USING SUPER CAPACITORS TO INTERFACE A SMALL WIND TURBINE TO A GRID-TIED MICRO-INVERTER

by

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Abstract

During the development of an educational renewable energy production platform, it was found that there were no low-cost, efficient grid-tie interfaces for a 160 W DC wind turbine. Typically, a small DC wind turbine is used in conjunction with a rechargeable battery bank or, if the wind turbine is directly interfaced with a grid-tie inverter, a regulator with a diversion-load. The use of batteries is undesirable due to their high-cost and high-maintenance characteristics. Diversion loads by nature waste power, as any excess energy that cannot be accepted by a battery or inverter is usually converted into heat through a resistive element.

Initially, a 24 V DC, 160 W Air Breeze small wind turbine was directly connected to an Enphase Energy M190 grid-tie micro-inverter. The 24 V DC Air Breeze wind turbine is designed to charge a battery or bank of batteries while the M190 micro-inverter is designed to convert the DC output of a 200 W solar panel to grid-tied AC power. As expected, the power-production response time associated with the small wind turbine and the power-accepting, load-matching response time of the micro-inverter were not compatible. The rapidly changing power output of the small wind turbine conflicted with the slow response time of the micro-inverter resulting in little power production. Ultimately, the response time mismatch also produced sufficiently large voltage spikes to damage the turbine electronics.

In this thesis, a solution for a low-cost, efficient grid-tie interface using no batteries and no diversion load is presented. A capacitance of eight Farads is placed in parallel with the small wind turbine and the micro inverter. The large capacitance sufficiently smoothes the potential abrupt voltage changes produced by the wind turbine, allowing the micro-inverter adequate time to adjust its load for optimal power conversion. Laboratory experiments and data from an implementation of such a parallel super capacitor wind turbine to grid-tie micro-inverter configuration are provided along with DC and AC power production monitoring circuits interfaced with a micro controller.

Table of Contents

List of Figures

Acknowledgements

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Thank you, Dr. Anil Pahwa, for leading this NSF funded project and for giving me this opportunity.

Dr. Ruth Douglas Miller's knowledge of and passion for sustainability and renewable energy is unmatched here at Kansas State University. Thank you for being an inspiration to all of us engineers.

Finally, Scott Geier and Steve Booth deserve my written gratitude. Scott helped me install "all the big stuff" and helped in many other ways - the installation of this project probably wouldn't have happened without Scott. Steve Booth helped me by rounding up parts, tools, materials, and gave me some good conversation from time to time. Thanks.

Dedication

This thesis is dedicated to my family and friends

My parents: Duke and Beth Eldridge for their financial support and encouragement
My siblings: Leah, Isaiah, Benjamin, and Abraham
My wife: Marlissa, for these wonderful 7 years in Manhattan, Kansas
My children: Clara, Anna, Samuel, and Colin
My grandparents: Bill and Devonne Gillum
My mother: Linda
My friends: Andy Hawley, Colin White, Nick Hogan, and Wade Walker

To the man who told me his only advice was, "Don't Quit" - that was all I needed.

Preface

The subject of this Master's Thesis represents a portion of the work and research I did during my four semesters as a graduate student at Kansas State University. However, this portion is the most complex and "novel" of my work and research. All of the work I accomplished revolved around the theme of introducing renewable energy and sustainability concepts into the Electrical Engineering educational experience. Most of my research was funded under NSF grant EEC-0935106.

I have worked closely as a Graduate Teaching Assistant with Dr. William Kuhn for these four semesters, teaching Labs and grading for the Introduction to Electrical Engineering (ECE210) course. Dr. Kuhn and I developed a new Final Project for the class. The goal of the Final Project is to introduce engineering students to applications and engineering issues of renewable energy technologies. The project is conducted in a laboratory environment so that students get hands-on experience with the measurement and usage of the DC power produced by 10 W photovoltaic cells that are powered by a 500 W halogen lamp. The project introduces students to concepts like maximum power point, charge controllers, battery charging/discharging, grid-tie inverters, and determining the efficiency of renewable energy processes.

I also constructed a portable small-wind turbine demonstration for the annual Kansas State Engineering "Open House" events. The demonstration includes a 12 V DC wind turbine attached to a base, about 4 feet from the ground, with its blades turned by a large industrial fan located about 7 feet from the turbine (creating "wind"). The DC output of the small-wind turbine is monitored while it powers an array of 72 LEDs, arranged in a fashion so that they display the letters "KSU ECE". The demonstration gives the viewer an intimate experience with the operation of a small-wind turbine.

Chapter 1 - Background and Introduction

From Fall 2009 to Spring 2011 Kansas State University was awarded a grant (Winds of Change in ECE: Infusing Sustainability into the Program) through the National Science Foundation (NSF) that involved infusing sustainability and renewable energy concepts into its electrical engineering education curriculum. Part of the obligations of this grant was for the electrical engineering department to install a renewable energy power production system with power production monitoring capabilities. It was decided that we would install a small grid-tied photo-voltaic (PV) panel power production system along with a grid-tied small-wind turbine power production system. While the installation of the grid-tied PV system was straight-forward, the installation and implementation of the grid-tied small-wind turbine presented a challenge, and the solution is presented here.

The Rooftop Installation Site

The rooftop of the Rathbone Engineering Building at Kansas State University has a large, steel-frame platform that supports two large dish receiving antennas. At a size of approximately 44’ x 23’, the platform had enough empty space to accommodate our proposed installation. The Rathbone rooftop also had an available 3-phase 208 V AC circuit that could be used for grid-tied power production. Furthermore, there was a conduit system that could be utilized for carrying power production monitoring communication lines down to the 2nd floor of the building, where the electrical engineering department is located.

Grid-Tied PV System

Two Canadian Solar 220 Watt PV panels [1] were installed on the Rathbone rooftop platform. Both panels are mounted to the steel platform, facing south, using a Unirac mounting kit. The DC output of each PV panel is fed to the input of an Enphase M190, a 208 V AC grid-tie micro-inverter that converts the DC power into acceptable 208 V three-phase power [2]. The Enphase micro-inverter delivers the power produced to the building through a suitable breaker-panel. The Enphase micro-inverter system collects data on its power delivery and communicates (over the Neutral power line) with an additional piece of installed hardware called the Enphase Envoy, which is located near the circuit breaker panel that the micro-inverters are tied to. For each micro-inverter, the Envoy stores DC input voltage and current along with the AC power produced. The Envoy's stored data is reported to the Enphase website where power production graphs and raw data are available for users to view and download, either directly, or through the ECE department's sustainability website [3].

Proposed Grid-Tied Small-Wind System

To broaden the scope of the renewable power production system, a small-wind turbine system was selected as a companion to the PV system. The goal was to install a grid-tied wind turbine for small-scale power production. A Southwest Windpower, Inc. 24 V DC Air Breeze wind turbine [4] was chosen for its small size and because its output power production is within the acceptable range of the M190 micro-inverter.

Scope of This Thesis

This thesis presents a unique solution for interfacing an Air Breeze 24 V DC wind turbine to an Enphase M190 grid-tied micro-inverter. Goals of the interface were to avoid rechargeable batteries and diversion loads. The major hurdle to overcome was the slower response time of the M190. Eight Farads of capacitance was placed in parallel with the wind turbine and the micro-inverter to smooth abrupt changes in the wind turbine's output and to absorb power from the turbine and deliver it at a later time when the inverter is able to accept it.

Figure 1-1 Rathbone Rooftop Installation Photo

Chapter 2 - Micro-Inverter and Wind Turbine Characteristics

This chapter presents technical data and experimentally determined operating characteristics of the M190 micro-inverter and the Air Breeze 24 V wind turbine used for the grid-tied power generation system.

Enphase M190 Micro-Inverter Characteristics

The Enphase Energy, Inc. M190 micro-inverter was chosen for interfacing the 24 V DC Air Breeze wind turbine with the available 60 Hz 208 V AC 3-phase grid connection. The M190 costs about $180 in 2010, has a footprint of 8” x 5 1/4” x 1 1/4” and weighs 4.4 lbs.

According to published data [2], the M190 has a maximum AC power output of 190 W at an output current of 0.92 A. The peak efficiency of the M190 inverter is given as 95.5% and its internal Maximum Power Point Tracker (MPPT) peak efficiency is given as 99.6%. The M190 is designed to be directly interfaced with the DC voltage output from a PV panel, typically 60 and 72 cell PV arrays. The M190 is compliant with UL 1741, IEEE 1547, and FCC Part 15 Class B.

The M190 inverter has a two-terminal input (positive and negative DC inputs) and has a input operating voltage range of 21 to 40 V (with power production starting at an input of 28 V) and a maximum input current of 10 A. The four terminal output of the M190 connects to a 60 Hz, 208 V AC 3-phase AC branch circuit with Line 1, Line 2, Line 3 and Neutral terminals.

During testing of the M190 micro-inverter it was discovered that the unit does not utilize Line 3 of the 3-phase electric system. All current (AC power) output by M190 is distributed equally between Line 1 and Line 2 only. A phone call with an Enphase Energy representative confirmed this behavior. While not implemented in our system due to its small size, a possible solution to this issue in larger systems would be to stagger the line connections of different inverters to the grid. Hence, this issue was not considered further.

M190 Micro-Inverter Operating Modes

The M190 micro-inverter effectively has four modes of operation – Off, Fault, Not Producing Power, and On. There is an additional important operational condition of the M190 called “Start-Up Delay” (described below). The operational mode of the M190 depends on its grid connection and level of DC input voltage present. The status of M190 operation is indicated by a tri-color LED.

When there is not a proper 60 Hz, 208 VAC 3-Phase grid connection available, the M190 micro-inverter is in the true “Off” mode. No DC power will be absorbed nor will any output AC power be generated in this mode. Typically, the mode-indicator LED will remain unlit in this mode. However, if a DC voltage is present on the M190 input terminals while the M190 is either not properly connected to the grid or the grid is out, the M190 LED will blink red.

“Fault” Mode indicates a ground fault or GFDI error. The indicator LED will steadily remain red in this condition. If this condition occurs, after remedying the ground fault, one must cycle power of both the connected DC source and the M190, and clear the GFDI error by either calling Enphase customer support or interfacing directly with the Envoy Communications Gateway device manually.

“Not Producing Power” mode occurs if there is too low a DC voltage present at the input terminals of the M190 (determined experimentally during this project to be around 21V), the M190 will not absorb or produce any output power – similar to Off mode. The indicator LED will be unlit in this mode.

The M190 micro-inverter will produce AC power under the conditions that there is a proper AC grid connection and a sufficient DC input voltage present (21V). “On” mode has two possible characteristics and can be confusing. If at least 21 V is present on the M190 input terminals, the M190 is "On" – but it won’t actually start accepting DC power or producing power until the input voltage reaches 28 V. When the input voltage reaches at least 28 V, the MPPT of the M190 will turn on and begin adjusting its impedance to the DC power source impedance and supplying current to the AC grid. "On" mode is indicated by a flashing orange LED. If the M190 is installed with an additional piece of Enphase Energy equipment, called the “Envoy”, its LED will flash green – indicating the M190 is producing power and communicating with the associated Envoy unit.

Unless the M190 is already in the On-Producing Power mode, the micro-inverter does not instantly absorb the DC power applied to its input terminals. Once the M190 senses a voltage of at least 21 V, it will turn on, after a period of approximately one minute. After the voltage reaches 28 V, further delays on the order of several seconds are experienced before the maximum power point setting is achieved. While acceptable in a PV installation environment, given the nature of the wind, these delay periods must be remedied if efficient generation of grid-tie wind power is desired.

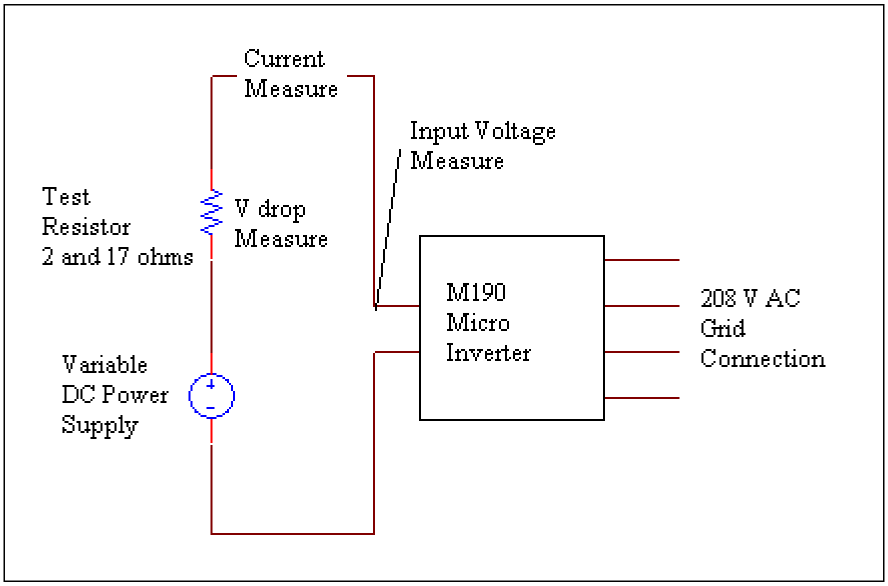
Bench Testing the M190 Micro-Inverter

Bench testing the M190 micro-inverter involved examining its various modes of operation (summarized above) while properly connected to a 60 Hz, 208 V AC 3-phase grid. Hence, a series of tests were performed in the ECE department's power lab.

The first test involved understanding the nature of the M190 start-up and “On-Producing Power” mode. A DC power supply and a resistor of 2 ohms were used to characterize the load-matching of the micro-inverter’s MPPT. The input voltage and current to the M190 were monitored with Digital Multi-Meters (DMMs).

A 2-ohm source resistance was inserted between the bench power supply and the M190 input. The voltage level of the power supply was adjusted within the known range of possible Air Breeze output voltages.

Figure 2-1 Micro-Inverter Load-Matching Test Schematic



Figures 2-2 and 2-3 show the measured current drawn by the M190 when a voltage is applied to its input terminals. The first plot starts with a voltage of approximately 17 V and is stopped around 32V. The second plot is merely a continuation of the measurements, except the voltage is now decreasing from 32V to around 18V.

It can be seen that the inverter draws little to no current until it senses an input voltage of around 28 V. At this point, the M190 will go into "On-Producing Power" mode - drawing current from the supply and outputting current into the grid. It was also found that the M190 will stop delivering power to the grid when the applied input power is less than approximately 11 W (or 21 V at 0.5 A).

Figure 2-2 Micro-Inverter Input Test, Increasing Voltage

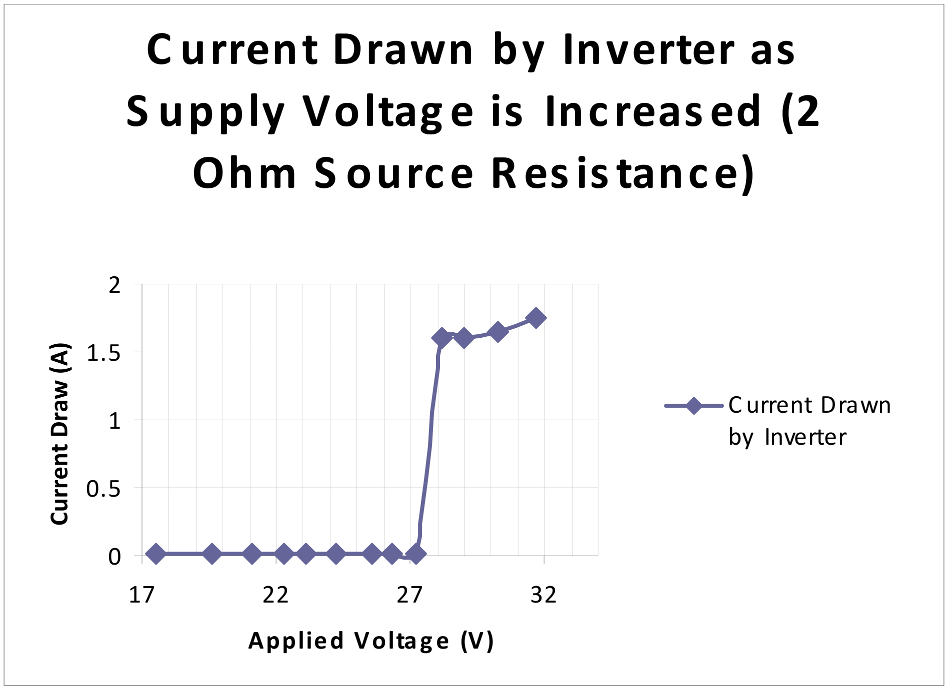
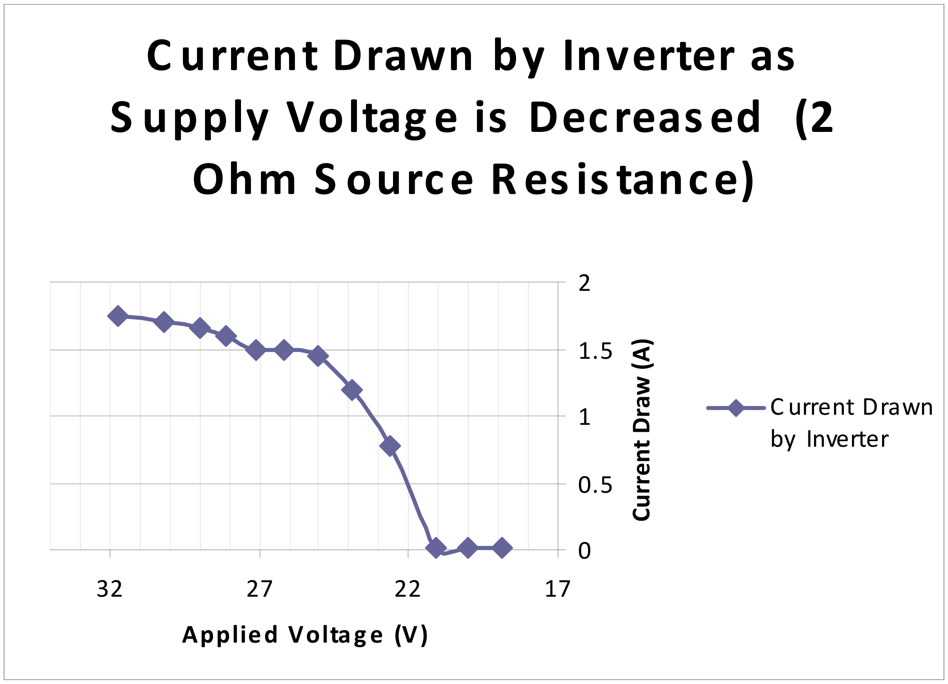


Figure 2-3 Micro-Inverter Input Test, Decreasing Voltage



The voltage after the source resistor (at the actual input terminal of the M190) and the input current (drawn by the M190) was also calculated during these tests. Using the known value of source resistance (2-ohms), the voltage dropped (V drop) across the test resistor is simply 2 Ohms times the current drawn, resulting in input voltages in the range of 22 to 28 V. While this is inconsistent with consuming the maximum power possible from the 2 Ohm Thevenin source used in the test, it is nearly ideal for the wind turbine source, which is optimized to charge a 24 V nominal battery load.

Using DC power supply with varying source resistances, it was found that the M190 would drop approximately 21 V across its input terminals under most conditions, and that a current of 20 mA is sufficient for the M190 to remain in the Producing Power mode when the source resistance is high. The M190 micro-inverter will not draw current greater than around 20 mA again from a source until a voltage of 28 V is sensed. This behavior is also well matched to the output of the small wind turbine as discussed below.

Air-Breeze 24 V Small Wind Turbine Characteristics

The Southwest Windpower, Inc. 24 V DC Air Breeze wind turbine costs about $650 retail in 2010. The Air Breeze has a weight of 13 lbs and its blade diameter is 46 inches. The Air Breeze has a rated power of 160 W in 28 MPH (12.5 m/s) wind speeds and requires a start-up wind speed of 6 MPH (2.7 m/s). The Air Breeze wind turbine is designed for charging a battery or bank of batteries.

Air-Breeze Operating Modes

The Air Breeze has five characteristic modes of operation: Free-Spin, Brake, Stall, Regulation, and Charge. Each of these modes is dependent on wind speed and/or the sensed voltage level of a connected battery. A red LED on the underside of the Air Breeze's body provides a visual indication of the operational mode that the turbine is in.

If the Air Breeze is not connected to an electrical load to supply power to and/or a voltage of at least 7 VDC is not sensed by its internal circuitry, it will be in a "Free-Spin" mode. Free-Spin mode produces no power and the turbine rotor will repeatedly rapidly spin and stop itself. This mode is undesired because it is both unproductive and causes unnecessary wear and tear on the turbine. In Free-Spin mode, the Air Breeze LED will not light.

The Air Breeze can be placed in a "Brake" mode by shorting its positive and negative output terminals. This mode essentially turns the turbine "off" and drastically reduces the speed at which its rotor turns (however, in strong winds the turbine rotor may still spin slowly). Brake mode is useful for installation of the Air Breeze and protecting the turbine from strong or possible damaging winds. A stop switch (which shorts the turbine output – engaging Brake mode) is recommended for installation. In Brake mode, the Air Breeze LED will not light.

The Air Breeze will enter "Stall" mode when it senses wind speeds of 35 (15.6 m/s) MPH or greater. The Air Breeze Stall mode stops the turbine rotor until a wind speed of 32 MPH (14 m/s) is sensed following release from this mode after a set delay period. The turbine produces no power while it is in Stall mode. In Stall mode, the Air Breeze LED will blink approximately ten times per second.

The Air Breeze wind turbine contains circuitry that monitors the voltage of the battery it is connected to and adjusts its behavior based on the voltage it senses. When the Air Breeze senses a battery voltage that exceeds the threshold of its internal regulation set point, the Air

Breeze will enter “Regulation” mode, where the turbine rotor reduces its speed and the turbine will stop producing power until the voltage becomes lower than the regulation threshold. The purpose of Air Breeze’s Regulation mode is to prevent over-charging (and subsequent damage) to any connected batteries. The voltage regulation set point of a 24 V Air Breeze wind turbine can be adjusted within a range of 27.2 to 34 V. In Regulation mode, the Air Breeze LED will blink approximately twice per second.

The mode for proper Air Breeze power production is named “Charge” mode. In sufficient wind conditions and while connected to an electrical load with a voltage that is lower than the Air Breeze regulation set point voltage (yet above the Free Spin mode voltage of around 7 V), the Air Breeze can produce DC power up to 160 W. Of the Air Breeze wind turbines’ five modes of operation, only Charge mode produces usable power. In Charge mode, the Air Breeze’s LED will be continuously lit.

Bench Testing the 24 V Air-Breeze Wind Turbine

Some basic electrical and operational characteristics of the Air Breeze were tested and monitored using typical lab instruments such as digital multi-meters and oscilloscopes. The turbine rotor was spun while its output was connected to various resistive loads and its output current and voltage was monitored.

A Lab-Volt 8960-20 motoring dynamometer was utilized to spin the rotor of the wind turbine in a controlled fashion. The motoring dynamometer has an encoder that allows the Revolutions Per Minute (RPM) of the motor to be set and controlled in real time. The blades were removed from the Air Breeze and a pulley of equal size as the motor's was attached to the shaft of the wind turbine’s rotor. The pulleys are connected with a belt as seen in Figures 2-4 and 2-5.

An apparatus was constructed to firmly hold the Air Breeze wind turbine at a level position and in place while its rotor was turned by the motoring dynamometer. The sling utilizes a tension rod to maintain proper belt tightness.

Figure 2-4 Wind Turbine Testing Apparatus, Side View

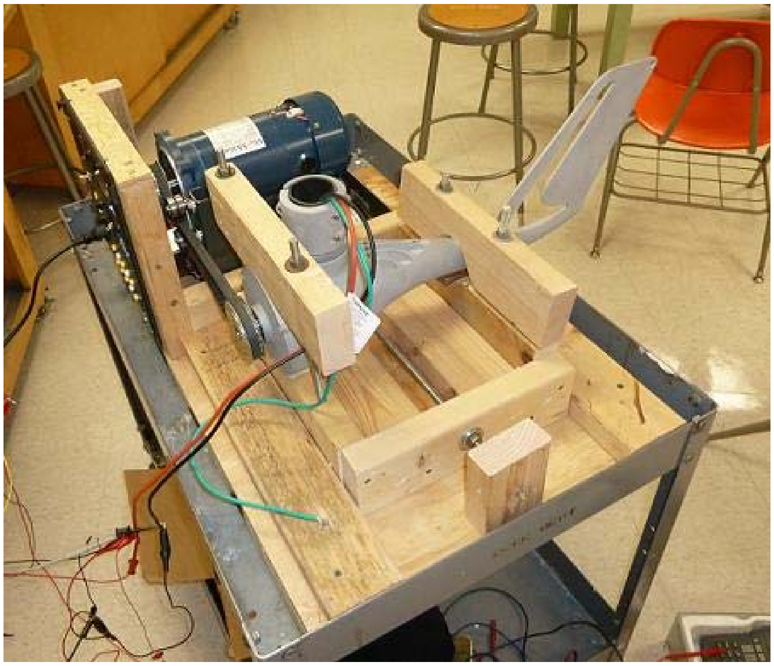
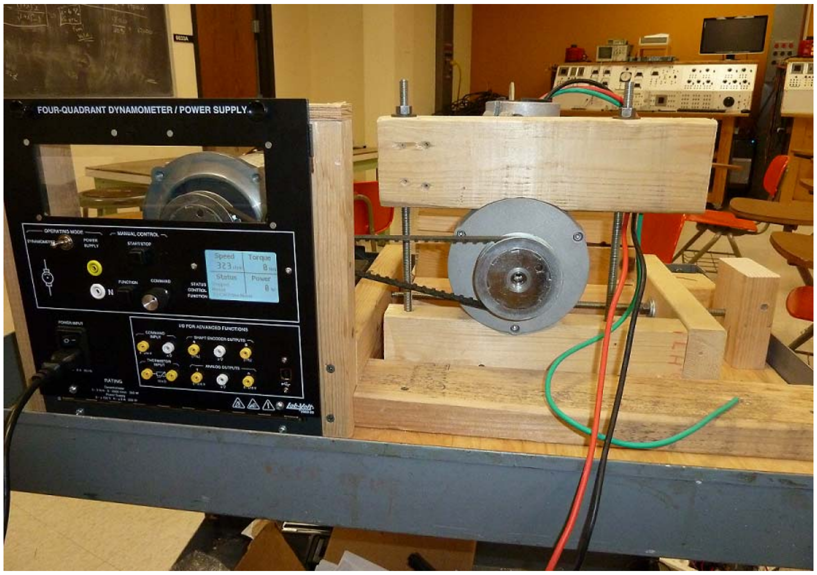


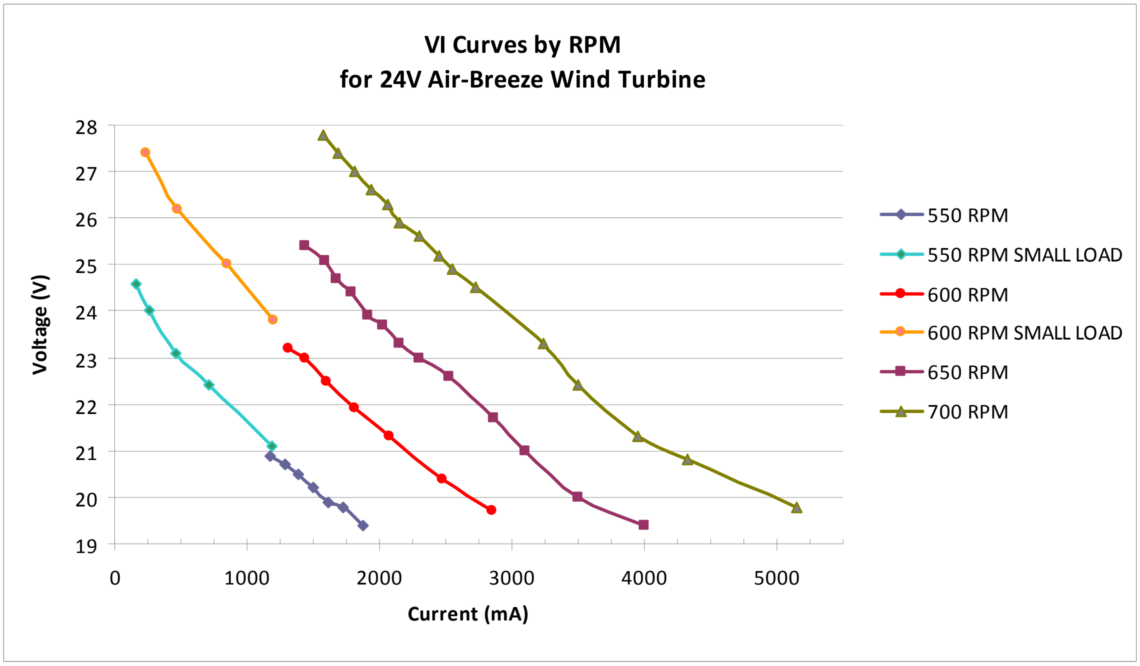
Figure 2-5 Wind Turbine Testing Apparatus, Front View



The Air Breeze output voltage and current were measured at fixed motor RPM settings of 550, 600, 650, and 700 corresponding to wind speeds of approximately 17 MPH and higher. For this testing, the range of output voltages was constrained between 20 V and 28 V by using a large power potentiometer to vary the resistive load on the turbine.

The plot of Figure 2-6 shows the wind turbine output voltage and current at given motor RPM settings. The effective output resistance of the wind turbine can be calculated by finding the inverse of the slopes, where R = V/I, in ohms. From the measured data, the output resistance of the Air Breeze is approximately 2.2 ohms.

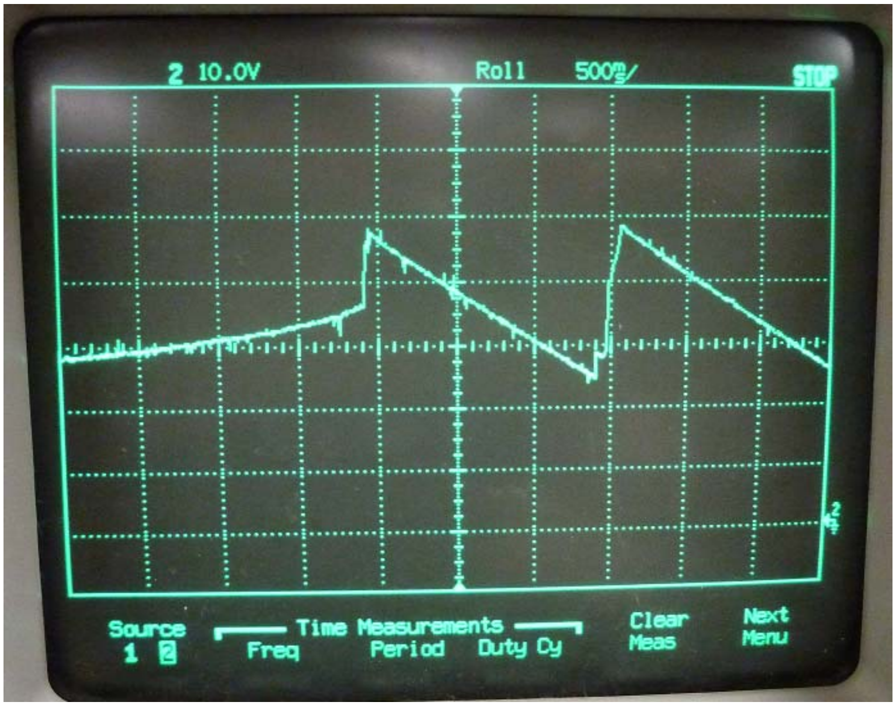
Figure 2-6 Selected VI Curves for 24 V Air Breeze Wind Turbine



To examine the Air Breeze’s behavior in Regulation mode, the wind turbine was connected to a 21 V power supply but not connected to an electrical load (open circuit). The turbine shaft was rotated by the motoring dynamometer and its output voltage brought up to the regulation set point threshold (approximately 35V) and then allowed to drive the turbine voltage beyond the regulation set point.

The oscilloscope screenshot in Figure 2-7 captures the Air Breeze’s behavior in open-circuit Regulation mode. It was found that once the Air Breeze reached its regulation point, the turbine would brake (violently stop) itself and its output voltage would almost instantly spike up to nearly 50V. After an approximate 1.5-second voltage decay (while the turbine is still under rotation by the motor) the turbine output voltage will spike up again – repeating the braking and voltage spike behavior.

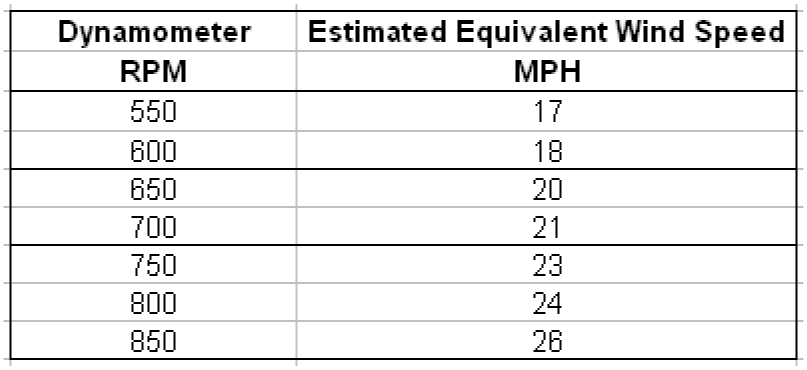
Figure 2-7 Air Breeze "Regulation Mode" Behavior



Air Breeze TSR Estimation

The Air Breeze was connected to a resistive load of 4.5 ohms and its rotor speed was increased by the motoring dynamometer until a power output of 160 W was measured. At an RPM of 940 the Air Breeze output 25 V and 6.5 A (162 W) into this 4.5 ohm load. To translate 940 RPM to blade tip speed, the circumference of the blade path is calculated and the actual tip speed will be the product of RPM and circumference, converted to MPH. 940 RPM represents a blade tip speed of 128 MPH. Dividing this tip speed by the published wind speed corresponding to maximum turbine output (28 MPH) results in an estimated Air Breeze TSR of 4.5. Now, equivalent wind speeds can be estimated using this TSR and the RPM levels used in testing assuming the TSR remains relatively constant under the applied load. Figure 2-8 shows some motor RPM to relative wind speed conversions.

Figure 2-8 Estimated Equivalent Wind Speed Under Load vs. Motor RPM



Dynamometer RPM	Estimated Equivalent Wind Speed MPH
550	17
600	18
650	20
700	21
750	23
800	24
850	26

Avoiding Batteries

According to the Air Breeze wind turbine manual, a 24 V Air Breeze is to be connected to a 24 V battery (or an array of batteries equivalent to 24 V) with a minimum capacity of 200 Amp-hours. Choice of battery type depends on expected temperature variation and ventilation.

A deep-cycle type battery is needed for applications where the batteries will be repeatedly deeply discharged and charged. There are many deep-cycle sealed lead-acid batteries available for renewable energy applications, such as storing energy from PV panels or small wind turbines. Internet searching uncovered some potential 24 V batteries, but none with the required minimum capacity of 200 Ah. Therefore, use of two 12 V, 200 Ah batteries was considered. However, at retail prices of over $300 for a single 12 V, 200 Ah battery, the cost is somewhat prohibitive for the desired grid-tied wind turbine configuration.

Furthermore, research on charging and discharging batteries uncovered other potential reasons for reconsidering interfacing the turbine to the micro-inverter with a battery. To maintain a reasonable battery life, battery charging and discharging must be carefully regulated, requiring good estimation of battery state-of-charge and control circuits to turn on and off the inverter at specific charge and discharge levels. Battery performance is also very sensitive to temperature. To properly regulate charging and discharging of a battery in a remote location such as a rooftop, temperature detection circuitry with automated adaptable regulation would be needed. A control system such as this would further add to the cost and complexity of the installation. Finally, there is a finite lifetime for batteries as a function of charge/discharge cycles, and preliminary estimates indicated the need to replace batteries on the order of once per year, making the system cost too high.

Therefore, it was decided that we would attempt to interface the Air Breeze wind turbine directly to the M190 micro-inverter.

Desired Goals of Micro-Inverter and Wind Turbine Operation

Given the basic attributes and characteristics of the Air Breeze wind turbine and the M190 micro-inverter there are two important challenges to overcome.

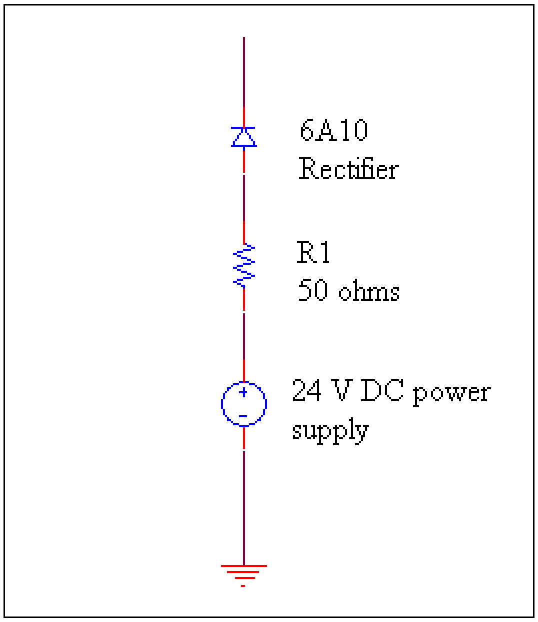
- Keep the M190 micro-inverter "Ready" – that is, keep the M190 input voltage at a value of at least 21 V with 20 mA to avoid its one-minute start-up delay.
- In sufficient wind, keep the Air Breeze wind turbine in Charge mode – by connecting the Air Breeze wind turbine to a sufficient electrical load (like a battery) with the proper voltage level for power production.

To partially defeat the Air Breeze wind turbine Free Spin mode (and enable power production), the circuit of Figure 2-9 was built. This circuit keeps both the turbine and the inverter ready even when the wind has fallen below the 6 MPH limit required for the turbine to deliver power.

To satisfy the wind turbine, it was experimentally determined that the Air Breeze must sense a voltage of at least 8 V. However, this voltage need not come from a battery - any voltage source will suffice. A 24 V DC power supply (commonly referred to as a “wall wart”) is used to supply the Air Breeze with a sense-able voltage.

The 24 V DC power supply is current-limited by the 50 ohm resistor while the 6A10 rectifier diode protects the power supply input and effectively disconnects (by no longer conducting current) the power supply when a voltage greater than 23.3 V is present at the positive node connecting the wind turbine to the micro-inverter.

Figure 2-9 DC Power Supply Configuration for Satisfying Turbine and Inverter



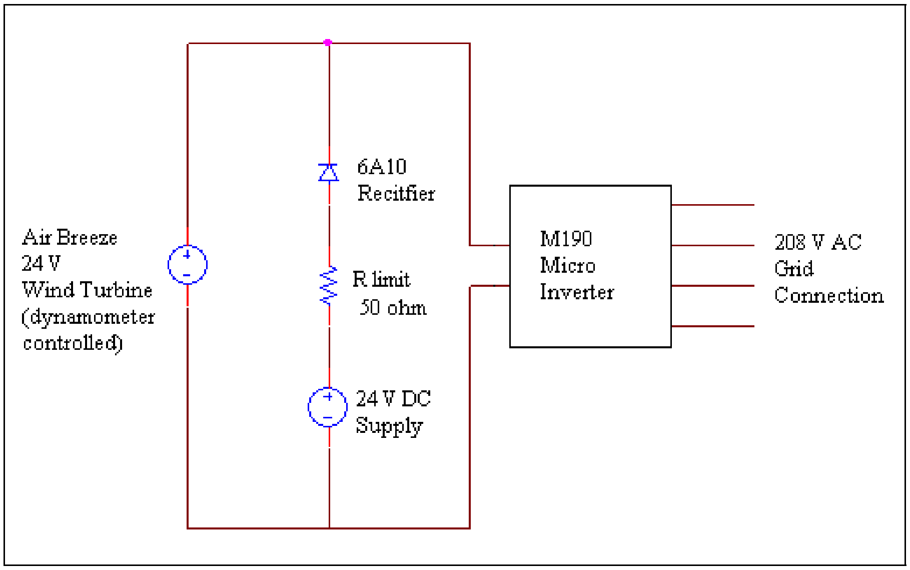
The same 24 V DC power supply used to keep the Air Breeze wind turbine ready to produce power keeps the M190 micro-inverter ready to accept DC power (avoiding the start-up delay time) and therefore able to convert the desired power from the wind turbine. To avoid too much current from being drawn from the 24 V power supply, a current-limiting resistor needs to be placed on the output of the power supply. Since it was determined that a current of 20 mA is sufficient for the M190 to remain in the Producing Power mode, the current-limiting resistor is set to 50 ohms (less than (24 - 21V) / 20 mA).

Chapter 3 - The Air Breeze and the Micro-Inverter Mismatch

Direct Connection Experiments

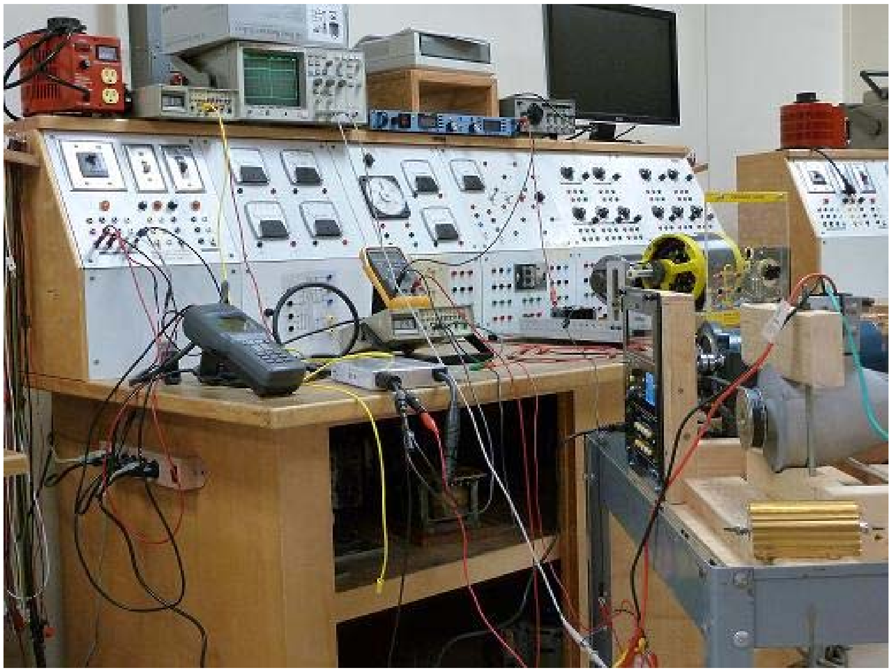
Now that the goals for proper power production and operation modes are understood, the Air-Breeze wind turbine and the M190 micro-inverter are connected with the 24 V current-limited DC power supply (discussed in Chapter 2) in parallel as shown in Figure 3-1.

Figure 3-1 Wind Turbine and Micro-Inverter Direct Connection Schematic



With the wind turbine under motored dynamometer control (see Figure 3-2, below), the turbine rotor is turned and the input to the M190 is observed with an oscilloscope.

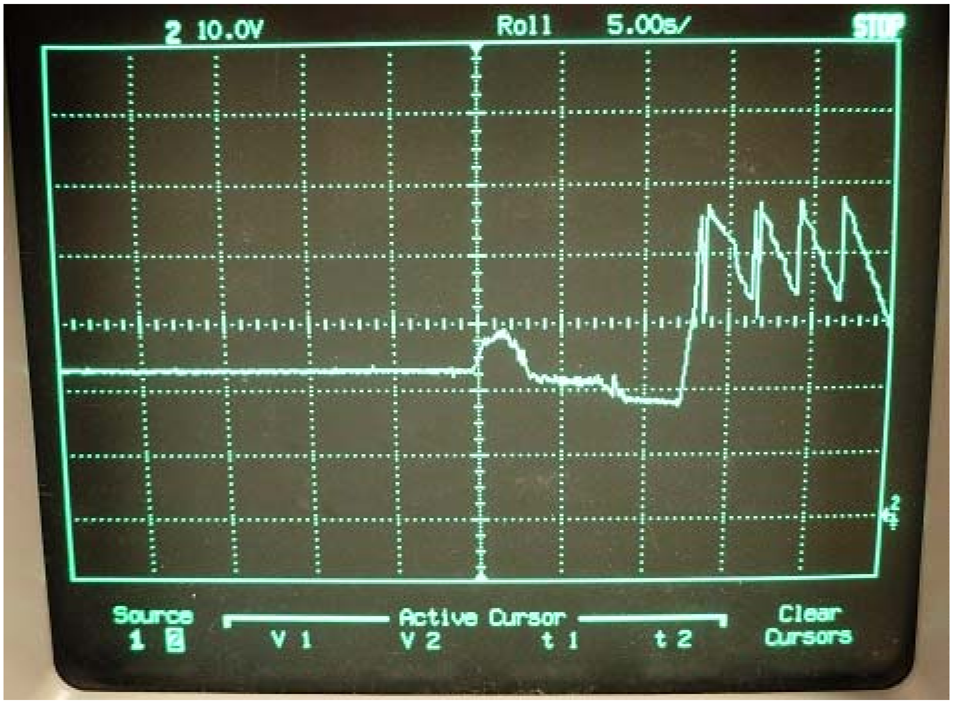
Figure 3-2 Picture of Wind Turbine and Micro-Inverter Direct-Connect Experiment



If the wind turbine rotor speed was gradually increased, the micro-inverter would begin to draw and produce power as its input voltage reached 28 V, as expected. The micro-inverter would drop 21 V across its input terminals and draw current from the turbine. However, it was found that when the wind turbine was rapidly brought up to a power-producing speed the micro-inverter could not respond quickly enough. This would cause the input voltage of the micro-inverter to rapidly increase upwards towards 45 V. This voltage level is well beyond the regulation voltage of the Air Breeze wind turbine (which was set to its maximum of around 34 V during these experiments).

The oscilloscope screenshot in Figure 3-3 captures the response time mismatch behavior. No power is produced during this series of events, as the wind turbine is conflicting with the micro-inverter, which is trying to match its load too slowly. A situation like this is typical of wind on a gusty day, where there will be little to no wind, and then a sudden gust of wind. It was experimentally determined that the M190's response time is somewhere between 3 and 6 seconds. The M190 behaved inconsistently in this regard and the experiment is very sensitive to small changes in turbine rotation.

Figure 3-3 Wind Turbine and Micro-Inverter Response Time Mismatch



To protect the Air Breeze and M190 from the 45 V spikes during its regulation response, a circuit was built to absorb any current when the voltage exceeds 33 V. This circuit is shown in Figure 3-4 and utilizes a Zener diode with a power NFET attached to a large heat-sink. The 30 V Zener diode will conduct when the voltage at its cathode is 29.3 V, causing a small current to flow through the 1k-ohm resistor. When the voltage at the Zener cathode is around 33 V, a sufficient voltage will be present at the gate of the IRF250 to turn it on, thereby conducting current through the FET and preventing voltages over 33 V from occurring. The resulting behavior is shown in Figure 3-5, which is a screenshot from the voltage at the cathode of the Zener diode, when the circuit is connected to the Air Breeze wind turbine in open-circuit mode.

Although this circuit is similar to a diversion load, that is not its intention. The circuit is a worst-case, fail-safe mechanism to protect the Air Breeze. The real problem to solve is not over-voltage, but the slow response time of the M190 micro-inverter. If the inverter does not draw power from the turbine during a wind gust, the turbine's power production will have a very low efficiency in all but the most steady wind.

Figure 3-4 A Fail-Safe, Over-Voltage Protection Circuit

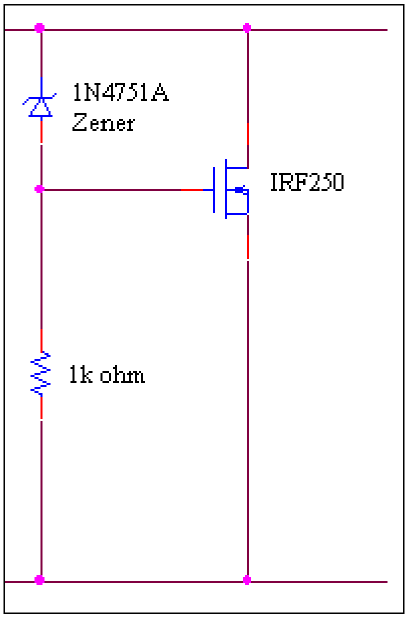
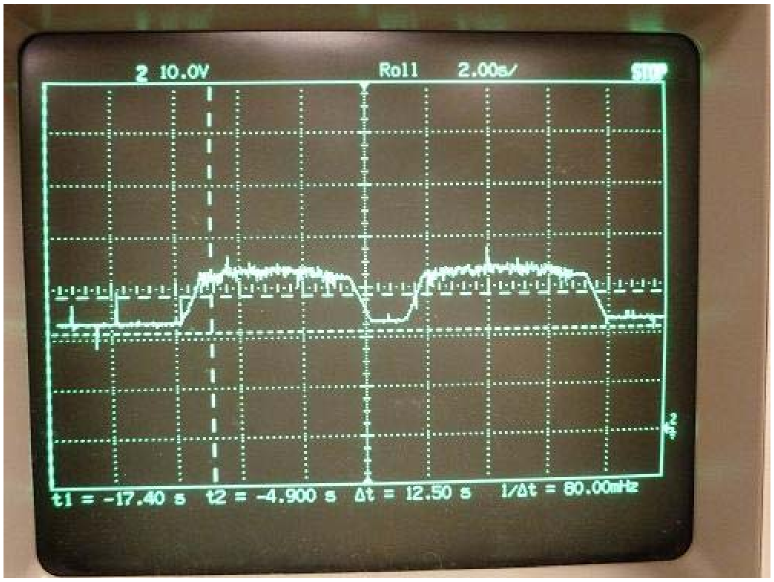


Figure 3-5 Over-Voltage Protection Circuit Behavior



Avoiding Diversion Loads

Based on product research, most wind turbine grid-tie inverters use a diversion load (also called a “dump” load) interface between the inverter and the power-producing wind turbine. A diversion load is a resistive element that, when used in conjunction with a voltage-sensing regulator, accepts any excess current (that cannot be accepted by the electrical load being powered) produced by a wind turbine and dissipates the power it receives as heat.

A diversion load is not an efficient device by nature, because power is converted directly into heat instead of electrical power. This is considered a waste of good energy for a grid-tied system. Furthermore, the only good a diversion load would do for the interface with the M190 micro-inverter is avoid the possible over-voltages.

The slow response time of the M190 would still remain the primary problem, as the M190 cannot keep up with the abrupt voltage changes presented by the Air Breeze wind turbine in most typical small-wind environments. While use of a battery is the most obvious solution to these problems, such a product would be too expensive, as previously discussed. The challenge is to provide a short-term energy storage mechanism to absorb power from the turbine and deliver it at a later time when the inverter is able to accept it. Hence, an alternative energy storage/release technology is needed.

Chapter 4 - Super Capacitor Solution

By experiment it was found that the proper voltage level for keeping both the M190 micro-inverter and the Air Breeze wind turbine in their optimum modes could be attained with a small DC power supply, as previously explained. The challenge to overcome is the slow response time of the M190 micro-inverter. An alternative to a diversion load or a battery storage system is needed. It is possible to emulate a battery's behavior by using a sufficiently large capacitor.

Capacitance Calculation

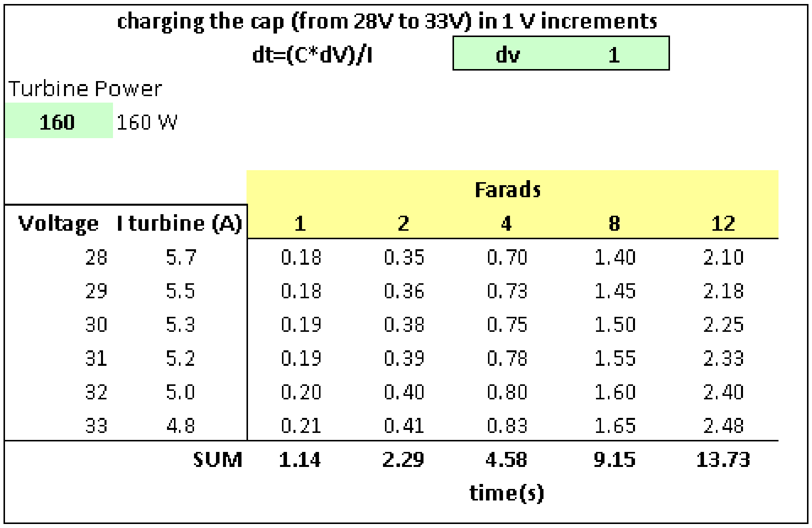
A capacitor of a large enough value can provide a smoothing effect to the potential rapid voltage changes of the wind turbine by increasing the time constant of the circuit, and give the M190 micro-inverter sufficient time to adjust itself to input power. A spreadsheet was created to solve equation 4-1 for the time required, given values of C and the constantly changing current that results from a fixed maximum power (160 W) being output by the wind turbine, to charge the capacitors. The total time (in seconds) is the summation of dt’s from solving six instances of equation 4-1, using a dv value of 1 V and values of capacitance ranging from 1 to 12 Farads. This process is essentially integration of equation 4-1, with dt computed in discrete steps.

Using an estimated M190 micro-inverter time constant of 5 seconds, maximum possible Air Breeze wind turbine current output at 160 W, and a total change in voltage of 5 V (28 V to 33 V), the value of capacitance needed is slightly more than 4 Farads.

$$i(t) = C\frac{\mathrm{d}v(t)}{\mathrm{d}t} \tag{4-1}$$

For system design robustness and due to the uncertain response time of the M190 micro-inverter it was decided that the 4 Farad minimum acceptable capacitance value should be increased. Figure 4-1 shows the calculated time it takes to charge capacitances of 1, 2, 4, 8, and 12 Farads from 28-34 V (the turn-on point of the M190 and the maximum allowable voltage to prevent turbine regulation) at the maximum Air Breeze wind turbine power output of 160 W.

Figure 4-1 Various Super Capacitor 28-34 V Charge Time for Max Turbine Power



charging the cap (from 28V to 33V) in 1 V increments

dt=(C*dV)/I

dv 1

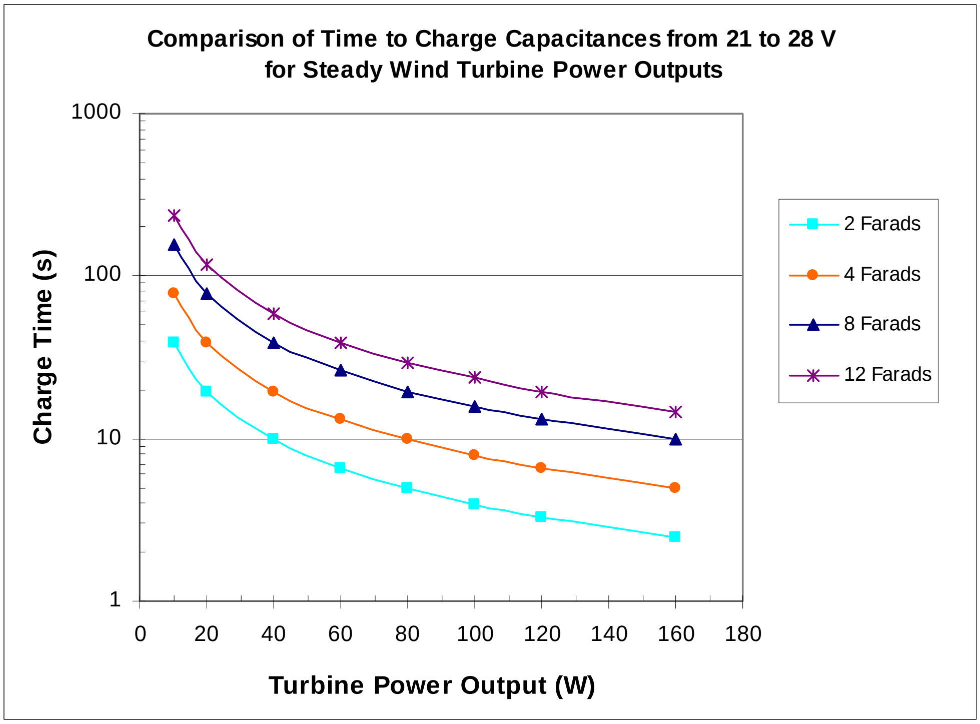
Turbine Power

160 160 W

		Farads				
Voltage	I turbine (A)	1	2	4	8	12
28	5.7	0.18	0.35	0.70	1.40	2.10
29	5.5	0.18	0.36	0.73	1.45	2.18
30	5.3	0.19	0.38	0.75	1.50	2.25
31	5.2	0.19	0.39	0.78	1.55	2.33
32	5.0	0.20	0.40	0.80	1.60	2.40
33	4.8	0.21	0.41	0.83	1.65	2.48
	SUM	1.14	2.29	4.58	9.15	13.73
				time(s)		

The plot in Figure 4-2 shows calculated approximate times for capacitor values of 2, 4, 8, and 12 Farads to charge from 21 to 28 V at different turbine output powers. This is useful for estimating the length of time it will take the wind turbine to charge the capacitors to 28 V - the point where the M190 begins producing power.

Figure 4-2 Super Capacitor 21-28 V Charge Time for Turbine Power Outputs

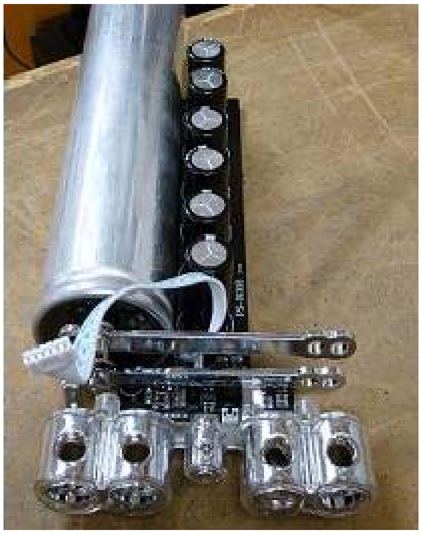


Search for Super Capacitors

Shopping for “super capacitors” yields many results for car audio products. A 30-Farad capacitor bank was found, with a reasonable price of $115. This capacitor device is designed to be connected in parallel with a car battery and a car audio power amplifier. The capacitor bank is rated at 15 V, so two of these will need to be connected in series in order to handle the possible 28 V from the Air Breeze wind turbine. Series connection of the capacitor banks will divide effective capacitance in half, to around 15 Farads.

After purchasing two of these super capacitor banks, it was found that the actual value of these capacitors does not match the advertised specifications. Bench testing was performed before installing the capacitor bank to determine its actual capacitance. The effective capacitance can be calculated by charging (or discharging) the capacitor bank at a fixed current for a fixed amount of time, and for a known change in voltage. Measurements of these devices found the capacitance to be approximately 1.5 F each. Since there must be two of these capacitor banks in series, the actual capacitance value would have been less than 1 Farad. At this strikingly low value (compared with the advertised specification of 30 Farads each), these are not suitable for the required application.

Figure 4-3 The Wrong Capacitors (actually 1.5 Farad)

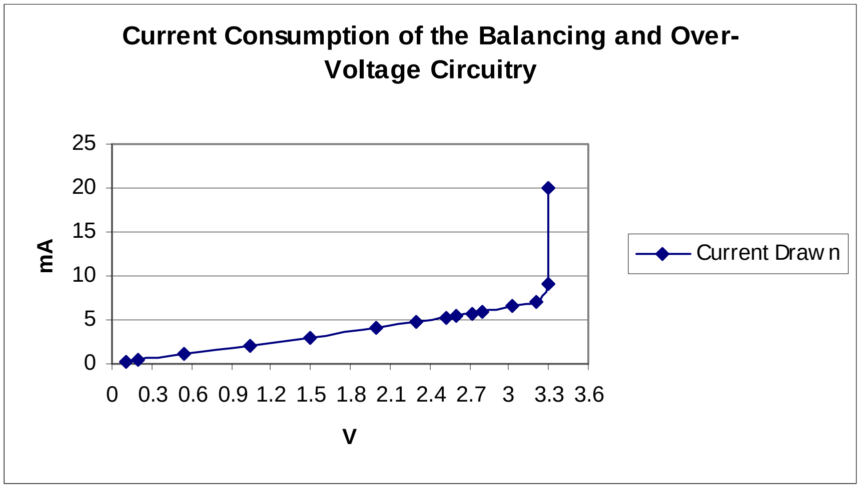


Fortunately, the capacitor device contains some circuitry that can be utilized (so not all money was wasted on these devices). The capacitor bank is arranged with six 2.7V super-capacitors in series on the circuit board and two other off-board capacitors (these components are not labeled) in parallel with these. To test the circuitry further, the original two off-board capacitors were disconnected and the six super-capacitors (marked as 60 F 2.7 V) were removed from the PCB.

The circuits perform a balancing operation on an applied voltage for the six series capacitors. The balancing circuit effectively distributes an applied voltage equally across each capacitor, even if the individual capacitors have unmatched values or leakage currents. For example, if 15 V is applied, each capacitor will have 2.5 V across it. An open-circuit resistance of 500 Ohms was measured and it was found that there is a 500 Ohm resistor used as the primary component in the balancing circuitry.

The balancing circuitry also performs an over-voltage operation (although it is doubtful it could survive for long, given the use of surface-mount devices with no heat-sinking). When an applied voltage across the balancing circuitry is greater than 3.3 V (for 6 capacitors in series, a total voltage equivalent to 19.8 V), supply current is shunted away from the capacitors – keeping the maximum voltage across each series capacitor to 3.3 V. A plot from these tests for the circuits surrounding a single capacitor site can be seen in Figure 4-4.

Figure 4-4 Testing the Capacitor Balancing and Protection Circuitry

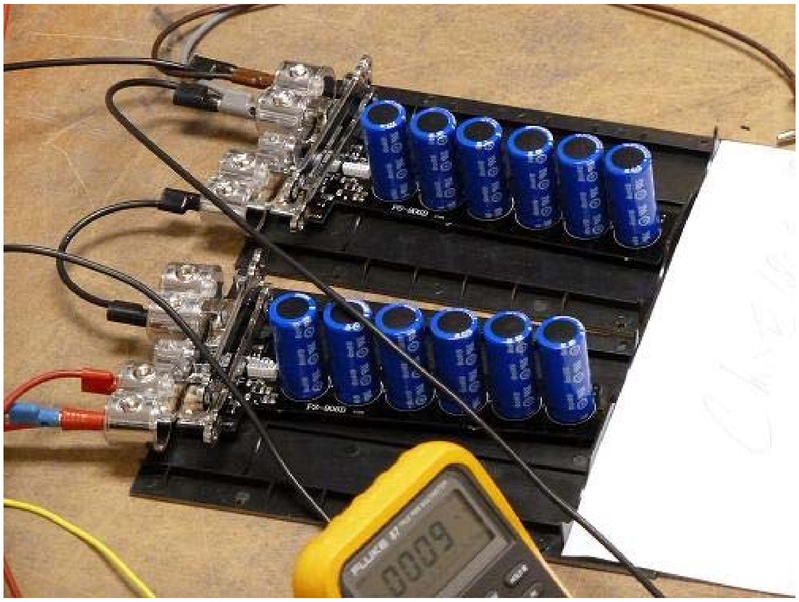


For a full bank of six super-capacitors in series, the balancing and over-voltage protection circuitry will consume a current of I=V/R, where V is the voltage across the capacitor bank and R is 6*500 ohms. This current should be multiplied by a factor of 0.5 since two of these capacitor boards will be used. For example, when V = 21 V (the voltage level at which the M190 maintains while in Ready to Produce Power mode), current consumption is around 3.5 mA. It is important that this current be accounted for by adjusting the current limiting resistor from the 24 VDC power supply used to keep the Air Breeze and M190 in their proper modes. (Note: On the PCB, there is other circuitry that consumes current, but cutting a trace on the circuit board effectively eliminated those unnecessary circuits.)

Since the value of the capacitance is less than the required value but its PCB contains useful circuitry, it was decided to purchase our own super capacitors and replace the bad capacitors in the PCB.

Maxwell BCAP0100T07 2.7 V, 100 Farad super capacitors were found at a US distributor and ordered for a price of $12 each. With 12 of these super capacitors in series, an effective capacitance of 8.33 Farads at a voltage tolerance of 32.4 V is achievable. The footprint of these Maxwell capacitors matches the PCB holes and so installation was straightforward and required no modifications. Testing confirmed that these capacitors are approximately 100 Farads each. While the maximum voltage of (12)(2.7V) = 32.4V is lower than the previously discussed protection circuit's cut-in value, the actual voltage tolerance for the capacitors should be higher than 2.7V each, so no adjustments were made to the 33V protection circuit.

Figure 4-5 The Right Capacitors Installed – Twelve Maxwell 100 F, 2.7 V Super Capacitors



Super Capacitor Interface Results

With the equivalent of 8.3 Farads installed in the balancing and over-voltage protection PCBs, the capacitance was placed in parallel with the Air Breeze wind turbine and the M190 micro-inverter and bench-level testing was performed on the system. The first test was to confirm that the capacitors smoothed any abrupt (increasing or decreasing) changes of the power output of the wind turbine. The schematic in Figure 4-6 shows the system configuration.

Figure 4-6 Super Capacitor Interface Schematic

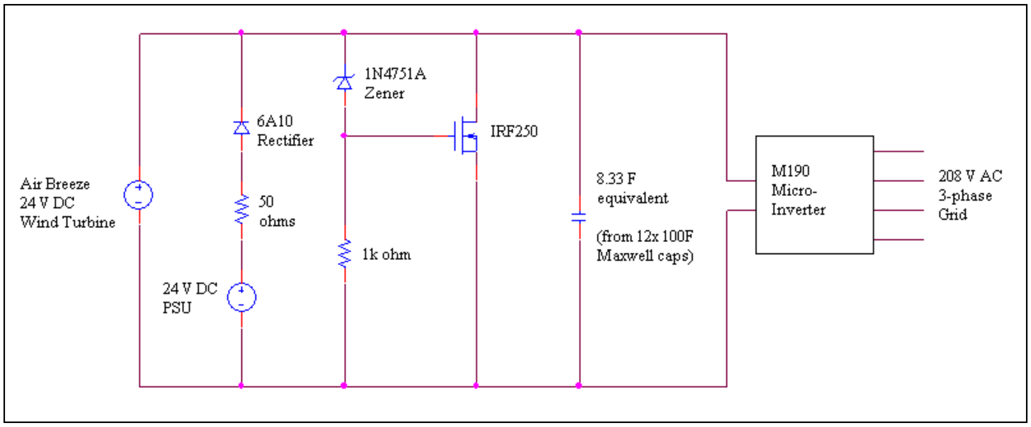
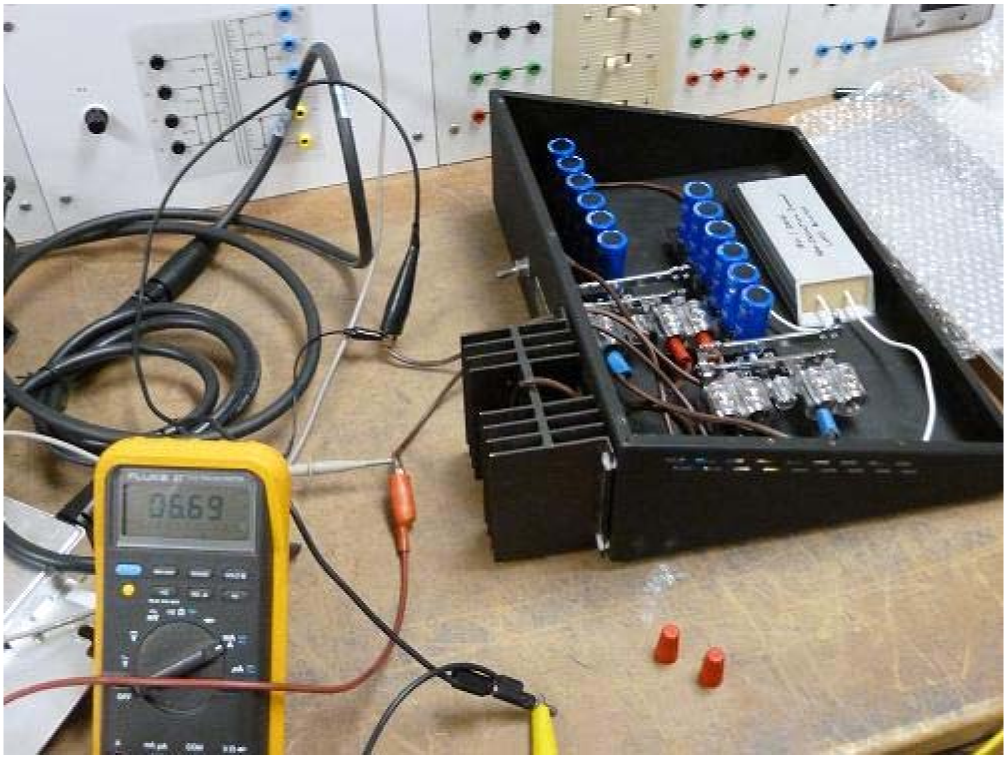


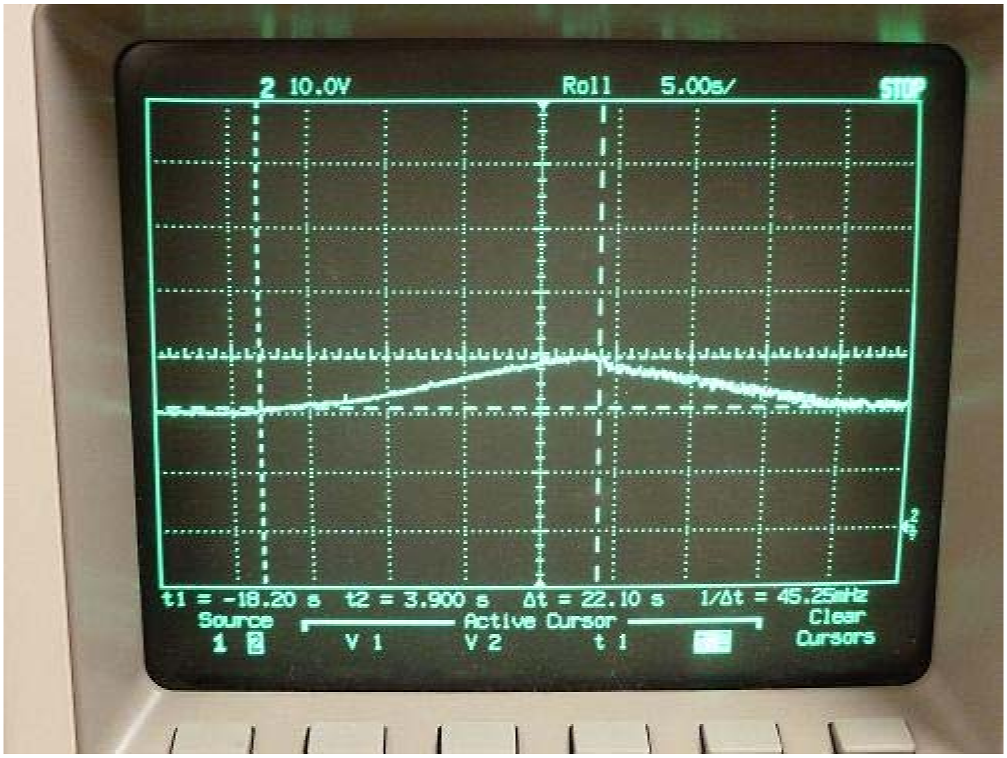
Figure 4-7 Super Capacitor Interface On The Test Bench



Starting at zero RPM, the wind turbine rotor was quickly (as fast as the motor could respond to the RPM rotary encoder being turned up) spun up to a level of around 800 RPM, which relates to around 140 W being delivered from the wind turbine. The oscilloscope screenshot in Figure 4-8 captures the charging of the super capacitors and the response of the M190 micro-inverter. The 8 Farads of capacitance take around 15 seconds to charge up to 28 V at this turbine RPM.

As expected, when the voltage at the M190 micro-inverter's input reaches 28 V, it begins to draw current and simultaneously dump AC current onto the grid. Once the M190 begins producing power (at the 28 V input point) it begins its MPPT algorithm and starts adjusting its internal load to match that of the wind turbine's sourcing capability. Since 21 V is the lowest acceptable power producing input for the M190, it lowered the voltage at its input to around 21 V and settled there, drawing current from the wind turbine. It takes around 16 seconds for the super capacitors to drain to 21 V.

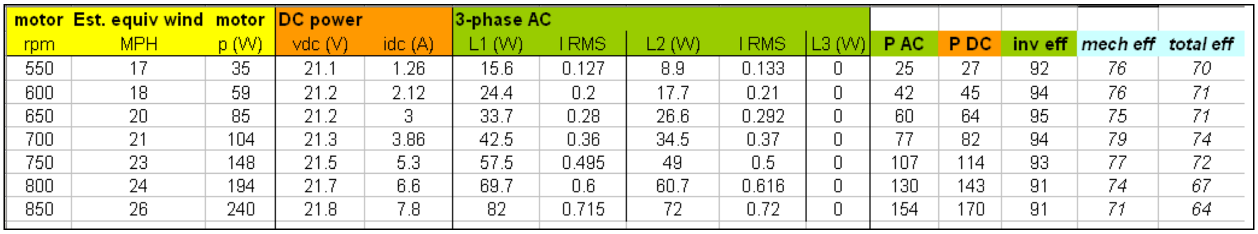
Figure 4-8 Smoothed Voltage Response and M190 Load Matching



Power production testing was also performed on the system while in the lab environment. With the M190 in power production mode (holding its input to around 21 V), the Air Breeze rotor was spun at fixed RPM levels. The DC voltage and current input to the M190 micro-inverter were measured with DMMs and the AC current output of the M190 was measured with an AEMC power analyzer. Figure 4-9 shows the recorded values along with the calculated efficiency (“inv eff”) of the DC to AC power conversion process. The inverter efficiency ranges from 91 to 95 %. Since the Lab Volt motoring dynamometer displayed the power (in Watts) being consumed to turn the pulley (attached to the Air Breeze rotor), this value was recorded to get an estimate of the mechanical and overall efficiencies of the process. In all cases, the efficiencies could be in error by a few percent due to accuracy limitations in the measuring instruments.

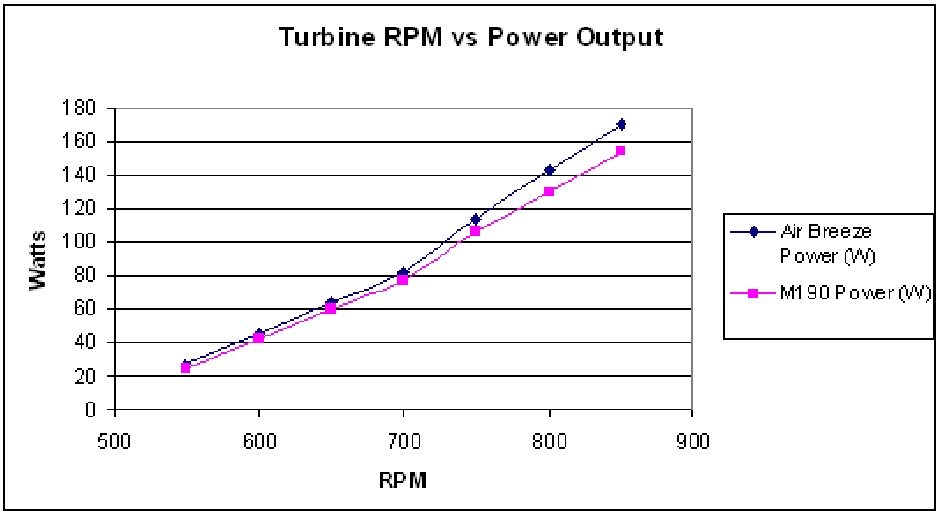
The plot in Figure 4-10 shows the DC power output of the Air Breeze wind turbine with the RMS AC power output of the M190 micro-inverter for fixed turbine RPM.

Figure 4-9 System Power Production Testing



motor	**Est. equiv wind**	**motor**	**DC power**		**3-phase AC**									
rpm	MPH	p (W)	vdc (V)	idc (A)	L1 (W)	I RMS	L2 (W)	I RMS	L3 (W)	**P AC**	**P DC**	**inv eff**	***mech eff***	***total eff***
550	17	35	21.1	1.26	15.6	0.127	8.9	0.133	0	25	27	92	*76*	*70*
600	18	59	21.2	2.12	24.4	0.2	17.7	0.21	0	42	45	94	*76*	*71*
650	20	85	21.2	3	33.7	0.28	26.6	0.292	0	60	64	95	*75*	*71*
700	21	104	21.3	3.86	42.5	0.36	34.5	0.37	0	77	82	94	*79*	*74*
750	23	148	21.5	5.3	57.5	0.495	49	0.5	0	107	114	93	*77*	*72*
800	24	194	21.7	6.6	69.7	0.6	60.7	0.616	0	130	143	91	*74*	*67*
850	26	240	21.8	7.8	82	0.715	72	0.72	0	154	170	91	*71*	*64*

Figure 4-10 DC Power and AC Power by RPM

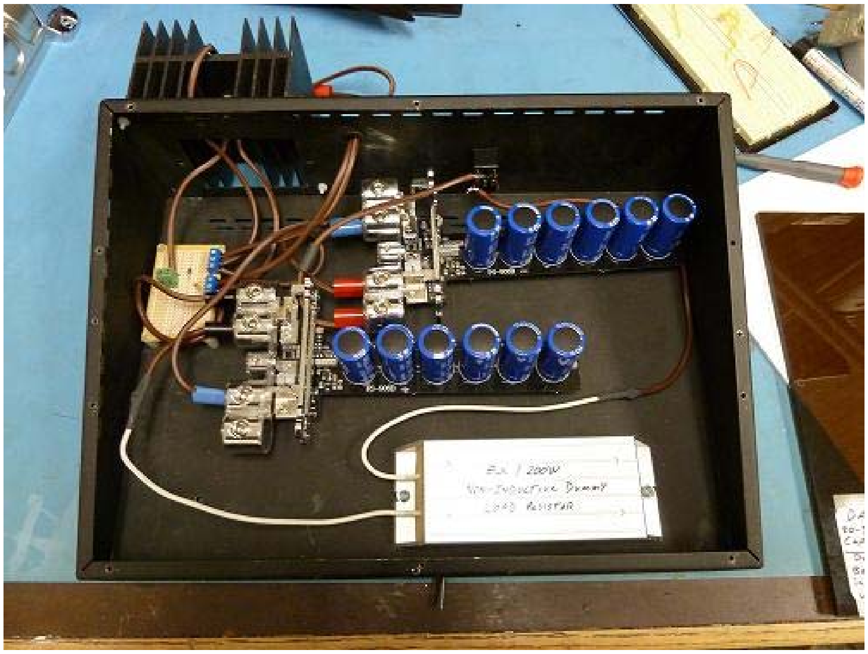


The picture in Figure 4-11 shows the super capacitor interface enclosure. The box has positive and negative input leads and is to be inserted in parallel with the Air Breeze wind turbine and the M190 micro-inverter. The “over-voltage protection” circuit (discussed in

Chapter 3) was also placed into this box, with an external heat sink for good dissipation. A capacitor “drain” option was added to allow draining the super-capacitor bank safely before removal or service of the box. A switch discharges the capacitors through an 8 Ohm, 200 Watt resistor.

Before any service is performed on the capacitor, any supply should be removed from the super capacitor box and then the “drain” switch should be engaged for approximately 5 minutes. The person servicing the circuit should check the voltage on the capacitors to verify the bank has been fully discharged.

Figure 4-11 Super Capacitor Interface Enclosure



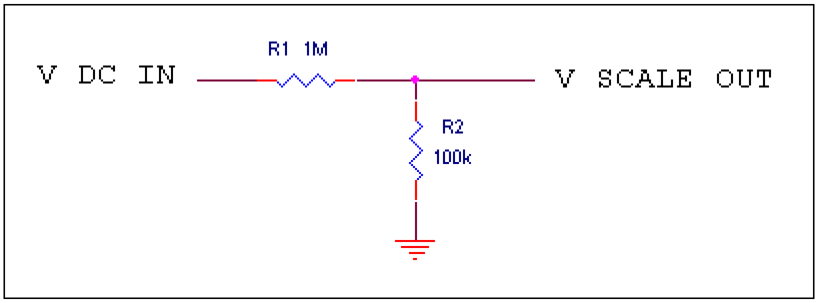
Chapter 5 - AC and DC Analog Measurement Circuits

To support the overall project of developing an educational renewable-energy experiment platform, circuits were designed to measure the power output by the turbine and the power fed into the grid by the micro-inverter when the system is installed in the rooftop application environment. To determine the electrical power produced by the turbine, the DC voltage and the DC current are measured. To determine the electrical power fed into the grid by the micro-inverter, the AC current is measured. While the inverter provides its own reported power production statistics, this AC current measurement circuit provides a further ability to observe the waveforms produced, and hence the power quality. The output of each measurement circuit is scaled to fit within the ADC voltage range of a micro-controller, taken to be 3.3 V.

DC Voltage Measurement

To measure the DC voltage of the turbine output, a simple voltage divider is used. The voltage divider scales the voltage by dividing it by ten. As designed, a voltage of 33 V will present a voltage of 3.3V to the micro-controller. The DC voltage is measured at the positive node of the capacitor bank and is simply tapped off the supply line. As shown in Figure 5-1, the maximum current drawn by the voltage measurement circuit will be 30 micro-Amps.

Figure 5-1 DC Voltage Measurement Schematic

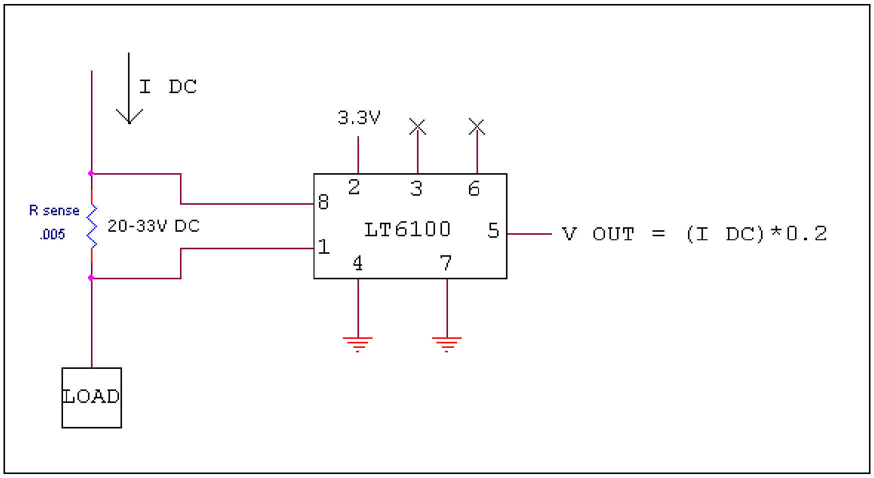


DC Current Measurement

There are two important places to measure DC current: the input side of the capacitor bank and the input to the micro-inverter. Since the wind turbine must charge the capacitor bank up to 28 V for the micro-inverter to begin accepting power, the product of the current measured at the input of the capacitor bank and the voltage at the positive node of the capacitor represents the electrical power generated by the wind turbine, in Watts. Once the micro-inverter begins to draw current, its input current can be separately measured to determine overall input power.

A current sense resistor of 0.005 ohms is placed in series with the turbine and the capacitor bank. To address the need for measuring the voltage across this resistance while it operates at elevated voltages up to 33V, a LT6100 IC has been used. It will present an output voltage proportional to the voltage across the sense resistor but within the zero to 3.3V range of the micro-controllers. As shown, the circuit will produce a DC voltage output, which represents the current sensed multiplied by 0.2. Therefore, a maximum achievable current of 10 A will produce an output of 2 V. Two of these DC current measurement circuits consume approximately 70 micro-Amps and the maximum power consumption of R_{sense} will be 0.5 W when 10 A is flowing through it (since there are two of these current-sense resistors in the signal path, a maximum of 1 W could be lost).

Figure 5-2 DC Current Measurement Schematic



AC Current Measurement

Since the voltage of the power grid is fixed and known (three-phase 208 V AC, giving 120V AC from each line to neutral), all that is required to determine AC power is a measure of the AC current. It has been determined that the M190 micro-inverter outputs current only on

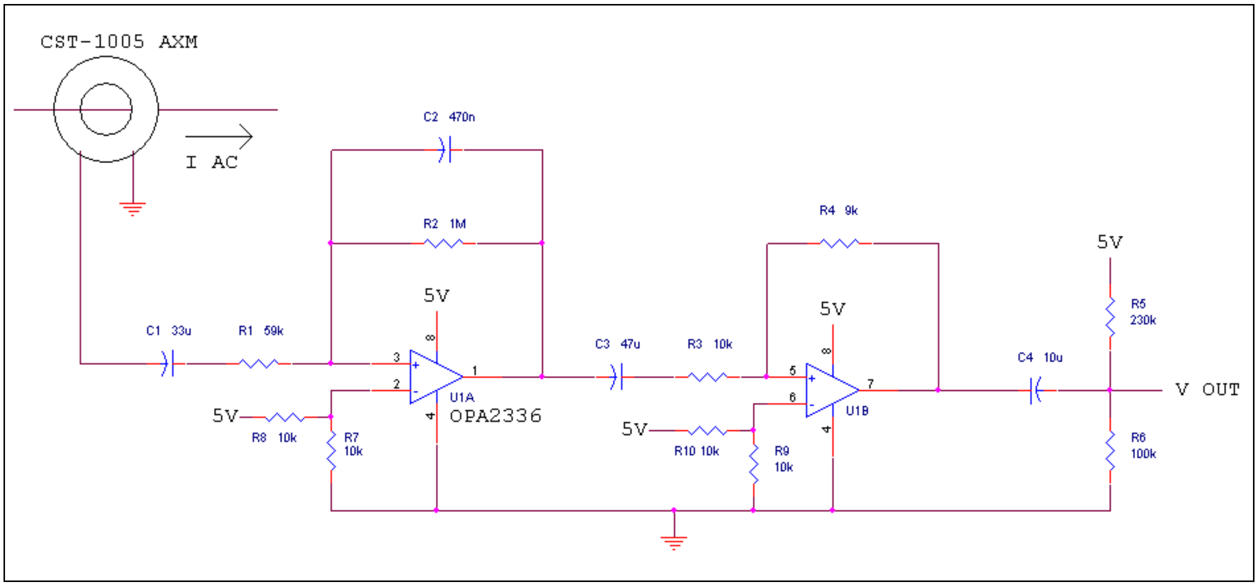
Lines 1 and 2, and a relatively equal distribution of current is split between the two. Therefore the goal is to measure the current on one of the Lines and then multiply that value by two to estimate the total output by the micro-inverter.

The approach used to measure AC current is to run a wire of the micro-inverter's grid-tied output through a current sense transformer. Since the current sense transformer is an inductor, the voltage across the transformer is a scaled version of the derivative (with respect to time) of the AC current traveling through the wire (see equation 5-1).

$$v(t) = L\frac{di(t)}{dt} \qquad (5\text{-}1)$$

The output of the transformer is therefore integrated (by an inverting integrator op-amp configuration) and then inverted to create a scaled AC voltage representation of the AC current passing through the transformer. As shown in the schematic of Figure 5-3, the circuit outputs an AC voltage waveform with an approximate 1:1 scale of RMS current. The output voltage waveform of the AC Current measurement circuit is centered at 1.5 V.

Figure 5-3 AC Current Measurement Schematic



Chapter 6 - Installation Photographs and Documentation

This chapter contains the basic documentation and layouts of the grid-tied Air Breeze wind turbine and M190 micro-inverter installation. The overall system schematic, 3-phase AC branch circuit, Air Breeze wind turbine and anemometer with wind vane installation, M190 micro-inverter installation, “main box” and “capacitor box”, and power measurement circuit boards are presented.

System Schematic and Operation

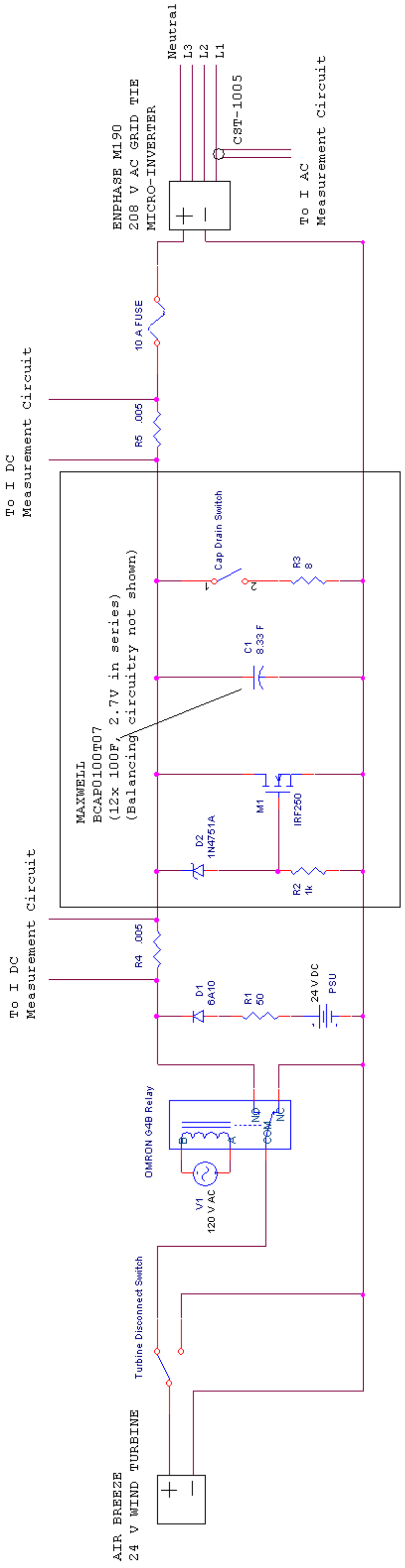
Figure 6-1 shows the overall system schematic with signal path. Starting from the left of the schematic, there is the Air Breeze “manual disconnect” switch that shorts the turbine output and leaves the remaining circuitry open. To protect the Air Breeze wind turbine from being in Free-Spin mode if there is an AC power failure, a 120 V AC relay was added to the signal path. This device, an OMRON G4B 120 V relay, is connected so that the wind turbine’s output will be shorted (and the remaining circuitry left “open”) when there is no AC applied to its coil. The relay coil is powered by Line 3 and Neutral (120 V) of the 3-phase 208 V AC grid. The relay consumes approximately 1.3 W from the grid.

To the right of the relay are the 24 V PSU and associated current-limiting resistor and protection diode. Next, the first DC current-sense resistor R4 (its voltage sensed by the circuitry described in Chapter 5) is inserted into the signal path and the DC voltage is measured at this node.

The super capacitors with associated “drain switch” and fail-safe over-voltage protection circuitry are to the right of R4. Connecting the super capacitor circuitry to the M190 micro-inverter is the second current-sense resistor R5 and a 10 A fuse.

The M190 micro-inverter is connected to the 3-phase 208 V AC grid. Line 1 of the AC grid goes through the loop of the AC current measurement current-sense transformer (discussed in Chapter 5).

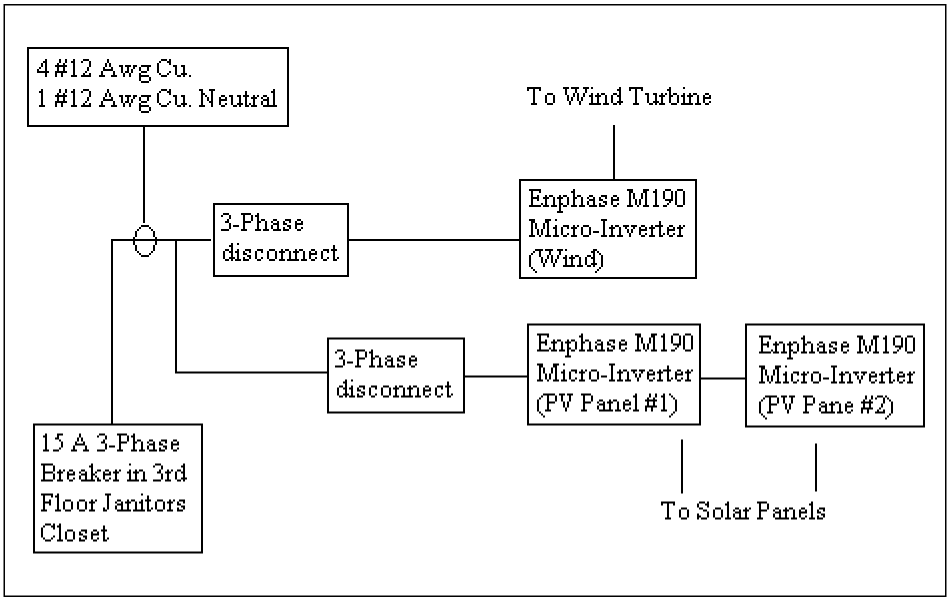
Figure 6-1 System Schematic



3-Phase 208 V Circuit and Wiring

The installed grid-tied solar panels and grid-tied wind turbine system share a 3-phase 208 V AC circuit breaker. The main AC voltage line comes from the 15 A circuit breaker in the building's 3rd floor "Janitorial closet" out to the roof on the south side of the platform. The AC lines (Lines 1, 2, 3, Neutral, and Ground) are #12 copper wire, run through a professionally installed conduit system and split to two disconnect switches. The solar panel installation has its own disconnect switch and the wind turbine system has its own disconnect switch (mounted near the wind turbine). The 3-phase lines from the disconnect switch go into the "main interface" box where they are tied to the M190 micro-inverter and associated circuitry in the box. Figure 6-2 shows a block diagram of the 3-phase wiring.

Figure 6-2 3-Phase Rooftop System Wiring Diagram



Turbine and Anemometer with Wind Vane Installation

The Air Breeze has been installed with an Air Breeze 20-foot guyed tower kit. The four guy wires connect to the Air Breeze tower 15 feet from its base and are connected to the platform in an approximate 22-foot square. A lightning arrestor has been placed in parallel with the turbine output to suppress any potential damaging electrical abnormalities from Mother Nature. The Air Breeze output wires run along the side of the tower pole to the base where it connects with the "main interface" box.

A Met One 34B anemometer and wind vane was installed on the same pole as the Air Breeze wind turbine. Cables from the anemometer and wind vane run along the side of the pole where they connect with a micro-controller in the "main interface" box.

Figure 6-3 Air Breeze Mounted with Met One 34B

M190 Micro-Inverter Installation

Figure 6-4 shows the M190 mounted to the east of the "main interface" box. Inside the "main interface" box, the M190 ties to the 3-Phase grid. The M190 DC inputs connect inside this box as well. An unshielded "earth-ground" wire connects the M190 to the rooftop platform.

Figure 6-4 Enphase M190 Installation Photo

"Main Interface" and "Capacitor" Boxes

Figure 6-5 shows the location of the "main interface" and "capacitor" installation boxes. Figure 6-6 labels the "main interface" box's input and output ports. Figure 6-7 labels the internals of the "main interface" box. Figure 6-8 is a photograph of the "capacitor" box installation.

Figure 6-5 Photo of Main Interface and Capacitor Boxes

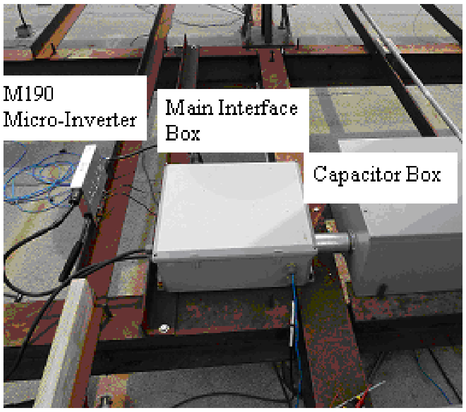


Figure 6-6 Main Interface Box Input/Output Port Labels

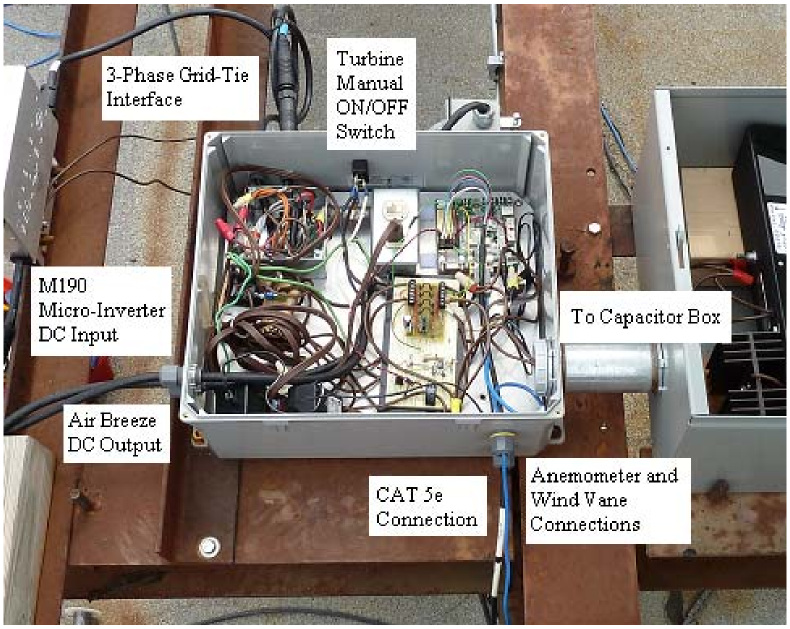


Figure 6-7 Main Interface Box Internal Connections Labels

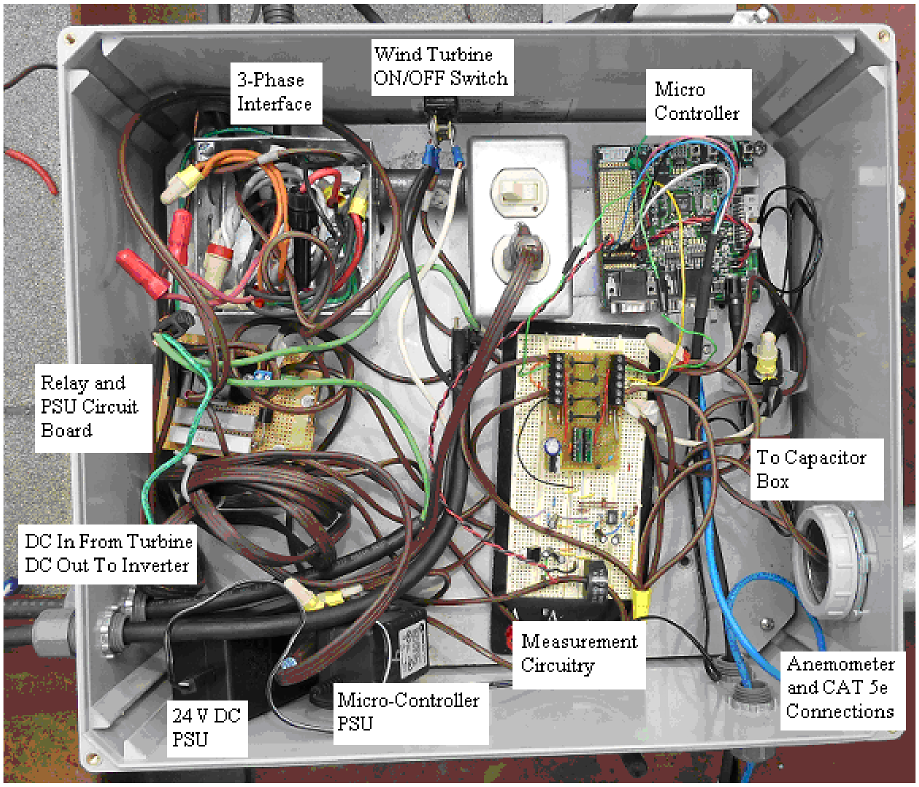


Figure 6-8 Capacitor Box Installation Photograph

DC and AC Measurement Circuit Boards

Figures 6-9 and 6-10 show the labeling of the DC and AC measurement circuit boards, respectively.

Figure 6-9 DC Measurement Circuit Board with Labels

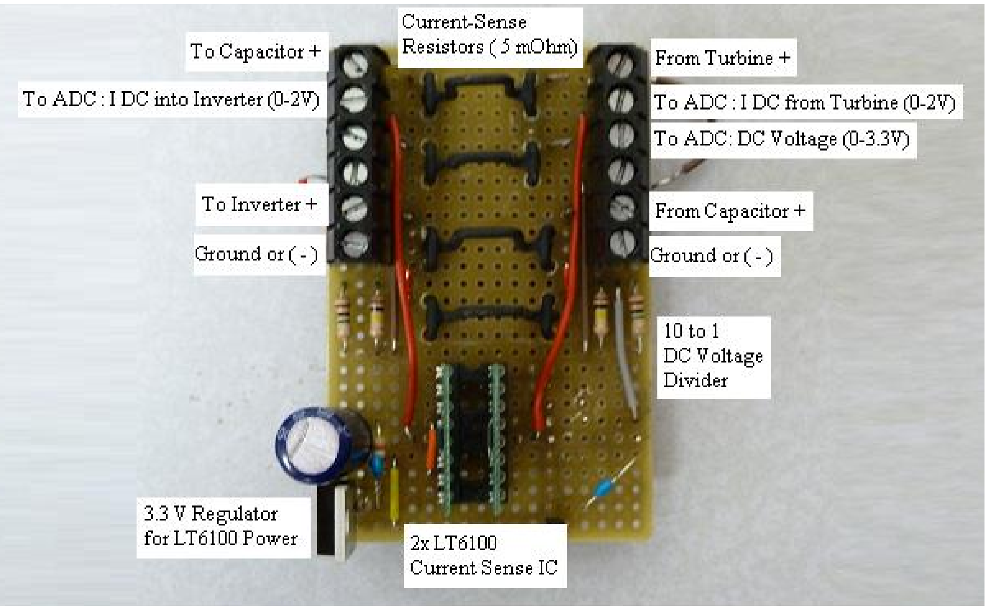
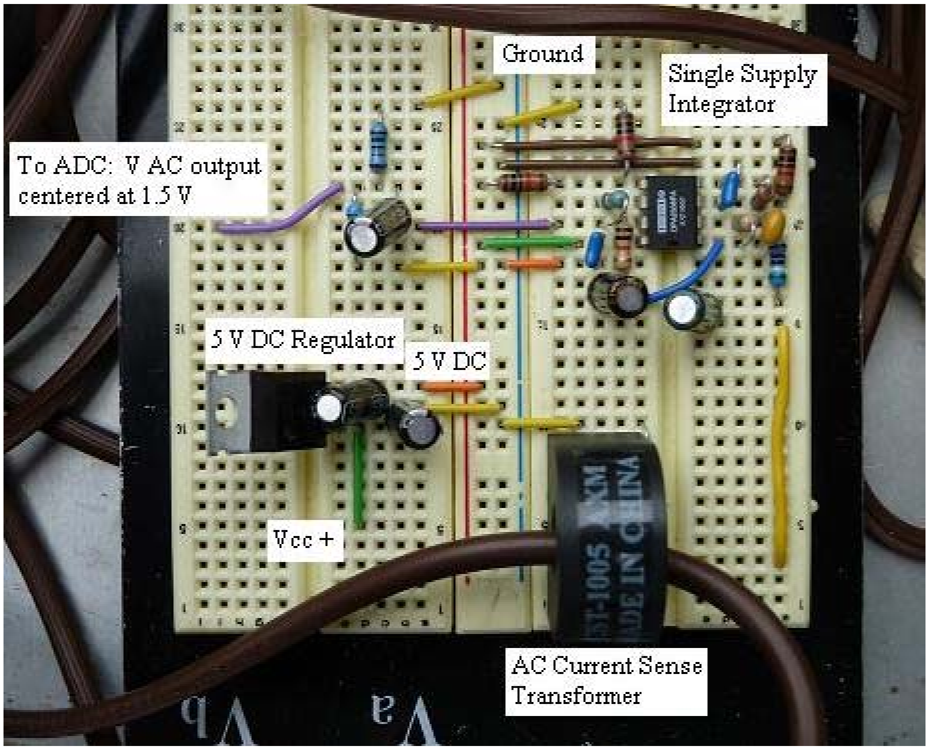


Figure 6-10 AC Measurement Circuit Board with Labels



Chapter 7 - Summary and Future Use

In summary, due to the lack of suitable grid-tie interfaces for a 160 W wind turbine, a solution was developed for an Air Breeze 24 V DC wind turbine and an Enphase M190 grid-tied micro-inverter using a parallel 8 Farad super-capacitor interface. The slow response time of the solar micro-inverter was remedied by the capacitor interface. Abrupt changes in the output of the Air Breeze small-wind turbine are smoothed and the charging of the capacitors absorbs potential large voltage transients. The capacitor interface is less expensive than a battery bank and more efficient than a diversion load regulator. The system produces usable and safe grid-tied power from a low-cost small-wind turbine.

To further support the overall project of developing an experimental platform for education in renewable energy systems, AC and DC current measurement circuits were developed for connection to a micro-controller. The circuit outputs are scaled to produce a voltage suitable for the ADC of a micro-controller. The grid-tied wind turbine power production system should be useful in an educational environment where efficiencies and system design are studied.

References

[1] Canadian Solar, CS6P datasheet, 2011. Rev 3.36.

[2] Enphase Energy, "Installation and Operations Manual", M190 datasheet, 141-00007 Rev 09.

[3] http://sustain.ece.ksu.edu/

[4] Southwest Windpower, "Air Breeze Owner's Manual", datasheet, Sept. 2008.