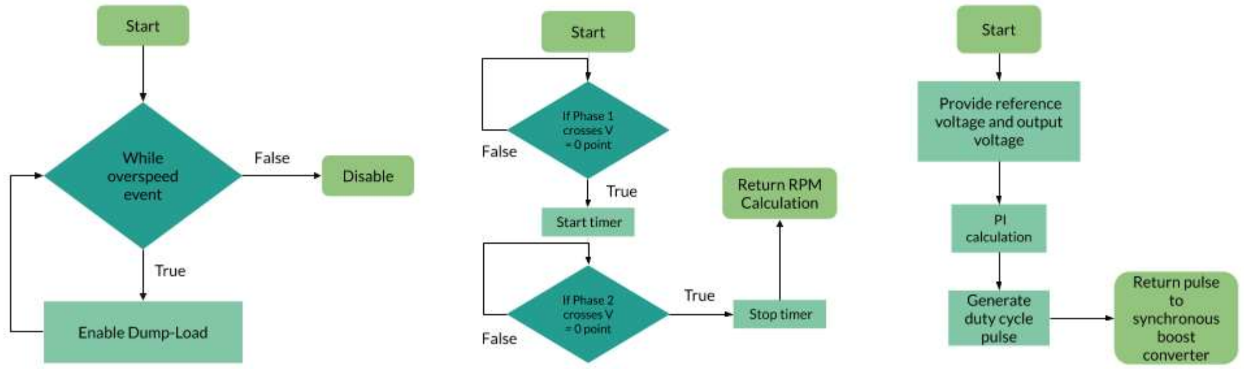
With these main points in mind to guide our design, we initially developed four essential subsystems. These are further broken down in the ***Work Breakdown Structure Metrics*** section above, but at a high level the project involves:

1. Some type of circuit design (we integrated all circuits into a single PCB as pictured in Appendix B)
2. Some way to control the circuits, assuming the team is not using strictly out-of-the-box components (we chose to use an Arduino Mega due to its many analog ports, and in terms of software we chose PI control, since it would provide the most stable signal on the load side of the PCC)
3. System integration and testing (not only do the electronics need to be integrated and tested, but the physical wind turbine needs to be considered as well in order to properly create a unified working system)
4. Final design and testing (since complex systems can usually be improved upon, this key subsystem not only allows for flaws in the original design to be fixed, but new features to be added and tested as needed)

Though the plan to tackle all subsystems above was well considered, it inevitably changed quite a bit. The first semester provided much of the integral background knowledge surrounding wind energy systems, the CWC, and essential converter topologies. The Fall semester also allowed us to develop prototypes (*see Appendix A for circuit diagrams*), which ensured that the full system design that followed would work as expected. We focused on the boost converter for our DC-DC converter system because it is effective and efficient. Our first prototype was a LM555 timer-controlled circuit. This circuit was chosen for its simplicity and because the IC controls the duty cycle of the converter, without the need for a microcontroller. This circuit is essential to our design, which focuses on a low cut-in wind speed. The LM555 boost converter is enabled when the rectified signal reaches ~1V. Since the duty cycle is fixed, the output of the converter is ~3 times the input, allowing the Arduino to be turned on as quickly as possible (with a manufacturer recommended source voltage between 7V and 12V), to begin controlling the second converter, and exposing the load to significantly more power that the turbine could generate independently at such low wind speeds. That second converter was the focus of our next prototype. Once a basic boost converter was built and controlled by the Arduino with a fixed pulse signal, we dove deeper into closed loop control simulations, and found that the Arduino could be directly flashed with a PI control algorithm from Simulink (*see Fig. 5*).

Once the Spring semester began, the schematic was developed (*see Appendix A*) which took care of the main design aspect of Subsystem 1. Once this design was finalized, we developed a PCB in Altium Designer that encompassed all aspects of the schematic (*see Appendix B*). PCB design was extended by a little over two weeks, due to an increase in circuit scope. The new scope included voltage dividers (so measurements could be taken at key intervals in the system), a current measurement, a power-dump circuit, and LEDs for visual feedback (sanity checks for testing and the competition).

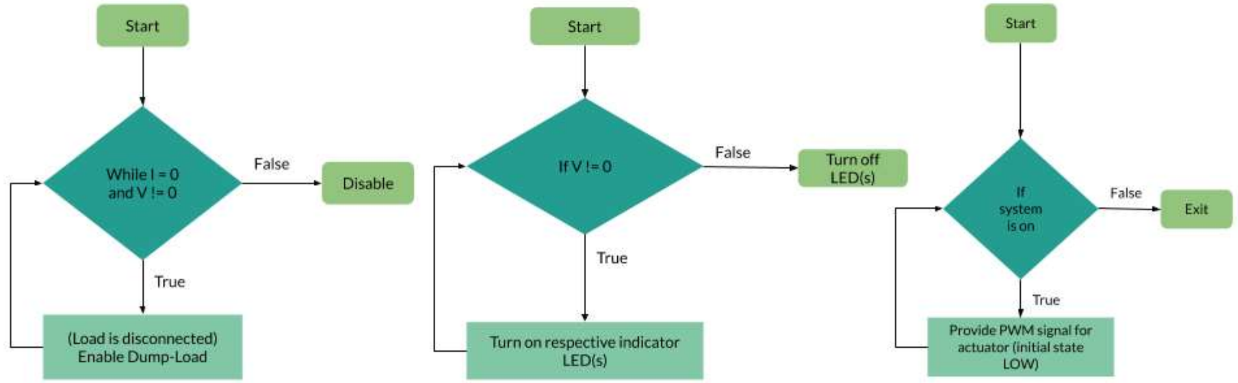
Another unforeseen delay in PCB design was due to a lack of accurate footprints for our components. Subsequently, we had to create these from scratch to ensure proper fit and connection of all discrete components. This pushed our testing schedule back, but allowed more time for us to develop our control theory, as seen in Fig. 13 below.



Dump-Load Circuit

Phase 1-2 Voltage Measurement

PI Controller



Current Sensor Measurement

Stage 2,3, & 4 Voltage Measurements

Actuator Signal

Figure 13: Control Modules

Subsystem 2 is centered around the PI controlled boost converter, though there are multiple other aspects of system control that needed to be developed. The six control modules that drive our control theory are closely related to the various regions outlined in Fig. 14 below. The wind speed versus power simulation was created with the mechanical team's data. The power curve represents the amount of power exposed to the AC-DC rectifier at various wind speeds. The turbine starts at 0m/s, and increases to 18m/s. An "overspeed" event is triggered at 25m/s and the turbine is forced to brake, finally resulting in 0m/s and 0W. Our control modules were designed to address the competition tasks that follow the curve in Fig. 14. Each flowchart in Fig. 13 represents the following:

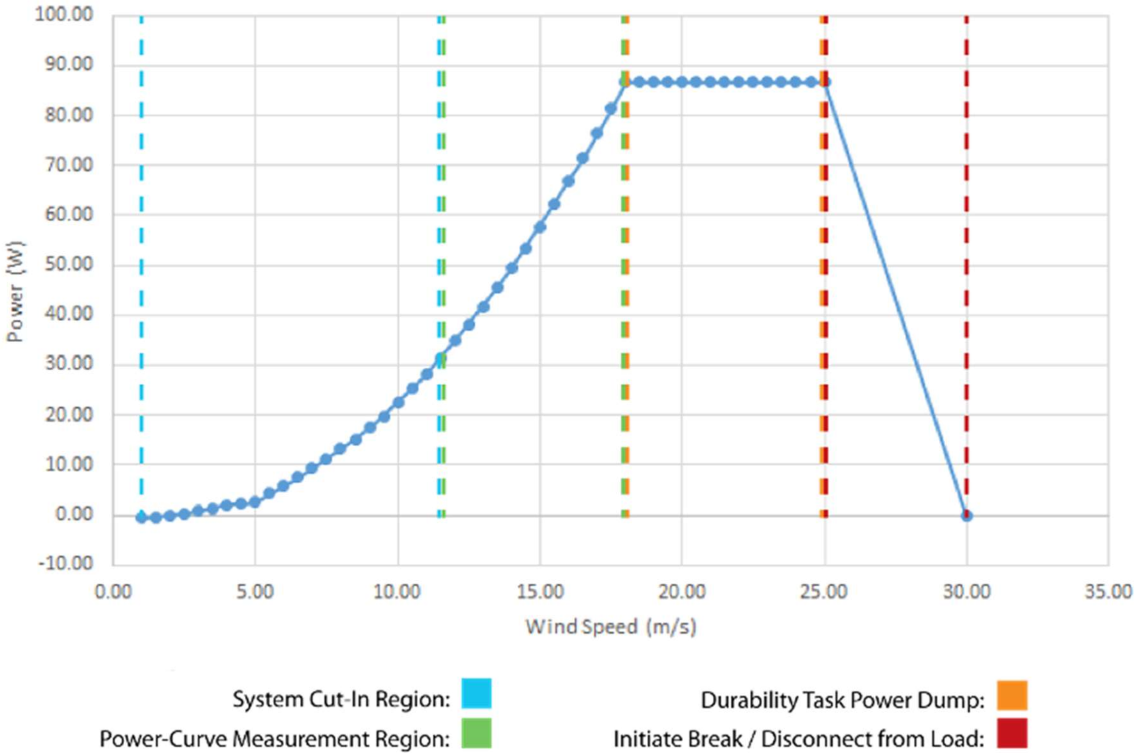


Figure 14: Power Curve with EE Teams Control Theory Regions

1. Dump-Load Circuit: when an overspeed event occurs, route the rectified signal through an external resistor to ground via the “Chopper Circuit” (*see Appendix A*). This control module is active only during the “Durability Task Power Dump” region.
2. Phase 1-2 Voltage Measurement: calculate the turbine rpm via phase 1 and 2 x-axis crossing point difference. This module occurs as soon as the microcontroller is powered on as to detect the point in time to trigger the system brake for the “Initiate Break” region.
3. PI Controller: utilizes proportional integral calculation to control second stage boost converter duty cycle.
4. Current Sensor Measurement: used to detect and signal if load is disconnected. This module is active as soon as the “System Cut-In Region” is reached and detects the “Disconnect from Load” region.
5. Stage 2, 3, & 4 Voltage Measurements: voltage divider circuits used to detect electrical potential at each key stage; trigger LEDs to provide visual feedback. This is also utilized to detect the “Disconnect from Load” region.
6. Actuator Signal: provides PWM signal for mechanical braking control and is utilized during the “Initiate Brake” region.

Subsystem 3, system integration and testing was largely cut short. This year’s competition was adjusted to address this change, as it affected every university that planned to compete. Testing and power quality measurements of the PCB with all soldered components was to take place immediately after receiving the PCB from the manufacturer. LEDs were integrated after each stage of conversion within the circuit to provide visual feedback to the tester, and an oscilloscope would be used to provide exact measurements per the CWC rules and requirements. The design (*see Appendix A)* featured the ability to change the capacitance values to decrease noise and increase signal integrity. Due to the modular capacitance and closed-loop control, additional filtering techniques would not likely be needed. The generator output would be tracked with the use of a dynamometer throughout this testing.

Subsystem 4 manifested itself in the PCB (*see Appendix B*) on a physical level, and the technical design report (a full collaboration with all EE and ME teams) on a conceptual level. The final competition deliverables will be in the form of a virtual question and answer session, as well as a formal presentation. Though we had some early generator power data (*see Fig. 1*), all testing deliverables after February 23rd were cancelled by the competition organizers. It was disappointing not to have a physical, completed turbine system to test and demonstrate, but our design, writing, and problem-solving prowess will certainly prove competitive at this year's virtual CWC.

Over the course of completing each of these four subsystems, we successfully researched, designed, and simulated an efficient and modern turbine electrical system. Though the last month looked a lot different than we had originally planned for, our design and virtual demonstration will provide some stiff competition for the other colleges on this year's virtual stage. We hope our challenges and insight, as developed further in the sections below, will help future NAU CWC teams get to the actual podium in Colorado!

Installation and Further Work:

The current “Rev1” edition of the PCB is lacking all soldered components. The team purposefully detailed each component name on the PCB in white (*see Fig. 15*), and each component corresponding part number is listed within an additional *User Guidance Manual*. This manual will be available to future NAU CWC teams through Dr. Yaramasu. The *User Guidance Manual* will have consistent iterations made until the June 2, 2020 competition date (subject to change). Any motivated individual can solder the components in accordance with these labels. However, it must be noted that all surface mounted components must be soldered using a reflow oven, and after that all through-hole components (including the Arduino Mega header pins) must be hand soldered.

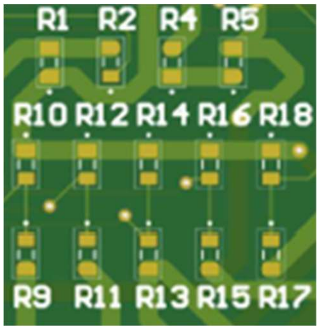


Figure 15: PCB Resistor Section with Labeled Part Names

No load resistor was selected or tested at the time of project completion. However, the team recommends a 300W power rating and 10Ω resistance load be used for initial testing.

Testing of the system must still be done to confirm functionality of the PCB. Please see ***Configuration and Use*** to understand the setup process for testing.

The Arduino Mega can be programmed through the use of MATLAB Simulink. To do so the user can start with our Arduino-ready PI controller Simulink model within the “Simulink.zip” file. To create and flash a module to the Arduino the user can follow these steps:

1. Install the Arduino support package (“Simulink Support Package for Arduino Hardware”)
2. Open the “Module” setting in the “Simulation” tab or “Hardware” setting from the “Hardware” tab
3. Select “Hardware Implementation” and choose the Arduino board (we used an Uno, and later the Mega)
4. Then expand the “Target Hardware Resources” tab, select “Host-board Connection”
5. Select “Solver” in the “Hardware” settings; set start time: 0 and stop time: inf
6. In “Solver”, choose “Fixed-step” as the “Type” and “Auto” as the “Solver”
7. Simulink Arduino blocks are now available at the bottom of the library
8. Arduino blocks are used for pin mapping you can use digital/analog input/output and choose the specific pin number
9. To test the design, open the “Hardware” tab and select “Monitor & Tune”
10. Finally, to flash the program to the Arduino for use without the computer connection, select “Build, Deploy & Start” instead of “Build Stand-Alone”

Once the Arduino is programmed via Simulink export of all control modules (encompassed in a single file) as described in Fig. 13, the system is nearly complete. The last step involves the final setup and external wiring, as discussed in ***Configuration and Use***.

Configuration and Use

The completion of the PCB and the simplicity of the turbine has circumvented much of the need for detailed instructions for using the system. However, there are still five external wiring connections needed to complete the PCB after soldering all components to the board. One can find all connection component names and locations as white labels on the PCB as illustrated in Appendix B. Henceforth, the reader will be expected to determine the locations of connections based on the provided name and approximate PCB location.

- The MAD 5012 generator is connected with external wires secured into the header connection P1 at points labeled “A”, “B”, and “C” near the bottom of the PCB. Other generators of a similar Kv rating can be used.
- A load resistor design can be connected by connecting a positive and ground wire into the “+” and “-” labeled terminals of the header connection P5.
- Header connection P3 has two possible modes of operation. One can connect the two terminals labeled “+” and “+” as to omit boost converter 1, or the user can connect the terminals labeled “BP” and the rightmost “+” to keep boost converter 1 connected. One of these two configurations MUST be wired prior to system operation.
- A power-dump resistor can be connected to the “+” and “-” terminals of header connection P2 to allow the chopper circuit to operate. This connection is highly recommended to be made prior to testing, as a lack of a dump-load resistor can lead to component damage.
- An optional boost converter can be connected at header connection P6; the boost convertor should have its transistor gate connected to the PWM signal labeled “+” and can be grounded with the terminal labeled “-”. The header connection P4 is used to power the boost convertor. The “+” and “-” terminals should be used for the positive and ground lines respectively when using this optional converter. In our intended final design, this convertor was used to power an actuator for a mechanical turbine RPM detector.

After completing these connections to the chosen load, generator, bypass configuration, and dump-load resistor, the user can run the generator with a dynamometer or within a wind tunnel. A quick sanity check can be obtained by observing the three LEDs mounted along the left side of the board. LED1 will light immediately after the Arduino Mega is supplied power, LED2 after the first boost converter, and LED3 after the second boost converter. The design’s power output can be measured at the PCC (*see Fig. 12*).

Maintenance

Since this is a unique competition each year, maintenance will not be required. This section will, however, provide guidance for future teams. As such, the following points are directly addressed to the EE sub-teams.

First off, we will provide some high-level project maintenance with these simple, albeit crucial, insights:

- **Read the rules** early on, and often: the CWC rules will be available from the moment your team is assigned to this capstone, we encourage you to read them in-depth, and continue to revisit throughout the duration of the project
- **Communicate** frequently and effectively with ME and EE teams: one would think this goes without saying, but it is surprisingly easy to forget how collaborative this project is
- **Build circuits**; do not exclusively rely on ideal simulations, the real-world is less than ideal
- **Simplify** as much as possible; minimize the number of parallel control operations, especially as it pertains to software (i.e. try not to add anything you cannot fully explain to another EE student who may be unfamiliar with the project)

With these four key points out of the way, when tracing through our system design you will likely find some potential problem areas. Here are the weak points we have identified:

- Through-hole components are subject to significant vibration; MOSFETs and packaged diode rectifier should be soldered carefully, and reinforced as necessary to minimize pin stress and breakage
- The simulations we created for the boost converter and PI controller (which Dr. Yaramasu will provide to you) will work as is, but pay careful attention to the dependent packages needed for Simulink to export to Arduino (*see **Installation and Further Work***)
- Altium Designer files (which Dr. Yaramasu will provide to you) are error-free, but pay careful attention to software updates; not all updates support full backward compatibility
- The schematic has a hard-wired bypass, as described in ***Configuration and Use***, in case the first boost converter needs to be taken out of the system; this should be tested and implemented with a digital switch if used in competition
- In the off-chance the closed-loop control fails provide signal stability within the required 22KHz noise margin (for power signal deliverable), place a simple LC filter on the turbine side of the load

Replacement parts can be purchased from any electronics supplier (such as Arrow or DigiKey) without many proprietary concerns. It is recommended to cross-reference our footprint library (located on the AMPERE Lab Admin account computer in the CWC2020 folder) to ensure proper fit. All three copies of the PCB feature the ability to add surface-mounted capacitors (of which we purchased ample extras) to increase capacitance if testing proves necessary. You will be building your own PCB eventually, but if you choose to begin by exploring our design, the

Trouble-Shooting section below will help you diagnose any issues that we hope never arise.

Trouble-Shooting

The PCB will be the central landscape for large and small system failures. As such, we have designed it in a way that will help to diagnose and locate system issues. The three LEDs on the PCB indicate when/if power has reached key sections of the circuit. When diagnosing the point of failure, first start with the components that will be easy to test/remove. Many surface-mounted components will be nearly impossible to remove without damage, so it is best to start by checking the through-hole components. If all components are working as intended, check that the power and communications lines of the PCB are intact and are not shorted/open (use your sense of sight and smell for this one!). This will require close inspection and probing of the PCB. There are two layers of metal, so be sure to check the top and the bottom.

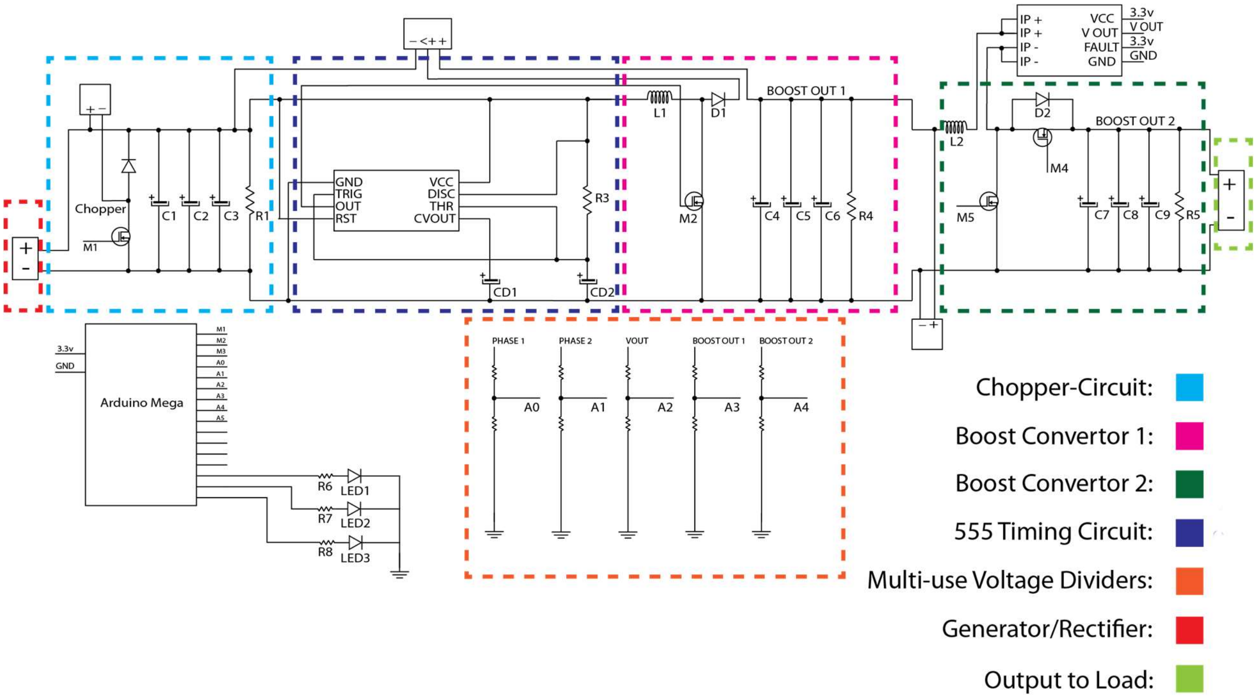
If issues persist while all components are operating properly, open the Simulink model of the PI controller. You can observe the system’s operation through the “Scope” in MATLAB, so long as all inputs/outputs are mapped to the correct pins. Run the simulation to assure that no errors are produced. Issues may arise when trying to use an older version of MATLAB than that of the currently loaded program, so make sure at least version MATLAB 2019b is being used. Flash the program to the Arduino Mega as described in ***Installation and Further Work***. If issues persist beyond the scope of this document, a physical manipulation of PCB traces may be necessary. If this is the case, design and simulate the circuit modification, cut the PCB traces and add external wires/components as needed. This modification can be added to the circuit schematic and integrated into a new PCB revision in Altium Designer.

Conclusion

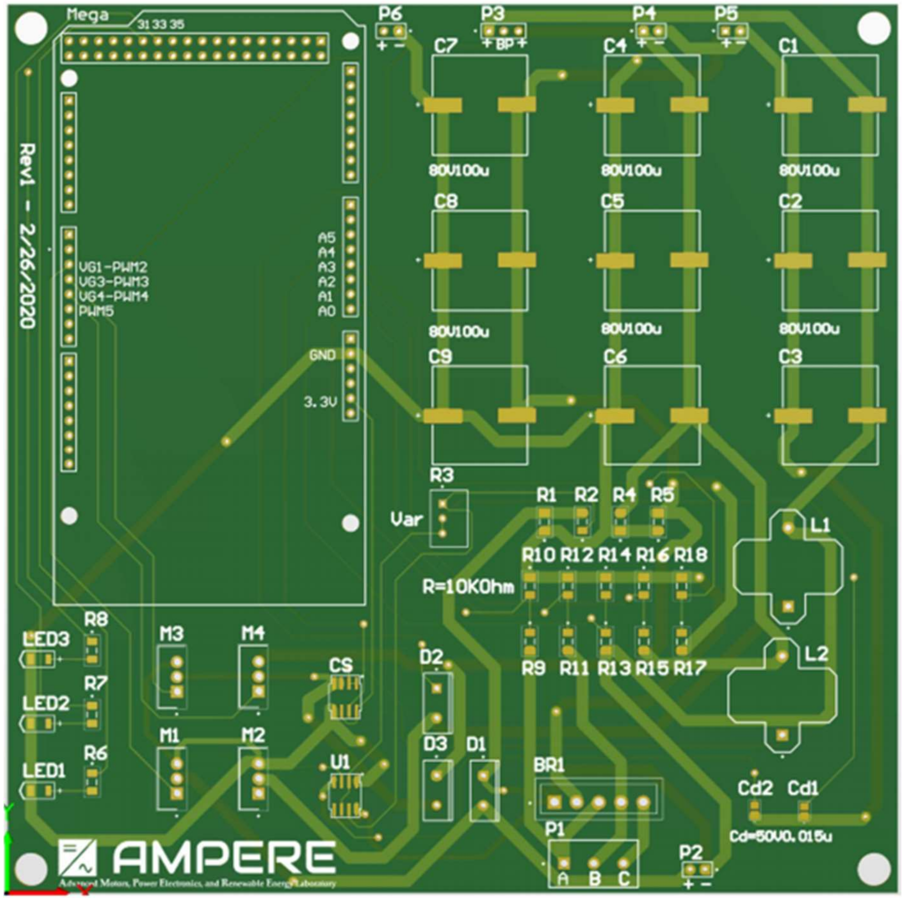
In closing, we hope that this document helps guide future NAU CWC teams through a successful capstone. We also wish that this document can inspire future teams to improve upon our design. We would like to thank our clients, Dr. Yaramasu and Mr. David Willy, for the opportunity to grow as engineers and researchers. As a team, we have grown and developed many valuable skills that will shape our careers as engineers.

Feel free to reach out to any of us with questions via our emails (listed on the cover page). We wish you all the best, and many CWC trophies in the years to come!.

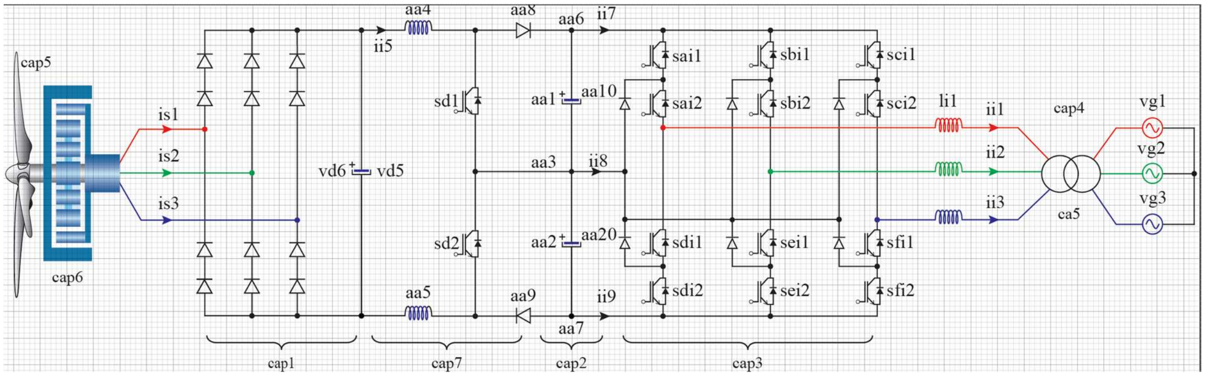
Appendix A: Schematic



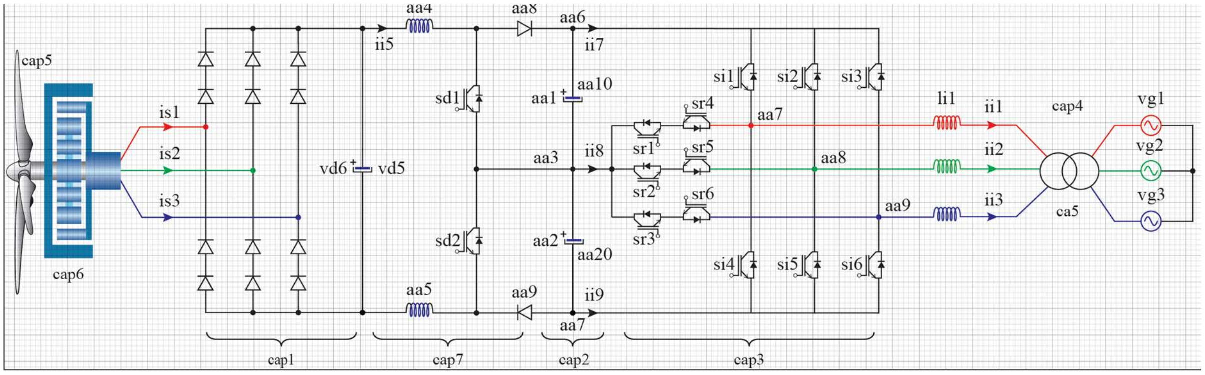
Appendix B: Printed Circuit Board



Appendix C: Adobe Illustrator Figures



Turbine with PMSG+Diode rectifier+3L Boost Converter+3L T-type converter



Turbine with PMSG+Diode rectifier+3L Boost converter+3L NPC Converter