

Iowa State University

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# Hybrid Wind and Solar Generation System

## Final Report

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Advisor: Venkataramana Ajjarapu

Team Members:

Ben Ryan

Xiaokai Sun

Shihao Ni

Riley O'Connor

Trevor Webb

Daoxi Sun

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# Project Design

## **Photovoltaic Array**

The amount of power generated by the photovoltaic array is dependent on the amount of solar irradiance received by individual solar cells. Our solar generation system will have two 1.5 x .668 meter solar panels. Nominal voltage of the two panels in series is 17V, and 7.63 A. The array gives us a nominal power of 270W at peak irradiance.

## **Maximum Power Point Tracking (MPPT)**

The MPPT is a device that tracks the power changes with varying voltage, and ensure the solar panels operate at the voltage where the maximum power output is achieved. It adjusts input to a boost converter to adjust the voltage level of the panels. The boost converter keeps the system as close to the voltage that achieves maximum power as possible.

## **Battery Bank**

Two 12V batteries are to be connected in series to achieve the desired 24V for the battery bank. The battery bank will be connected in parallel to the inverter and load in order to store charge at the desired level of voltage and feed the load when necessary. A switching mechanism will be used to determine which of the generation systems is charging the battery, and when to disconnect the battery when fully charged.

## **Permanent Magnet Synchronous Machine**

The amount of power generated by the permanent magnet synchronous machine (PMSM) is dependent on the wind speed readings taken by the anemometer. A higher wind speed results in a faster rotational speed and more power. A lower wind speed has the opposite result in the wind system. The PMSM is mechanically coupled to the permanent magnet generator and thus their rotational speeds will be the same. The machine is controlled by a constant speed Simulink motor drive which is loaded onto the T.I. F28035 microcontroller. The drive utilizes vector control to maintain the speed of the PMSM in rotor frame of reference. The drive includes watch variables to monitor q and d axis voltage and current values.

## **Permanent Magnet Synchronous Generator**

Zoning laws prohibits us from having a wind turbine on top of Iowa State University buildings. The permanent magnet synchronous generator (PMSG) is a simple 12 pole three phase generator removed from a 400W terrestrial wind turbine. The PMSG is mechanically coupled to the PMSM to simulate a real wind turbine. The rotational speed of the PMSM and the PMSG will be the same. Because wind turbines have relatively low rated speeds compared to PMSMs, we will have to derate the power rating of generator. The output voltage and frequency of the PMSG is linearly proportional to its' rotational speed. As wind speed (PMSM speed) increases, the three phase output voltage and frequency of the PMSG will also increase.

## **Rectifier**

The rectifier converts the three phase AC output voltage from the PMSG to DC voltage. The rectifier is a simple three phase diode bridge rectifier with a filter to smooth out the output DC voltage. The rectifier is mounted on a large heat sink to dissipate heat loss in case of future expansion. Since the three phase voltage from the PMSG is a function of the PMSM rotational speed, the DC output voltage is as well. The variable frequency component of the input AC voltage is also eliminated in the rectification process.

## **Boost Converter**

The output of the rectifier filter is connected to the DC to DC boost converter. The purpose of the boost converter is to maintain a constant DC voltage output. A constant DC voltage is desirable to properly connect the batteries and the inverter with the solar generation system. The boosted voltage of 24V is ideal because the charged batteries will be at 24V as will the output of the solar generation system. At the output of the boost converter, a constant and smooth 24V DC is observed regardless of the PMSM rotational speed.

## **Inverter**

The inverter will convert the 24V DC input to the standard single phase 120V 60Hz AC used in America. The inverter utilizes pulse-width-modulated control signals to regulate the switching to create steady 60Hz, 120V AC for the load. The inverter will take about 10 seconds to be powered up.

## **Load**

The solar generation system utilizes a standard 120V AC load that is purely resistive. The load will be connected to the output of the inverter. We designed a variable load such that the user can switch between different power consumption levels for testing and demonstration purposes. The variable load is built with four light bulbs connected in parallel.

Due to inductive issues when connecting the boost converter from the wind system to the inverter, we were not able to incorporate the inverter into the wind generation system. We isolated the boost converter and inverter from the system and tested them individually using the lab equipment but to no avail. Thus, we opted to use a variable DC load connected to the output of the boost converter. The principle of the system remains the same for demonstrative purposes.

# Implementation

## Solar

We put two solar panels in series to increase the voltage we produced. This allowed us to power the inverter, as well as enable our system to send more power through the MPPT. In order to get as much sunlight as possible, we moved them away from their original location and adjusted the facing angle. The current configuration of the panels can be seen below.



*Figure 1.1: Solar panel configuration*

The MPPT is powered by the battery input. We connected the batteries and solar panel to the appropriate terminals to observe how the MPPT altered solar panel voltage. The current was only observable when we connected our load to the load terminals.



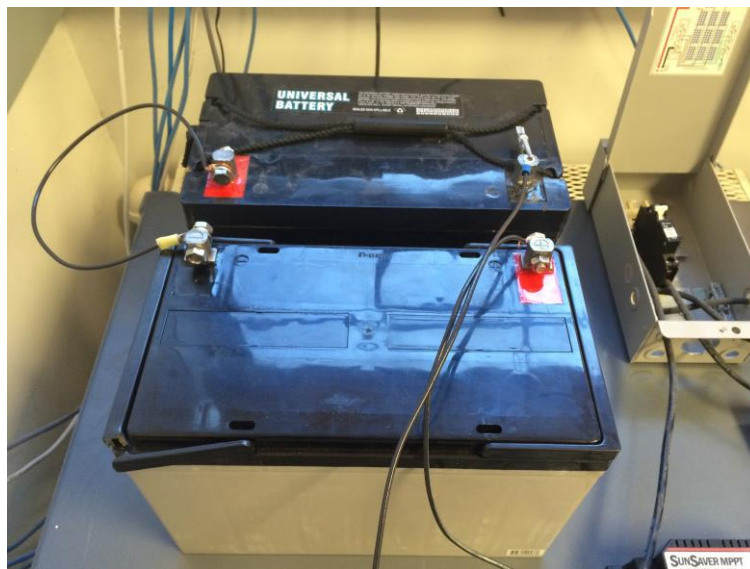
*Figure 1.2: MPPT with solar panel, battery, and load terminals*

The solar panels are connected to the rest of the system using the solar panel combiner, as seen in figure 1.3. The positive cable goes through a 15 A circuit breaker. This allows us to conveniently enable or disable to power going into our system.



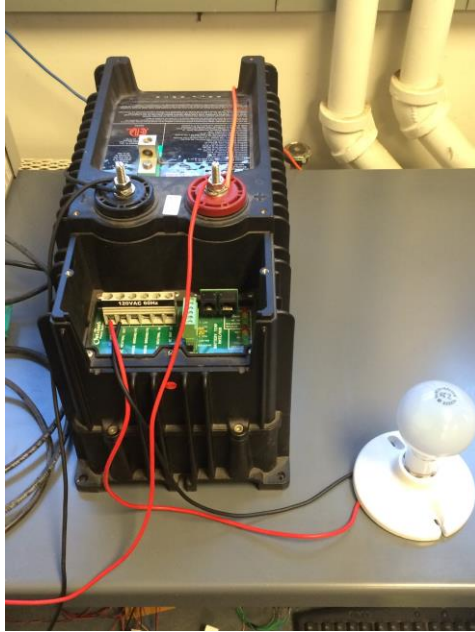
*Figure 1.3: Solar panel combiner*

Two 12Vt, 90Ah high-capacity lead-acid batteries were connected in series to provide the inverter with the necessary voltage level to power it. The 24V combination allows 400 W to flow through the MPPT, as opposed to only 200 W with A 12V battery level.



*Figure 1.4: Battery bank*

The Outback inverter converts the DC voltage to single phase AC voltage. The MPPT output terminals are connected to the 21-35V input terminals on top of the inverter. The 120V AC output is accessed through the positive and neutral pins above the green board as seen in figure 1.5. Figure 1.5 depicts the inverter connected to a single 150W light bulb during our testing.



*Figure 1.5: Inverter connected to simple load*

A mount was built to hold four standard light bulbs of various wattage. Three switches allow the user to conveniently adjust the size of the load by disconnecting and connecting the parallel light bulb mounts. The default size of our load is between 100 and 400W, with four 100W light bulbs. The adjustable AC load can be seen below in figure 1.6. The load is connected to the positive and neutral terminal ends of the inverter output block to achieve 120V AC.



*Figure 1.6: Variable load mount*

## **Wind**

The permanent magnet synchronous motor (Anaheim Automation EMJ-04APB24) is used to simulate a wind driven turbine blade. To control the speed of the motor, we are using a vector control drive to maintain rotational speed in the rotor frame of reference created by Nicholas David. The controller developed by Nicholas David allows for more precise control and the ability to tweak the drive as necessary. The drive was created entirely within Matlab Simulink and incorporates watch variables so all

necessary parameters can be monitored in real-time. Noise filters can also be tweaked to allow for precise control. The Simulink controller created by Nicholas David also allowed us to implement simulated wind speed effects to drive the PMSG as if it were connected to a wind turbine blade. We added simulink blocks to that will change the rotational speed of the motor in a manner similar to wind speed behaviour. However, the drive is currently limited to driving the motor at a rotational speed of 1000 RPM due to the increased electrical noise from the high required DC input voltage. Figure 1.7 depicts a screenshot of the Vector motor controller developed by Nicholas David in Matlab Simulink.

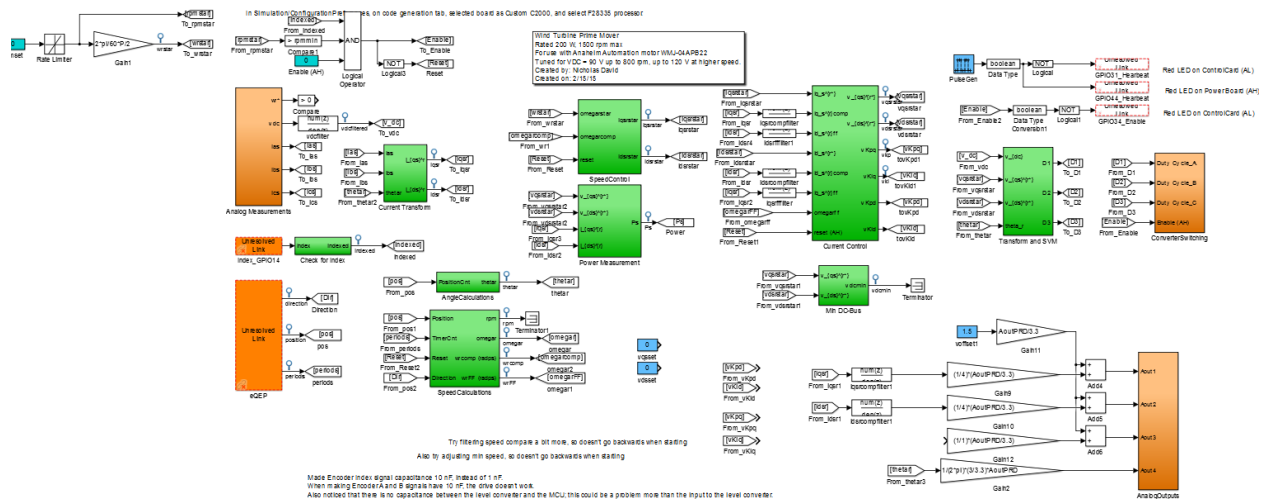


Figure 1.7: Simulink PMSG vector controlled drive developed by Nicholas David

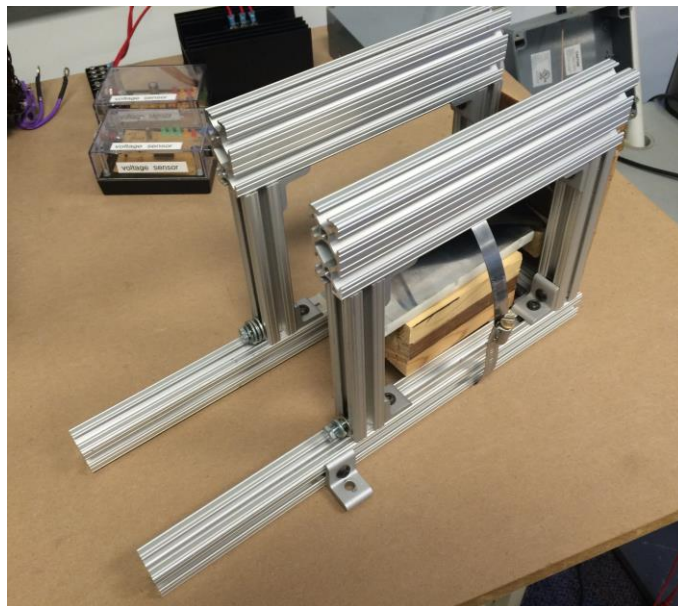
The permanent magnet synchronous generator was taken from a 2008 Air-X terrestrial 400W wind turbine. It is called a permanent magnet synchronous generator because the rotor contains north and south pole pairs to create a magnetic field. This particular generator has 12 north and south poles or 6 pole pairs. There are three phase coils wound on the stator which is around the rotor. As the rotor spins, a moving magnetic field is subjected to the coils on the stator. The changing magnetic field causes an induced voltage in the stator coils. When a load is applied to the terminals of the stator coils, a current flows. The permanent magnet synchronous generator can be seen below in figure 1.8.



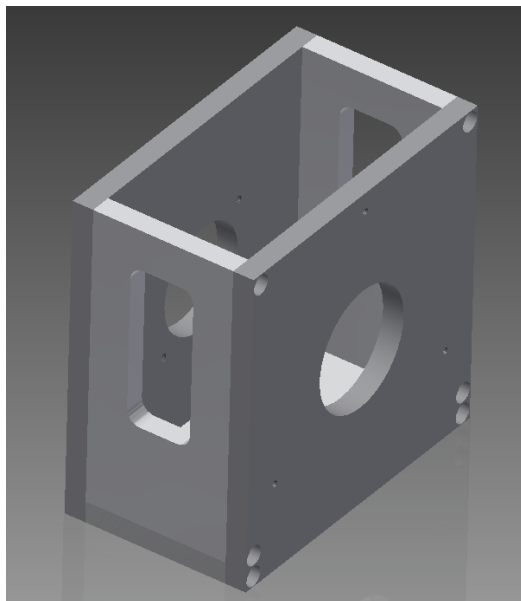


*Figure 1.8: Permanent magnet synchronous generator from 2008 Air-X 400W wind Turbine*

The PMSM and PMSG mount/coupling system from the previous design team did not provide sufficient support. We designed a new mount in a 3D drafting program called Autodesk Inventor. The mount was cut and drilled from thick aluminum aluminum plates using a computerized numerical control (CNC) machine. The new mount securely couples the PMSM with the PMSG, minimizing vibrations and frictional losses that occur from a poor mount. Figure 1.9 depicts the previous mount that we decided to abandon. Figure 1.10 is the three dimensional Autodesk inventor model of the coupling mount we designed. Figure 1.11 is the finished and assembled coupling mount.



*Figure 1.9: Previous PMSM-PMSG coupling mount*



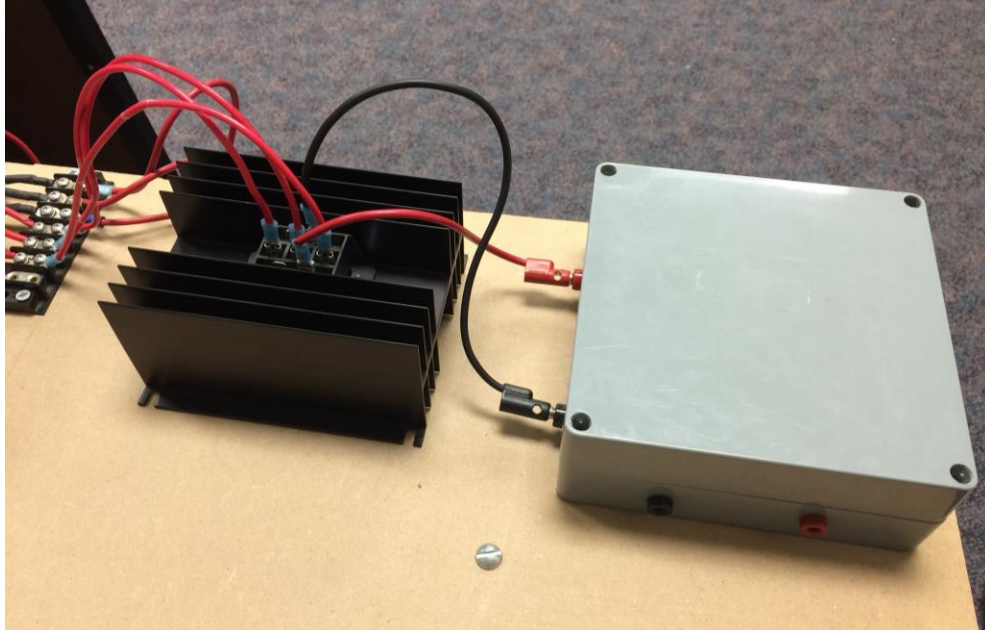
*Figure 1.10: Autodesk Inventor model of the new coupling mount*



*Figure 1.11: New CNC machined custom coupling mount assembled*

We decided to disregard the previous team's rectifier. The old rectifier utilized individual TO-220 package diodes that offered no heat dissipation. The maximum forward current for the old diodes was only 6A, leaving a small margin of error for safety. The maximum reverse voltage for the old diodes was only 40V DC. The output of the generator will approach this value and leaves no engineering safety margin. We opted to buy a three-phase bridge rectifier that has a maximum forward current of 58A and a maximum reverse voltage of 1200V DC. With these parameters, we can be sure that there will be more than enough safety tolerance to keep the bridge rectifier safe from high voltages and currents. We also place the bridge rectifier on a large heat sink to accommodate future designs that may utilize a larger load. The previous team's rectifier did not include any filtering components. Upon testing the rectifier, we found the ripple voltage to be large (~2V) and unacceptable for the purpose of this project. We created

calculation books to determine the minimum capacitance and inductance values to obtain the desired voltage ripple. We designed the rectifier to have less than a 1% voltage ripple which corresponds to a parallel capacitor of  $200\mu\text{F}$  and a series inductor of  $3.3\text{mH}$ . The rectifier and the smoothing filter can be seen below in figure 1.12.



*Figure 1.12: Three-phase bridge rectifier and smoothing filter*

The boost converter steps up the input voltage to a regulated 24V DC. There are two purposes of the boost converter. The first is to eradicate the wind speed dependant voltage from the system by maintaining a constant 24V DC output. The second purpose is to allow for the parallel combination for the battery system and the solar system. Although we ended up purchasing the boost converter, we created calculation sheets that provide all necessary calculations for a proper 24V DC output. The boost converter requires a minimum input voltage of 12V DC before boosting can be enabled. Thus, an approximate minimum speed of the PMSM is 600 RPM. This speed is near the start up speed of the Air-X 400W wind turbine of 500 RPM under normal operation. Figure 1.13 depicts the boost converter used for our project.

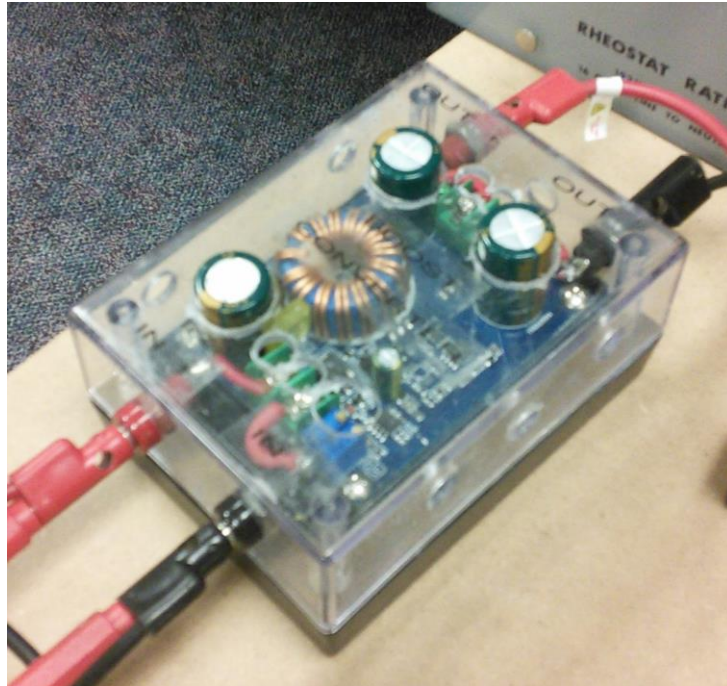


Figure 1.13: DC-DC Boost converter

Because the Inverter draws more power upon startup than the motor can supply at its current maximum rotational speed (1000 RPM), we decided to utilize a DC load to demonstrate the wind system. The DC load consisted of a large rheostat connected to the output of the boost converter via diode. The diode is in place to prevent current from flowing back into the system. This could occur when the batteries are fully charged and connected to the 24V DC bus. Figure 1.14 depicts the rheostat connect via the protection diode.

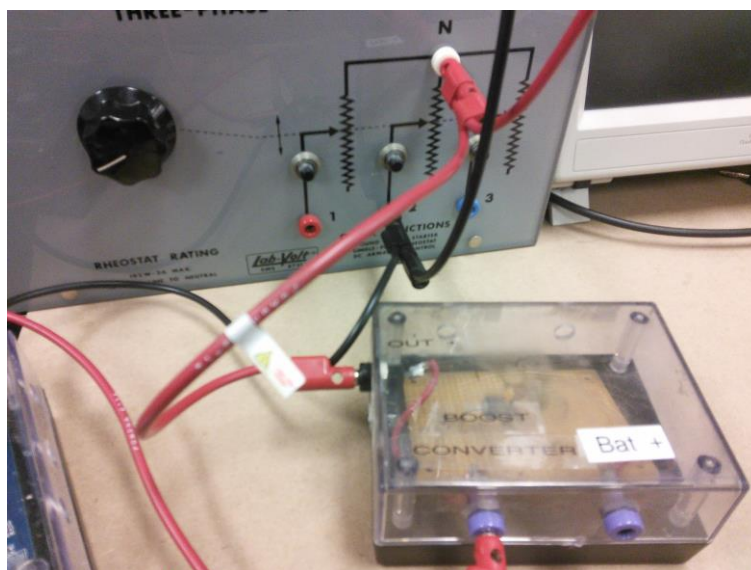


Figure 1.14: rheostat resistive load connected via protection diode

# Testing Process

Several devices were connected to measure desirable output from the solar generation system. To measure current from the solar generation side, three Hall Effect current sensors were connected to an oscilloscope and attached to the positive output wires of the solar panel, battery, and load. Oscilloscope output can be seen in figure 2.1.

An analog voltmeter was used to measure voltage at the solar input, since the battery and inverter voltage levels are generally constant and we were restricted by room for our system.

Finally, a wattmeter was implemented to observe the power flowing into the load. Current and voltage for the wattmeter are taken from the output of the inverter. The wattmeter and voltmeter can be seen in figure 2.2 below.

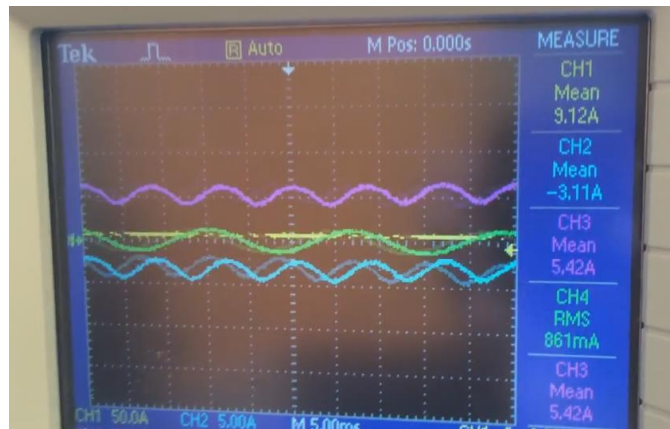


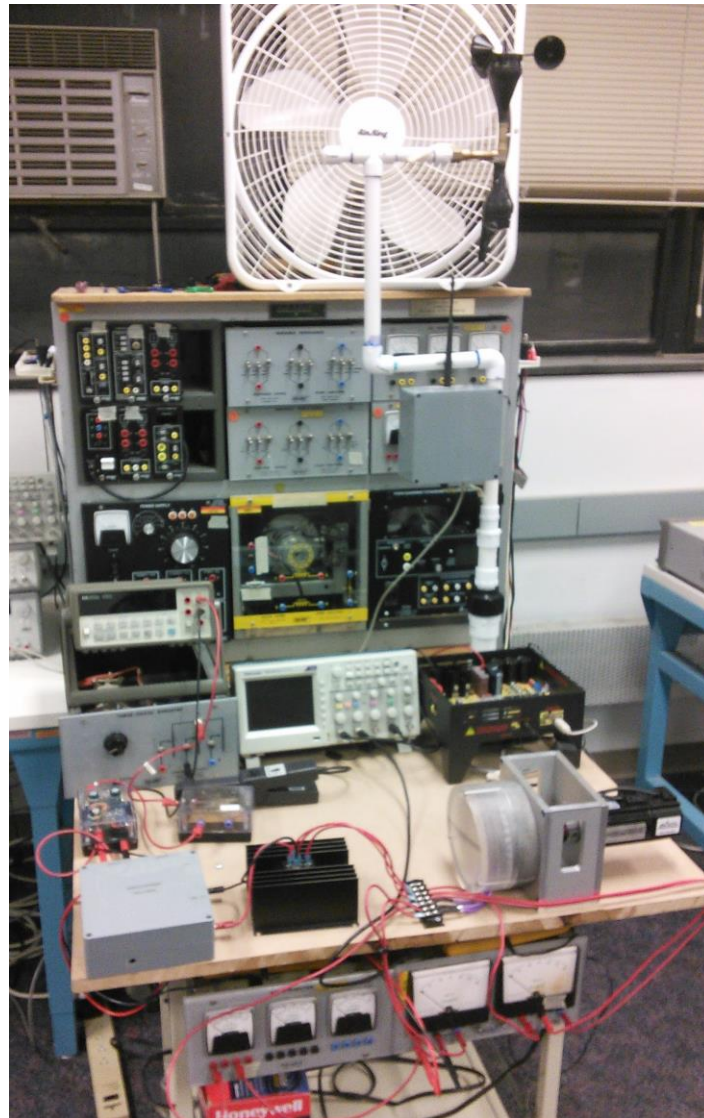
Figure 2.1: Current measurements of panels (yellow), load (purple), and battery (blue)



Figure 2.2: Switching load power to observe current supply behavior

It is crucial to understand and be aware of the correct inputs and corresponding outputs of every component at every stage in the design process. For this reason, we measured voltage and current at all

essential nodes in our wind system. The PMSM controller developed by Nicholas David can monitor line current, voltage, and speed. Thus, the electrical input power can be calculated and displayed on the control PC. We utilize Lab-volt watt meters, ammeters and an oscilloscope voltage probe to monitor the electrical output power of the generator. We also use an oscilloscope voltage probe and hall effect probe to monitor current and voltage in to the boost converter. Thus, the power at the input of the boost converter can be monitored. We also use an oscilloscope hall effect probe to measure the DC load current. A digital multimeter reads the constant 24V and the load power can be calculated. Measuring the power at each essential node in the system allows us to see the losses associated with each component. We can also observe how a changing wind speed affects the voltages, currents, and power through the system. Figure 2.3 depicts the wind system with all measurement devices in place.



*Figure 2.3: Wind system with measurement devices in place*

# Testing Results

After deciding on a parallel configuration for our solar panels, batteries were acquired to power the MPPT at 24V. These two inputs feed into the MPPT and provide power for our AC load up to 350 W. This constraint is due to the maximum 400W output of the MPPT, and the slight inefficiency of the inverter as it converts the DC power of the batteries to AC power. Using our measurement systems, we were able to verify that the solar panel charges the battery while powering the load, given sufficient irradiance. The battery supplies current to the load to make up for any lull in solar output. The system can handle any shift in load, provided it does not exceed the maximum 400W allowance of the MPPT.

We also computed the largest load that the solar can supply while keeping the battery charged indefinitely, given a few variables. The second block of code in Appendix IV shows our load analysis for the month of July. Depending on winter or summer months, we can power a load between 50-85W for as long as the system is able to run. With less-frequent load usage, or the ability to charge the battery with other means, the load can be greatly increased.

Each component of the wind system was tested individually. We provided a calculated input so that a desired output could be observed. We observed the expected outputs from each component of the wind system. All of the maximum voltage and current parameters in each component are within the limits of the system.

We saw the same result upon testing the system as whole. Under no load, there were very small currents throughout each component. Voltage magnitudes were within the calculated tolerances. The DC voltage ripples were also within the designed 1% tolerance. We also observed the expected results upon loading the wind system with a DC load. We saw that the electrical power input to the PMSM was higher than the electrical power produced by the PMSG. The power output of the PMSG was higher than the power output of the rectifier. Finally, the power output of the rectifier was higher than the load power. This verifies and demonstrates the small power losses that should be observed in the system. The power losses were lowest with a small DC load and increased as the load increased.

# Appendix I: Operation Manual

## I. Setup

When running properly, the system will use wind, solar, and battery power to supply power to a variable load. Wind and solar contributions are highly dependent on weather, so these factors should be considered when selecting load size. The recommended load size is between 100 and 350 Watts.

## II. Operating the Solar Generation System

The solar generation system consists of two twelve volt batteries connected in series whose output is connected to the MPPT, solar panels which are connected to the MPPT through a circuit breaker, an inverter which receives the output of the MPPT, and an AC load which receives the output of the inverter.

To operate the system, the switch that connects the batteries to the MPPT must first be closed. This must be done first because the MPPT will not operate without receiving at least seven Volts from the battery input terminals. Next, the switch on the circuit breaker that connects the solar panels to the MPPT can be closed. The MPPT should now be on and this can be verified by checking the status light on the MPPT. After a few seconds, the inverter will power on and AC power will be delivered to the load. The status of the inverter can also be verified by a LED display on the inverter. It is normal for a humming noise to accompany the activation of the inverter.

The variable load is configured so that the first lightbulb will automatically turn on, unless there is not enough power from the solar panels and the MPPT to power that first lightbulb. The second, third, and fourth light bulbs can be added to the total load by closing the associated switch. However, the lightbulbs are connected in series so the switches must be closed sequentially. Four 100W light bulbs represent the systems maximum load because the MPPT is not rated to handle more than 15 A. A 400W load at 24V draws 16.6A which exceeds the rating. If the rating is exceeded the MPPT turns itself off for protection.

## III. Operating the Wind System

The wind generation system consists of an anemometer, coupled PMSM and PMSG, PMSM controller, rectifier, boost converter, and protection diode. To operate the system, the PMSM drive needs to be loaded on to the T.I. F28035 microcontroller. This is done through Code Composer Studio V5.3. Verify that the workspace, target configuration, and program files are correct before loading the code. Be sure to enable continuous updating of the watch variables to see live data. The controller utilizes vector control to control the rotational speed of the PMSM, thus the controller needs to find the rotor frame of reference. The rotor frame of reference is determined by finding the home location on the encoder of the PMSM. The home position is a single marking on the encoder that marks the axis of the q-axis. While all power is turned off, manually spin the rotor of the motor until the watch variable “indexed” turns from a 0 to a 1. Connect the terminals BS5 and BS6 to the variable DC output (7-N) on the Lab-Volt power supply. Increase the DC voltage until 80V is reached. Verify that the “DCvoltage” variable is properly measuring



this voltage by checking its value against a digital multimeter. Enable the “enable” variable in the Code Composer Studio interface. Set the “rpmset” variable to the desired RPM between 150 and 1000 or enable the “windspeed\_control” variable by changing its value from a 0 to a 1. The motor will begin to spin. The generator will begin to spin and voltages and currents can be observed. To achieve a 24V DC output from the boost converter, the minimum rotational speed of the PMSM is 600 RPM. It may be necessary to disconnect any load on the system before starting the motor. The rheostat load is a variable resistive load. The resistance values can be adjusted anywhere from  $.6\Omega$  to  $16\Omega$ . The maximum current allowable through the rheostat is 2A, which corresponds to approximately 48W when the boost converter is on; keep this in mind.

# Appendix II: Alternative Designs

In this section, we outline different versions of our current project design. These alternatives were generally dismissed in favor of designs that more suited our design specifications or merely worked better with certain components of the system. Our client, Dr. Ajjarapu, never dramatically shifted design specifications to the point of forcing us to make major changes.

## **I. Solar Panels in parallel, 12V battery level**

One alternative setup for solar panels was to have the panels in parallel, rather than in series. This creates a nominal voltage of 17.7V and current of 15.26A. This is the same total power that the panels in series would produce. This would mean that only a single 12V battery would be necessary to power the MPPT and complement supply to the load. Since our goal is to keep the battery around full charge, having fewer total ampere-hours is not a major issue.

However, we discovered that the MPPT will allow 15A to pass through it at any given time. This means at a 12V battery level, the maximum size load can never be greater than 200W. The 24V system will allow for the supply of our maximum load level of 400W. Additionally, two panels in series made for a less cluttered solar combiner. An additional benefit is that the entire photovoltaic array may be enabled and disabled with a single circuit breaker with a series configuration.

To turn off the system, first open the switch for the circuit breaker which will disconnect the solar from the system. Then open the switch that connects the batteries to the MPPT. The inverter will shut off and the system will not be powered.

## **II. Live anemometer control of motor**

We tried to implement many methods to read the anemometer readings, convert them to an appropriate PMSM rotational speed, and spin the PMSM accordingly. Due to Simulink support for real time serial communication code generation constraints in Matlab simulink, we were not able to achieve this. Thus, we recorded the wind speed readings from the anemometer over a 15 minute period. We then simulated that data using a lookup table. The lookup table with simulated wind speed readings was then generated to code and built on to the T.I. F28035 microcontroller.

## **III. Alternate motor controller**

Our first plan to control the motor was to utilize a GUI made for our stepper motor (Anaheim Automation EMJ-04) by Mathworks. We opted to use a vector control drive created by Nicholas David to control the motor. The controller developed by Nicholas David allows for more precise control and the ability to tweak the drive as necessary. The drive was created entirely within Matlab Simulink and incorporates watch variables so all necessary parameters can be monitored in real-time. Noise filters can also be tweaked to allow for precise control. The Simulink controller created by Nicholas David also allowed us to implement simulated wind speed effects to drive the PMSG as if it were connected to a wind turbine blade.

#### **IV. Boost Converter**

We attempted to use the T.I. Piccolo F28035 microcontroller to act as the source inductance and provide proper switching to build a boost converter capable of maintaining a 24V DC output. We began by successfully building a buck converter using the F28035. Altering the switching configuration proved to be more of a challenge than expected. We opted to purchase a constant voltage boost converter as a backup plan.

#### **V. Connection to inverter**

We attempted to connect the output of the DC-DC boost converter to the inverter to drive a 120V 60Hz AC load. We were not able to do this due to the 1000 RPM limit of the PMSM. At this limited speed, the PMSM was not able to provide enough torque to provide for the start up power demands of the inverter. The controller began to lose speed control of the motor and the system had to be shut down. As a result, we opted to demonstrate the system providing power to a DC load. Provided the DC load is smaller than the torque the PMSM can provide at the given rotational speed, the system will operate flawlessly. We believe that if we could either reliably spin the PMSM at the rated speed of the PMSG (1800RPM) or use a motor that can produce a higher torque at low speeds, that our system would be able to connect to the inverter without an issue. Because we did not connect the wind system to the inverter, we also did not connect the batteries to the system. We did however add in a protection diode on the 24V DC bus for the batteries or the output of the solar system to tie into for future design teams.

## Appendix III: Other Considerations

An interesting consideration is the situation when there is not much solar or wind power, and thus the load will rely entirely on the battery. The battery needs to have enough capacity to power the system for a decent amount of time, and be recharged by the solar later on.

An important aspect of the PV system is that solar power needed to be prioritized over battery power when the solar power is available. The MPPT that the PV system uses does this automatically. So any and all solar energy that is generated will be used to either power the load or recharge the batteries.

Also, in case we have too much power coming from solar array and wind turbine, and battery is already fully charged, we need to have a way to either dissipate the redundant energy or to cut off connection to the power source in order to protect the battery and load. This disconnect can be done manually.

# Appendix IV: Code

1. Code Written in Arduino to receive Anemometer data, converter it to a speed in MPH, and send it to the PC via USB.

```
/*
 * Windspeed measurement sketch using NRG 40C anemometer whose signal has been
 * massaged into a TTL square wave.

 * Edited by: Ben Ryan 02/13/2015
 */
#include <EEPROM.h>
#include <NewSoftSerial.h>

int anemPin = 4;    // digital sensor is on pin 4 of Arduino
int vanePin = A0;   // Analog wind sensor is on pin A0 of Arduino
double sensorOne, oldval = 100; //Wind speed sensor
int sensorTwo;     //Wind angle sensor

void setup()
{
  Serial.begin(9600);    // start serial port at 9600 bps:
  pinMode(anemPin, INPUT); // Set digital sensor as input
  Serial.println("Serial Communication OK");
}

void loop()
{
  // Arduino begins timing once it reads a low pulse since waveform is inverted.
  sensorOne = pulseIn(anemPin, LOW);
  // Read value from wind vane
  sensorTwo = analogRead(vanePin);
  // Convert analog value to degrees
  sensorTwo = sensorTwo * (360.0 / 1024.0);

  if (sensorOne == 0 || sensorOne < 0 )
  {
    // Arduino begins timing once it reads a low pulse since waveform is inverted.
    sensorOne = pulseIn(anemPin, LOW);
    // Read value from wind vane
    sensorTwo = analogRead(vanePin);
    // Convert analog value to degrees
```

```

    sensorTwo = sensorTwo * (360.0 / 1024.0);
}

else
{
    // Convert half period to hz
    sensorOne = 1 / ((sensorOne / 1000000) * 2);
    // Convert hz to mph as specified by the datasheet
    sensorOne = (sensorOne * 1.711) + 0.78;
}
// Display sensor values over serial:
Serial.println(sensorOne);
}

```

2. Matlab code for sizing the maximum load that solar panels and battery can reliably power, without depletion of the battery.

```

%ee 492 Solar Output Calculator
%user-defined input
%solar panel is 270 W
V_batt = 24;           %battery voltage level in volts. MPPT also sets load voltage at this level
Ah_max = 90;          %battery ampere-hours
W_batt = V_batt*Ah_max; %Power produced by battery in watts
P_load = 70;          %Power drawn by load in watts
Iph = P_load/V_batt; %amperes per hour drawn by the load

%Solar Panel Output, all times in military time
%July input. Other inputs available by request.
P_t= [3 49    138    200    211    165    77    8];
%each element is average power for a 2-hour time span, starting at 4 am
%all other times, P = 0 W

%initial settings for time burden
P_chrg = [0 0 0 0 0 0 0 0]; %excess power from panels for charging battery
t_PV = 0;                   %time in hours that solar panel powers load + batt
t_batt = 16;                %time in hours that battery powers the load
k=1;

for k = 1:8
    if P_t(k) >= P_load %determines how much time solar panels power load
        t_batt = t_batt - 2;
        t_PV = t_PV + 2;
        P_chrg(k) = P_t(k)-P_load;
    end
end

```

```

    end
end

k = 1; %reset counter

%calculate how many Ah battery uses in one 16-hour period
t_batt_max = W_batt/P_load; %how many hours battery can fully supply load
t_batt_rem = t_batt_max - t_batt; % how many hours remain after 16-hour period
fraction_batt_rem = t_batt_rem/t_batt_max;
Ah_rem = Ah_max * fraction_batt_rem; %fraction of the battery Ah remaining
Ah_used = Ah_max - Ah_rem; %amount of Ah supplied over 16-hour period

%calculate total Ah battery is recharged by the solar panel
Ah_charged = 0; %default value for Ah charged to battery from solar panels

for k = 1:8
    Ah_charged = Ah_charged + P_chrg(k)/V_batt; %sum Ah charged to battery by solar panels
end

k = 1; %reset counter

%display results
fprintf('Battery uses %d Ah over the 16-hour period.\n', round(Ah_used));
fprintf('Solar panel charges %d Ah over the 16-hour period.\n', round(Ah_charged));

if Ah_charged >= Ah_used
    disp('Solar panels CAN keep battery charged. Consider LARGER load');
elseif Ah_charged < Ah_used
    disp('Solar panel CANNOT keep battery charged. Consider SMALLER load');
end

```