Wind and Hydroelectric Power Simulation for the DC House Project

by

Randy Lormand
and
Christopher Goloskie

Senior Project

Electrical Engineering Department

California Polytechnic State University

San Luis Obispo

June 2013

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

Table ***Page***

Figure

Acknowledgements

We would like to thank Dr. Taufik as well as the rest of the Cal Poly EE department for their support in the completion of the project.

Variable speed drives and DC motors were provided by Dr. Taufik and the Cal Poly EE department and additional funding was provided from the donations of various companies to the EE department.

Abstract

This project details the design and integration of a wind and hydroelectric power simulation system in correlation with the DC House Project. The simulator uses variable speed drives to rotate a DC motor which then drives a generator to produce output. This output is then regulated using a DC to DC converter which holds the voltage level constant making it easier to interface with other power sources for the house. The test results indicate that the simulator will be able to produce two separate power outputs that will provide at least 70 Watts of power in the acceptable speed range of 500-1100 RPM and substantially more power for speeds in excess of 1100 RPM. A simple wind power analysis has also been provided to help explain how easily the system can be adjusted to produce the specific wind power or hydroelectric power available in a geographic region.

I. Introduction and Background

The goal of this project is to create a system that simulates wind and hydroelectric power generation. It is a subsection of a much larger project, called the "DC House Project," whose main goal is to provide electricity to small, isolated groups of people, like those in third world countries. Despite the continual advancement of technology, many communities around the world are still without power. This is often the result of being geographically isolated from the power grid. The people living in these communities often live in poverty without access to basic needs such as heating and lighting. The question then becomes, how do we deliver electricity to these people?

The Problem

When small communities are separated by large distances, it makes it very difficult to transmit power to them. According to [2], "Remote, sparsely populated and/or low-income regions make grid extension economically unviable." For instance, it doesn't make sense economically to run several hundred miles of cable to provide a small community with electricity. It is hoped that the "DC House Project" will rectify this situation by utilizing renewable energy sources in the surrounding environment to provide electricity to these communities. These energy sources will simultaneously connect to a DC house to provide electricity, which give those living in the house access to heating, lighting, refrigeration, and other basic needs, all of which would raise the standard of living.

	2004	2015	2030
Sub-Saharan Africa	575	627	720
North Africa	4	5	5
India	740	777	782
China	480	453	394
Indonesia	156	171	180
Rest of Asia	489	521	561
Brazil	23	26	27
Rest of Latin America	60	60	58
Total	**2 528**	**2 640**	**2 727**

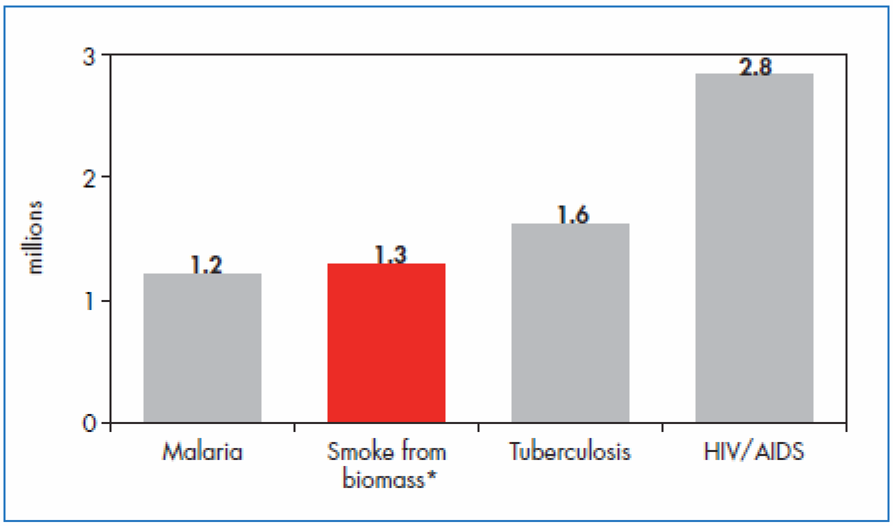
Figure 1-8: People Relying on Traditional Biomass for Cooking as of 2004 and Estimates of the Increase in Reliance Due to Population Growth in 2015 and 2030 [3]

Current Technology and Solutions

The majority of poor rural communities depend on energy in the form of burning biomass (wood, fuels, etc.) [3]. When poor individuals and communities don't have access to electrical power, their only option is to create fires which provide heat and a means to cook. Figure 1-1 shows the number of people (in millions) that rely on biomass energy for cooking as of 2004 and estimates how population growth will increase this reliance if no action is taken to offer

alternative energy sources. This is a primitive energy solution for people who don't have access to sources of energy, and it creates additional problems in regards to the health of the people and the surrounding environment.

According to [4], "A vast majority of biomass is used for cooking in open cook stoves, which is inefficient and can lead to excessive consumption, deforestation and desertification. Wood burning also creates particle emissions which have been identified as a risk factor in acute lower respiratory infection, one of the leading killers of children in developing countries." Figure 1-2 shows some of the leading causes of death annually. It can be seen that 1.3 million people die annually due to smoke from biomass, and the numbers will continue to increase with population expansion.



* IEA estimate based on WHO figure for all solid fuels.
Source: WHO Statistical Information System, available at www.who.int/whosis.

Figure 1-9: Annual Deaths Worldwide by Cause [3]

The adverse effects caused by traditional energy generation on both people and the environment have caused a global shift toward renewable energy generation. There are several ways to generate energy using renewable sources including solar power, wind power, and hydroelectric power generation. These methods are not only better for the environment; they also provide a means for generating electricity in areas that are isolated from the electrical grid [2]. This would seem to be an ideal solution to the problem; however renewable energy systems experience their own shortcomings. The major problem with using sources like wind and water individually is that it is difficult to generate a significant amount of energy without a large substation. Since the goal is to power a 250-500 Watt house, these solutions cannot be implemented individually without significant investment.

Solar technology is one of the fastest growing renewable technologies around, and as the technology advances, the price of solar power continues to go down. According to [2], "Individual home solar installations and micro- or mini-grids can serve rural areas, especially when installed with electricity storage technology or in combination with fossil fuel generators." The benefit of solar grids is that they are fairly inexpensive and can generate a significant amount of energy throughout the day. The problem with solar technology is that it suffers from intermittency problems [4]. In other words, the performance of solar panels varies based on sunlight exposure. This can vary by region and is dependent upon weather conditions. Another problem with solar technology is the fact that no energy is generated at night while the sun is down. While none of these renewable technologies are able to provide an adequate solution separately, a combination of several smaller, less expensive installations would be sufficient.

The DC House Solution

A diagram of the conceptual DC house has been provided for reference (see Figure 1-3). As you can see from the diagram, the DC house will use multiple renewable energy sources in hopes of producing between 250-500 Watts of electricity. The boxed portion in the top left corner pertains to energy generation from wind and hydropower sources. The goal of this project, as a subsidiary of the "DC House Project," is to simulate and determine the amount of energy that can be generated from these two sources. When completed, the "DC House Project" should be able to provide clean renewable energy to individuals and communities who are isolated from an AC power grid.

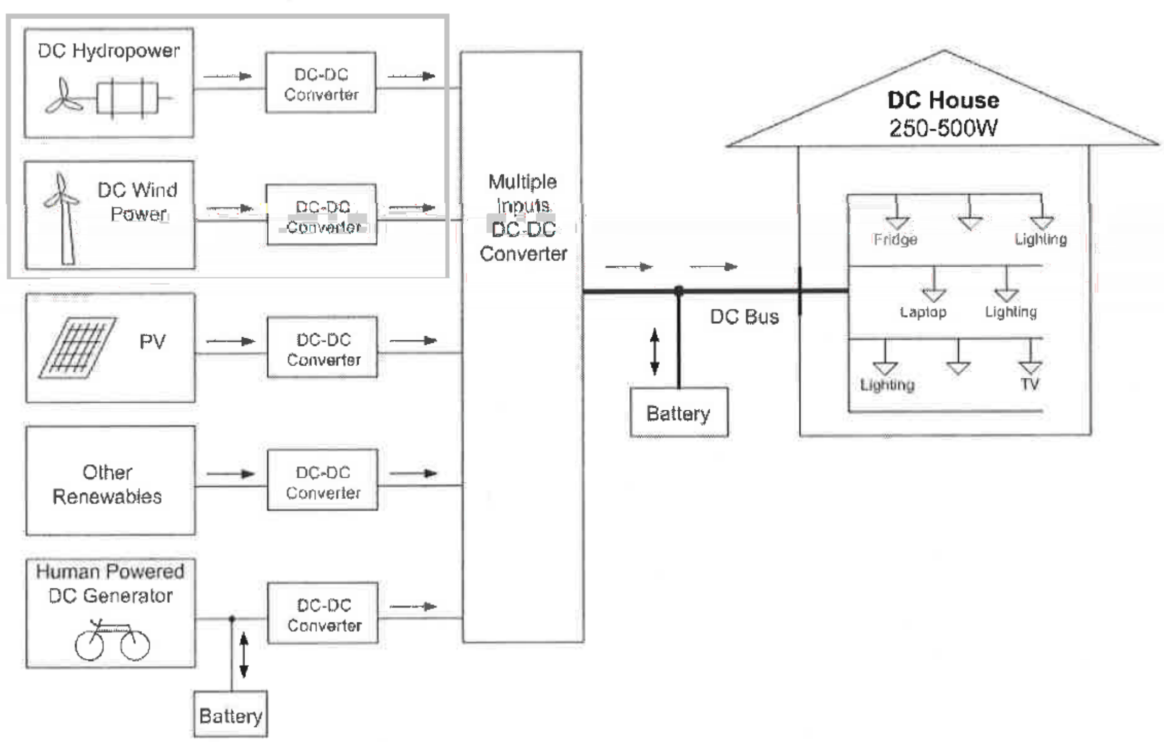


Figure 1-10: DC House [1] with Boxed Section Representing the Subsystems Simulated by this Project

Importance of Simulation

Our project is meant to be functional and easy to use. The two simulation systems, representing wind power and hydropower, will be side by side in a portable case, and adjusting the speed of the electricity producing generators will be done manually. This means that a wide range of simulated wind/water speeds can be supplied quickly and easily, allowing for more efficient testing of other components in the house, such as the MISO converter. The DC generators used in each simulation system will be similar to the generators used in the actual wind and hydroelectric systems in order to provide accurate data during testing. The speed of the DC generators will be set by variable speed drives, which convert an AC input voltage into a variable DC voltage based on user input. Each generator will simultaneously supply a DC voltage based on its respective rotational speed. This voltage will then be sent through a DC-DC converter in order to produce a constant output voltage of 24V in each system.

An advantage of this solution is that it can provide a specific amount of power based on the user's input. This will allow the user to simulate different wind and water conditions as well as test the system using different loads. Although the simulation systems will be designed to be as identical as possible to the actual power generation systems, the project is still only meant for testing purposes. The actual systems may function differently or require different components than the ones our project uses. Also, this project requires AC voltage to run. The purpose of the DC House is to obtain power from renewable sources of energy, making our project obsolete in terms of the finalized house.

II. Requirements and Specifications

The overall goal of this project is to take in AC voltage from a typical wall outlet and output 24VDC at 100-150W based on user input. The project will contain two identical systems, each taking in 120VAC and outputting 24VDC, and the user must be able to separately adjust the amount of power output by each system. Figure 2-1 depicts a high-level block diagram of one of the two systems included in the project design. The variable speed drive requires both an AC input voltage as well as a user input in order to set the desired output DC voltage. The motor is then powered by the DC voltage that is output by the speed drive. The generator is driven by the coupled motor and outputs a DC voltage based on its RPM. The converter then regulates this voltage to the necessary value. A digital tachometer will be implemented in order to view the rotational speed of the generator, and a digital ammeter/voltmeter will be implemented in order to measure the power produced by the complete system.

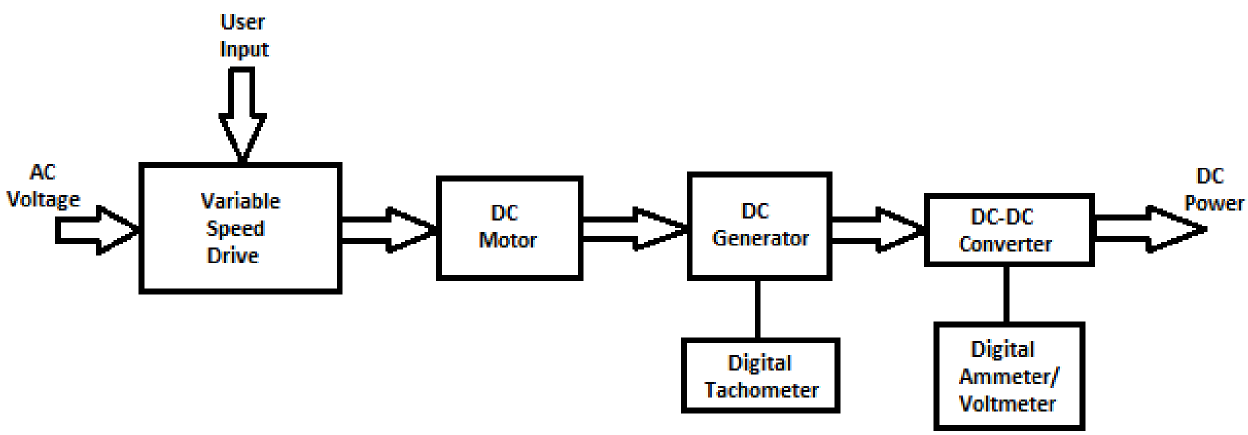


Figure 2-1: Single System Block Diagram

Component Electrical Requirements

Due to cost restrictions, the variable speed drives and DC generators were provided. Therefore, selection of the other components must be made by taking into account the specifications of the speed drive and generator as well as the functional requirements of the overall system. Figure 2-2 shows the specifications of the 15DVE DC Drive that will be used. The specifications indicate that the speed drive requires an input of 120VAC at 60HZ in order to function. This will be taken into account when determining the physical requirements. It is able to output 0-105VDC at 0.15-3A based on the user input, which means that the connected DC motor must have a maximum input voltage greater than 105VDC and a maximum current greater than 3A in order to operate safely. The provided DC generators are said to produce 150W from 24VDC at 100RPM. Assuming a non-ideal DC-DC converter requiring more than a 150W input, the generator RPM will need to be higher. This means the DC motor must be able to produce at least a few hundred RPM.

13DVE Rev.A /15DVE Rev.A MODEL SPECIFICATIONS

AC Input Voltage	± 10% Rated Line Voltage
Input Voltage - 13DVE Rev.A	12 VAC or 24 VAC
- 15DVE Rev.A	120 VAC or 240 VAC
Amps - DC Output	150mA to 3 Amps
Input Frequency	50 / 60 Hertz
I.R. Compensation	Adjustable - full range
Max. Speed	Adjustable (40 - 120% of Base Speed)
Min. Speed	Adjustable (0 - 30% of Max)
Output Voltage - 13DVE Rev.A(12 or 24 VAC Input)	0-12 or 0-24 VDC
- 15DVE Rev.A(120 or 240 VAC Input)	0-105 or 0-210 VDC
Overload Capacity	200% for 1 minute
Shunt Field Voltage - 13DVE Rev.A	.75 Amp max, 10 VDC at 12 VAC
	.75 Amp max, 20 VDC at 24 VAC
- 15DVE Rev.A	.75 Amp max, 100 VDC at 120 VAC
	.75 Amp max, 200 VDC at 240 VAC
Speed Control	5K Ohm Speed Potentiometer
Speed Range	25:1
Speed Regulation	± 1% of Base Speed
Temperature Range	-10° to 40° C. Ambient (15° to 105° F.)
Transient Protection	G-Mov
Dimensions	13DVE Rev.A / 15DVE Rev.A: 3.78" wide, 5.53" high, 3.49" deep
Weight	13DVE Rev.A / 15DVE Rev.A weighs 13.76 oz.

A-5-2728C-B
LT03

Figure 2-2: Dart Controls 15DVE Variable Speed Drive Specifications [5]

The entire system must be able to output 150W from 24VDC. This means the selection of the DC-DC converter, which outputs the final voltage, is crucial. Because the generator is able to output the desired power of 150W at 24VDC, the nominal input range of the converter must include 24V. It must also be able to boost the voltage to 24V and have a maximum output current of approximately 6.3A. Tables 2-1 and 2-2 give the electrical requirements of the various components.

Table 2-1: System Component Electrical Input and Output Requirements

Device	Required Input	Required Output
Variable Speed Drive	120VAC @ 60Hz	~
DC Motor	> 105VDCmax ; > 3Amax	> 300RPM
DC Generator	~	150W @ 24VDC
DC-DC Converter	24VDC	150W @ 24VDC

Table 2-2: Measurement Device Electrical Input Requirements

Device	Required Input Range
Digital Tachometer	0-500RPM
Digital Ammeter/Voltmeter	0-20A ; 0-100V

Physical Requirements

The completed project must be portable and housed in a case which provides safety to both the user and the different components. Requirements for the case are shown in Table 2-3 below. The variable speed drive requires a 120VAC input, which means the project must have access to a wall outlet in order to be used. An extension cord, as well as a surge protector, may

be used to provide each of the speed drives with the necessary voltage. The DC motor and DC generator must be able to be joined together by a coupling. The digital measurement devices must have LED displays and must be able to be mounted on the outside of the case. They must also be moisture proof if the project is to be used outside.

Table 2-3: Project Housing Requirements

Requirements	Justification
Dimensions: 2' x 2' x 2'	The case must be able to fit all the required devices and circuitry.
Support weight of both systems	The case must be able to support the weight of all components in order to prevent injury or system failure.
Include ventilation/cooling system	There must be a way to keep the components from overheating while be operated in order to prevent injury or system failure.
Include openings for speed drive and measurement devices	User must have easy access to the speed drive in order to manually adjust RPM. The measurement readouts must be visible on the outside of the case.
Offer protection from the environment	Because the project may be used outside, the case must be able to prevent system failure due to environmental issues such as wind or rain.
Include wheels on the bottom	The case must be able to be easily moved.

III. Design

The first step in the design process was to characterize the equipment provided to our group. Figures 3-1 and 3-2 show the provided adjustable speed drive and DC generator respectively. Characterizing these devices required some initial testing to insure that the devices would interface correctly with the motors and dc-dc converters purchased later.

Figure 3-1: Dart Controls 15DVE Variable Speed Drive

Figure 3-2: Original Permanent Magnet DC Generator

Initial test results from the variable speed drives (see Table 5-1 in Testing Procedures and Results) revealed that the maximum output voltage produced by either of the drives does not exceed 92V. This means that the motor selected to drive the DC generator must have a maximum operational input voltage of at least 92V. We were fortunate enough to find a pair of Baldor AP7402 90V DC motors that were not being used in the laboratory and obtained permission to incorporate them into the design. After obtaining the motors, we drew up a preliminary CAD design of the project (see appendix A) based on measurements taken from the motors, generators, and speed drives. This initial design provided the minimum dimensions needed to enclose the devices within a rigid structure as detailed in the requirements.

When testing, it is important to know the speed at which the generator must rotate to produce a certain amount of power. Rotational speed is commonly measured in RPM (rotations per minute) using a tachometer. Tachometers can be either contact or non-contact, meaning that they attach directly to the device that is rotating or they measure the rotational speed from a

distance. Contact tachometers are very accurate but they can slow down or interfere with the rotation of an object. For this reason non-contact tachometers (see Figure 3-3) were chosen to insure that the rotation of the generator is not effected, thereby preserving the efficiency of the entire system.

Figure 3-3: CyberTech Non-contact Digital Tachometer

After obtaining the tachometers, the generators were tested in order to determine the range of output power available and rotational speed required to produce this power. This is where we ran into our first major problem. Initial tests showed that each generator, when loaded, output a maximum of 10-20 Watts of power even at very high rotational speeds. The limited information available for these custom-made generators indicated that they would output 150 Watts of power at low speeds (~100 RPM). For this reason we had to find a new set of generators for the project.

Because the generators are such an integral part of the project, we thought it would be important to confer with Dr. Taufik (our customer in this case) and present him with several alternative options. He indicated that he wanted as close to 150 Watts of output power as possible at low speeds ranging from approximately 500-1000 RPM. After extensive research and several meetings with Dr. Taufik, we decided to purchase a single Ametek 50V permanent magnet DC motor/generator, shown in Figure 3-4, and test to see if it would fulfill our requirements.

Figure 3-4: Ametek (90-09020-001) 50V Permanent Magnet DC Motor/Generator

Initial tests on the Ametek generator (see Table 5-3 in Testing Procedures and Results) show that it is able to supply a sufficient amount of power at reasonably low rotational speeds (500-1000 RPM). The generator was also chosen based on the limited budget available for the project. Ametek generators were originally used in tape drives, and are now available as surplus generators which make them a cost-effective alternative for wind and hydroelectric power systems. After verifying the test results, a second Ametek generator was ordered allowing the design to move forward.

The completed systems will provide power to a MISO converter that requires inputs of 24V. However, each generator will provide a constantly varying voltage based on its rotational speed as well as the load. For this reason, a DC-DC converter is required to regulate the voltage. Each system is required to output roughly 150W of power at 24V, and we estimated that each Ametek generator would produce about 40V at the maximum desired RPM. Based on these specifications, as well as cost, we decided to use a Mean Well RSD-150B-24 DC-DC converter. This converter has a nominal input range of roughly 14V to 34V and outputs 24V at 0-6.3A [6]. Another advantage of the RSD-150B-24 is that it is enclosed within a chassis, preventing any harm to the user or any damage to the converter electrical components.

Since the overall goal of the project is to provide a wide range of simulated wind power and hydropower, it's important to know exactly how much power the two systems are providing at any given time. This is easily tested by placing a power meter in between the output of a single system and its load, but it's impractical to reconnect two different power meters each time components of the house are being tested. One of the major facets of the design is that it is functional and easy to use. With this in mind, we decided to pursue smaller portable meters to permanently install in the final design.

A suitable meter must be able to handle both the rated voltage and current of a single system (50V and 6.3A). A single GDD5135A series digital LED Amp & Volt Meter (shown in Figure 3-5) was initially ordered because of its wide range of voltage and current capabilities (200V and 200A with a shunt). However, after receiving and testing the meter, we discovered

that the device produces very inaccurate results under 3A of current. Since each system operates with less than 6.3A, this would eliminate nearly half the range of useful values.

Figure3-5: GDD5135A Series Digital Amp Volt Meter

For this reason, an alternative meter was needed to display more accurate measurements within the needed range. A second meter, the VAM9020 voltage ammeter shown in Figure 3-6, was also ordered and tested to verify that it would fulfill the needed requirements.

Figure 3-6: VAM9020 Series Digital Voltage Ammeter

The device provides 0-90V and 0-20A readings and can be powered using an external supply or by its internal voltage regulator. When the device is not powered externally, it requires an input voltage greater than 10V to display any readings. This proved beneficial to our project because the output of the system never falls below 10V when the system is loaded, eliminating the need to provide external power to the device. It is important for the user to know both the power being output by the DC generator as well as the overall system output. After verifying the results of the first meter, we ordered three more to provide voltage and current readings at these critical points in each system.

IV. Construction

In order to test the power output of the generators at higher rotational speeds, both the Baldor motor and the Ametek generator had to be couple together and securely mounted. Mounting the devices aligns their shafts to make sure they rotate on the same plane, reducing vibration and preventing motor bearing damage. It also insures that they are not forced apart when the rotation of their shafts exceeds approximately 1200 RPM. To accomplish this goal, the two devices were mounted on the same piece of wood, starting with the motor. After mounting the motor, the height of the generator was adjusted by placing it atop two pieces of wood. Because of its circular shape, the generator can be easily raised or lowered by bringing the two pieces of wood together or spreading them apart. This technique was used to align the centers of the two devices and provide a stable mechanical connection as shown in Figure 4-1 below.

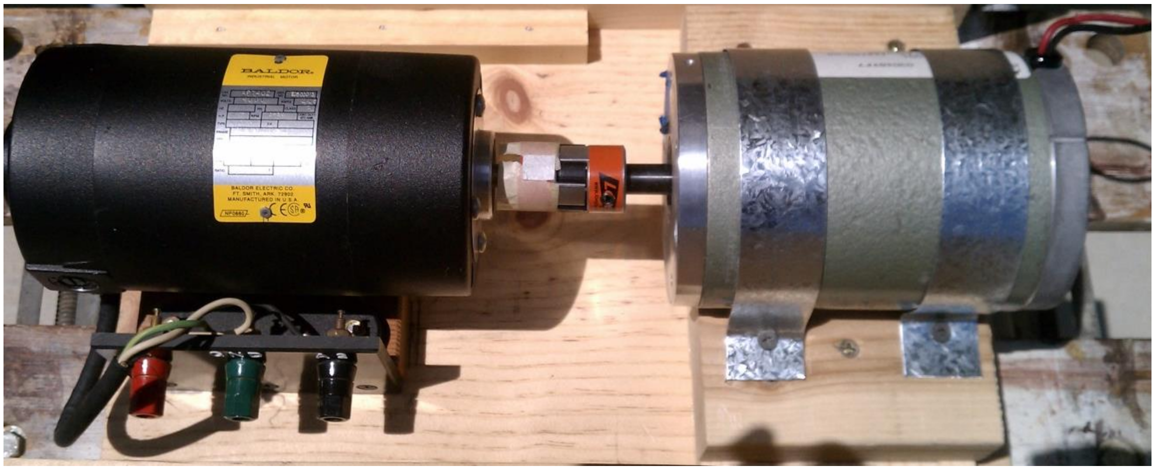


Figure 4-1: Alignment of Motor and Generator Shafts

A coupling was needed in order to provide a mechanical connection between motor and generator. Due to the differing shaft diameters, a 3/8” x 1/2" coupling was used to securely connect the two devices. Metal tape was used to hold the generator in place and assure that the devices are not forced apart while rotating. Figure 4-2 shows that wooden walls were also added to the structure for additional mechanical support, vibration reduction, and protection from any external sources. This procedure was repeated for both of the motor generator combinations.

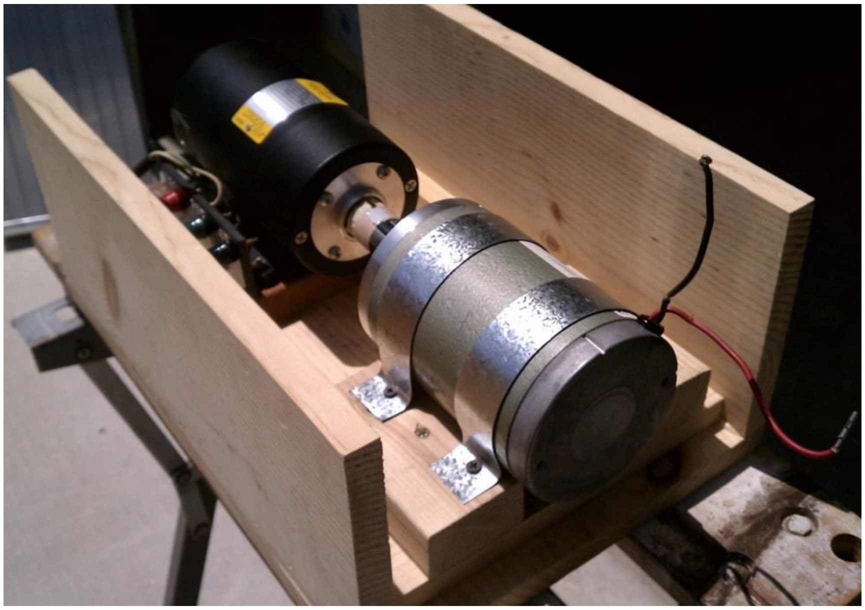


Figure 11-2: Completed Motor-Generator Housing

Housing requirements for the entire project can be seen in Table 2-3 in the Requirements and Specifications section. The design called for the two systems to be set up side by side. It also required that all necessary components fit within the enclosure and be mounted securely so they do not move when the motor and generator are spinning. The motor-generator subsystems were mounted next to each other with approximately 3 inches of space between them to safely feed wires from the front of the case to the back of the case. The DC-DC converter chassis were then mounted to the base of the enclosure about 1 inch from the generators. Both variable speed drives run off of 120VAC, so a Belkin power strip was mounted at the back of the case in order to minimize the number of wall outlets required by the project. The exact positioning of these components can be seen in Figure 4-3, which shows a top-down view of the completed case. After mounting these components and leaving space for wiring, the final housing base dimensions measured 26” x 27”, which are very close to our estimated requirement.

The user must have direct access to the variable speed drives and measurement devices which means they must be affixed on the sides of the case and be accessible from the outside. We decided to frame all the speed drives and meters on the front of the case (shown in Figure 4-4) for easy access. Holes were cut in the front panel to mount the meters and attach the wires from the speed drives to the motors and power strip, which are all within the case.

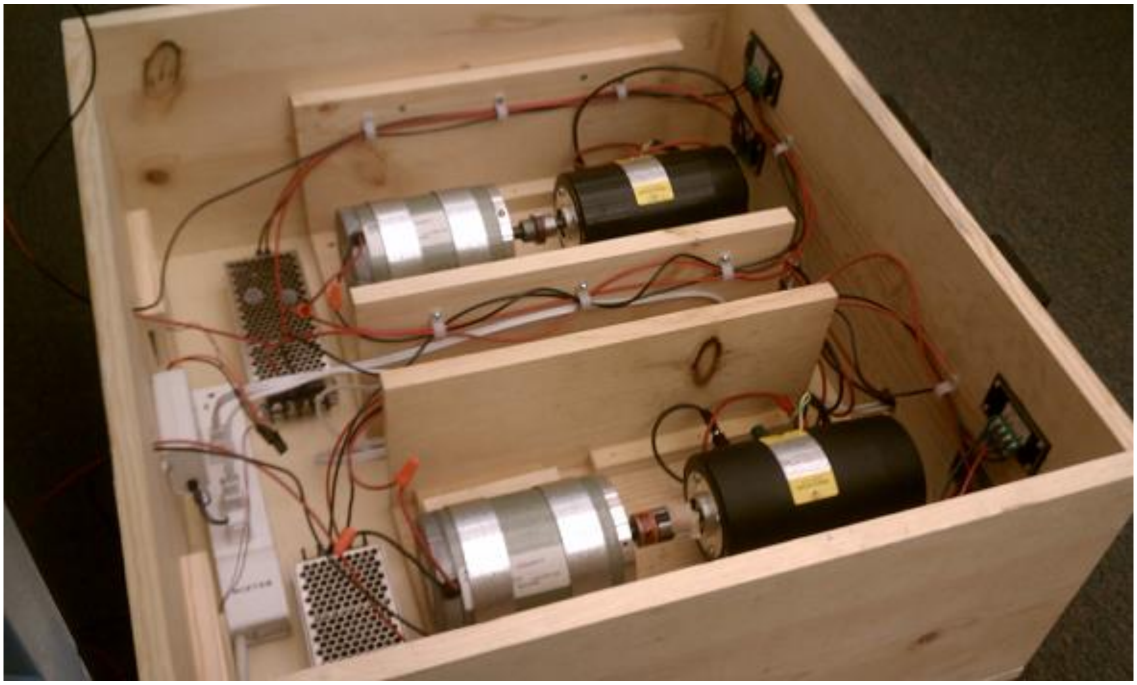


Figure 4-3: Top-Down View of Project Housing Structure

Figure 4-4: Project Housing Front Panel

Ventilation is greatly decreased when the lid is placed on the case. A lot of heat is created when the devices are active, meaning there must be some sort of alternative cooling system. We were able to procure two 80mm computer fans to dispel heat within the enclosure and decided to mount them on the back panel adjacent to the DC-DC converters since these were

the main devices we wanted to protect from overheating. Each fan runs on 12VDC input from an external source. We used a Mean Well APV-25-12 LED power supply, which converts 120VAC voltage to 12VDC voltage, to power both of the fans. The input of the power supply was connected to one of the power strip outlets, and the fans were connected in parallel to the power supply output. Because the power strip is used to power both the fans and the variable speed drives, the speed drives are unable to supply any voltage unless the fans are running, preventing any unintended overheating.

Wiring of the system was the final step in our construction phase and it was also one of the most crucial. The wire gauge used in the design must be able to handle both the voltage and current produced by the devices as well as limit the amount power lost due to transmission through the wires. The specifications for possible wire choices are shown in Table 4-1. Based on the power transmission current rating and wire resistance, size 12 AWG (American Wire Gauge) seems like the ideal choice. When taking into account cost and wire diameter however, size 14 AWG is a suitable alternative. The current rating of 5.9A is very conservative [7] and we never approached that limit during testing, which means the wire is able to safely connect the system devices. Ring terminals and spade terminals were used to connect wires to the DC-DC converters as well as the meters, and wire connector caps were used to connect wires to the DC generators. Banana connectors were attached to the system output wires so they can easily be connected to different laboratory load simulation equipment such as decade power resistors or electronic loads.

Table 4-1: American Wire Gauge Characteristics and Limits [7]

AWG Gauge	Conductor Diameter (Inches)	Resistance per 1,000 Feet (Ohms)	Maximum Amps for Power Transmission
12	0.0808	1.588	9.3
13	0.072	2.003	7.4
14	0.0641	2.525	5.9
15	0.0571	3.184	4.7
16	0.0508	4.016	3.7

V. Testing Procedures and Results

The basic test plan throughout the completion project was to characterize each device individually and then integrate the pieces one by one. Testing was also performed sequentially following the single system block diagram shown in Figure 2-1.

The variable speed drive is the first device in the system block diagram. It requires 120VAC and user input (in the form of rotating a knob) to control the output voltage. Initial tests were performed by plugging the device into an AC wall socket, rotating the knob position, and recording the output voltage. The results shown in Table 5-1 and Figure 5-1 indicate that the maximum output voltage will not exceed 92V for speed drive #1 or 79V for speed drive #2. Both devices also maintain a consistently low output voltage until the knob reaches position 6 when the voltage begins to ramp up quickly.

Table 5-1: Variable Speed Drive Output Voltage Based on Knob Position

Speed Drive #1		Speed Drive #2	
Knob Position	Output Voltage (Volts)	Knob Position	Output Voltage (Volts)
0	1.916	0	2.175
1	1.916	1	2.196
2	1.913	2	2.198
3	1.917	3	2.198
4	1.913	4	2.198
5	1.913	5	2.193
6	17.89	6	8.980
6.5	33.40	6.5	23.78
7	41.68	7	37.50
7.5	46.88	7.5	44.26
8	73.00	8	63.20
8.5	83.20	8.5	73.20
9	89.50	9	76.65
9.5	91.00	9.5	78.70
10	92.00	10	79.00

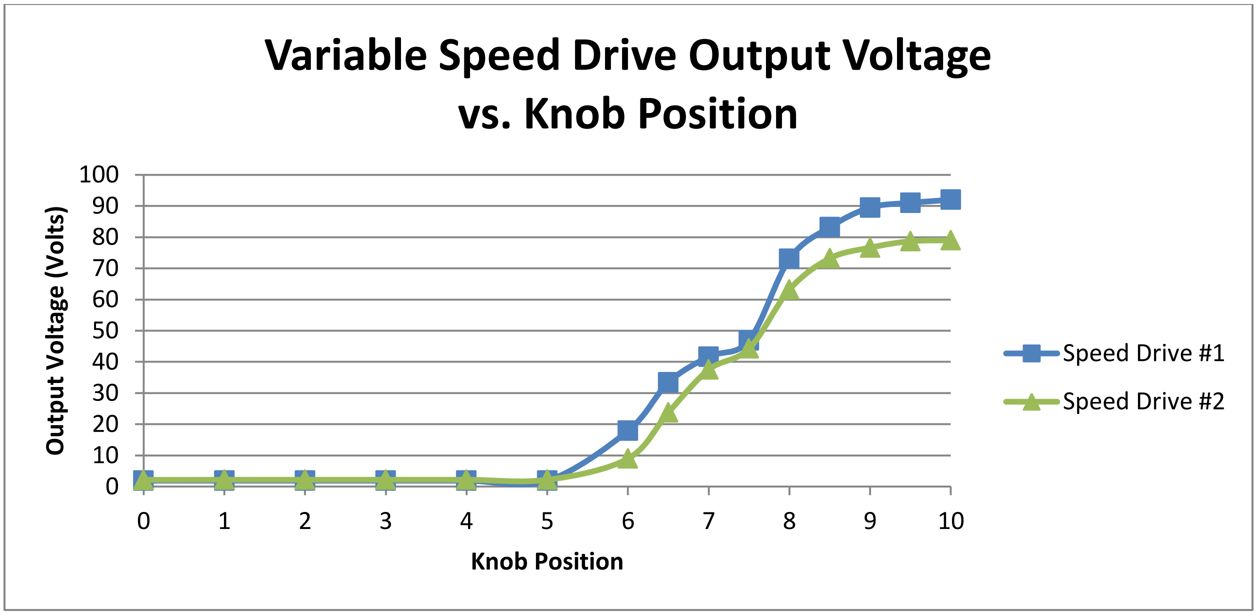


Figure 5-1: Variable Speed Drive Output Voltage vs. Knob Position

The DC motor is the second device in the system block diagram. It requires an input voltage ranging from 0-90V which causes the shaft to rotate at different speeds at the output. The DC motor was tested by applying small DC voltage increments from the DC Power Supply and measuring the rotational speed of the shaft with a tachometer. The results of this basic test are shown in Figure 5-2.

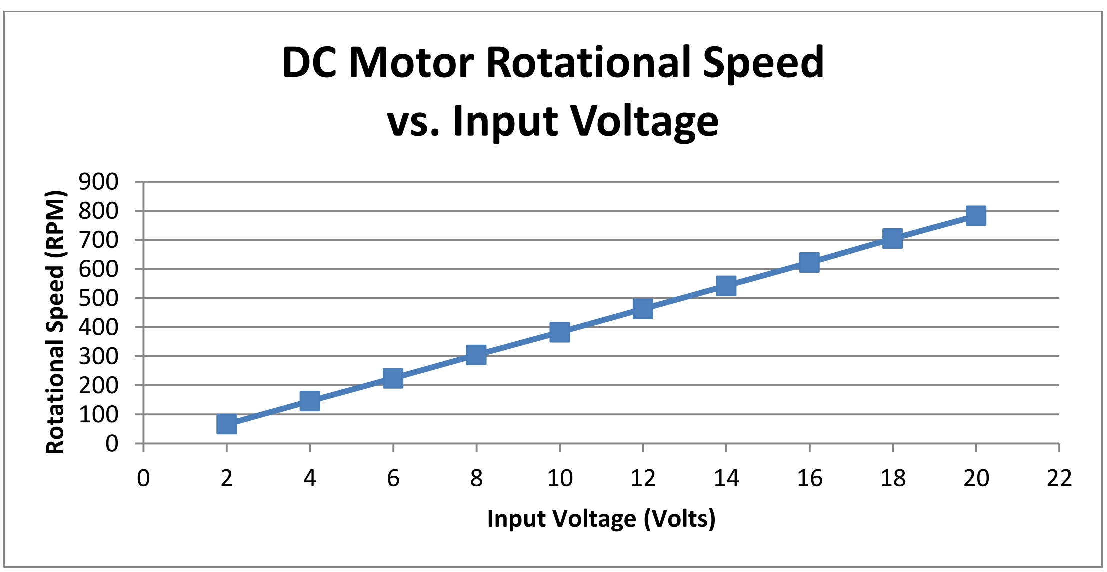


Figure 12-2: DC Motor Rotational Speed vs. Input Voltage

These results will not correlate to the completed system because the rotational speed of the motor will be reduced when it is being used to drive the generator. Nevertheless, it is important to characterize each device and get a general idea of how it will react to different inputs. Figure 5-2 shows that the speed of the Baldor AP7402 DC motor increases linearly as the input voltage increases. This is ideal in terms of our project.

The DC generator is the third device in the system block diagram. It requires rotation of its shaft to produce an output voltage. A DC generator is the same type of device as a DC motor. The only difference is that the inputs and outputs are switched. Testing the generators required the immediate integration of the motor and generator. In order to produce useful results, the generator must be rotated at a consistent speed, which is easily controlled by driving it with the motor. The devices were mechanically connected using a motor coupling which is detailed in the Construction section. In order to produce current flow out of the generator, the device must also be loaded. This was done using decade power resistors shown in Figure 5-3. Careful consideration was given to insure that the output current did not exceed the 5A rating of the resistors. In order to avoid reaching this limit during testing at high voltages, the power resistors were set up in parallel to split the load current flowing through each one.

Figure 5-3: Decade Power Resistor Used for Testing Generators

Two sets of generators were tested over the course of the project since the custom generators provided were incapable of providing the necessary power output. Table 5-2 shows that even with a small output resistance (5 ohm load), one of the original generators was only capable of producing ~8.5 Watts of power at the maximum desired RPM. The initial project requirements designated that an individual system should be able to output at least 150W, which meant that the custom generator would not suffice. When tested, both of the original generators produced similar results. These generators were eventually replaced with the Ametek 50V DC generators as described in the Design section of the report.

Table 5-2: Custom DC Generator Output Power Based on Rotational Speed at 5Ω Load

Input Speed (RPM)	Vout (Volts)	Iout (Amps)	Pout (Watts)
100	n/a	n/a	n/a
200	3.00	0.658	1.97
300	3.90	0.850	3.32
400	4.90	1.07	5.24
500	5.30	1.16	6.15
600	5.60	1.22	6.83
700	5.85	1.28	7.49
800	6.00	1.32	7.90
900	6.10	1.33	8.11
1000	6.23	1.36	8.47
1100	6.26	1.37	8.58

New tests were performed once the Ametek DC generators arrived. The testing procedure was kept exactly the same to that of the original generators in order to achieve reliable results. Parallel decade power resistors provided a 5Ω load and data was taken as the shaft rotational speed was increased in steps of 100RPM. The results in Table 5-3 indicate that the Ametek generators are capable of providing much higher output power. At 500RPM, the Ametek generator was producing roughly six times more power than the original custom generator. No measurements were taken over 700 RPM because the motor-generator mounting assembly had not been completed at this point in the project and further testing without it would have been too dangerous. Nonetheless, it was clear that the new generators could reliably provide the required power.

Table 5-3: Ametek 50V DC Generator Output Power Based on Rotational Speed at 5Ω Load

Input Speed (RPM)	Vout (Volts)	Iout (Amps)	Pout (Watts)
100	n/a	n/a	n/a
200	6.00	1.25	7.50
300	8.00	1.64	13.1
400	10.4	2.16	22.5
500	13.3	2.75	36.6
600	14.0	2.90	40.6
700	18.2	3.75	68.3

Although the results were not documented, the meters were also tested to verify that they would properly display voltage and current readings within the needed range (10-50V and 0-7A). A DC power supply was used to provide a varying input voltage to the meters and a resistive

load was placed across the output using a decade resistor. The devices are able to accurately measure the voltage or current at a node to one decimal of precision until the input voltage drops below ~9V and the device shuts off.

After testing each device individually and verifying compatibility between system stages, it was finally time to integrate all of the pieces and perform a system-wide test. Testing the completed system would present the most useful data and verify that the components function properly in the system, rather than individually. In order to obtain definite results, the motor-generator housing discussed in the Construction section was used to align the motor and generator and keep them stable while in operation. Banana connectors and alligator clips were used to connect wires between the various components and measuring equipment. Figure 5-4 shows the system-wide testing layout we used.

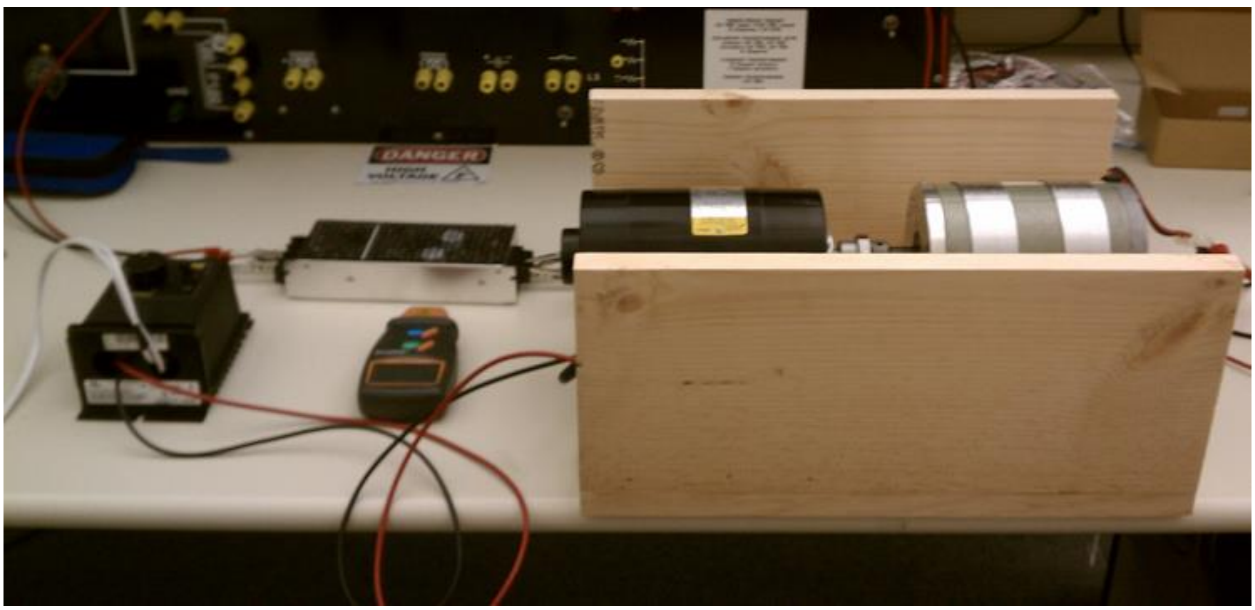


Figure 5-4: Testing Layout for Complete System

An Instek GPM-8212 power meter was used to measure and display the voltage and current being output by the DC generator. A BK Precision 8540 electronic load was used to simulate different loads as well as display the current and voltage being output by the DC-DC converter. We also used the non-contact digital tachometer discussed in the Design section to measure the rotational speed of the generator shaft. Figures 5-5 and 5-6 show the power meter and electronic load used to test the system.

Figure 5-5: Instek GPM-8212 Power Meter

Figure 5-13: BK Precision 8540 electronic load

Each complete system was expected to function with a load from 0-6.3A. However, results were needed to determine how large of a load could be handled at the desired rotational speeds (500-1000RPM). One purpose of this project is to allow the user to understand the output characteristics of each generator at the different speeds. For this reason, voltage and current measurements were taken at the output of the generator. Voltage and current measurements were also taken at the output of the converter to determine if the system was outputting the required 24V at all potential loads and rotational speeds. Tables 5-4 through 5-9 show the results of increasing the generator shaft speed at different loads. V_{in}, I_{in}, and P_{in} represent the DC generator output voltage, current, and power respectively. V_{out}, I_{out}, and P_{out} represent the DC-DC converter output voltage, current, and power.

Table 5-4: Complete System Characteristics Given a 0.5A Load

Rotational Speed (RPM)	Vin (Volts)	Iin (Amps)	Pin (Watts)	Vout (Volts)	Iout (Amps)	Pout (Watts)	Efficiency (%)
400	12.4	0.58	7.20	10.0	0.50	5.00	69.44
500	15.8	0.95	14.9	24.0	0.50	12.0	80.54
600	19.6	0.77	15.1	24.0	0.50	12.0	79.47
700	23.0	0.67	15.4	24.0	0.50	12.0	77.92
800	26.3	0.60	15.7	24.0	0.50	12.0	76.43
900	28.8	0.56	16.0	24.0	0.50	12.0	75.00
1000	31.4	0.52	16.3	24.0	0.50	12.0	73.62
1100	35.1	0.48	16.8	24.0	0.50	12.0	71.43
1200	40.6	0.43	17.5	24.0	0.50	12.0	68.57

The rotational speed was stepped up in increments of 100RPM. Given a 0.5A load, the system begins to output 24V at approximately 500RPM and remains constant as the speed is increased. However, the generator output voltage (V_{in}) increases relatively linearly with rotational speed. This signifies that the DC-DC converter is working properly to regulate the voltage at 24V. According to the Mean Well datasheet, the RSD-150B-24 DC-DC converter has an input voltage range of 14.4-33.6V [6]. This means the system will not output 24V below 500 RPM, which is when the generator provides 15.8V. When the variable speed drive was set to cause the motor to spin at less than 400RPM, the shaft remained stationary due to the converter not being able to output any power. The generator-converter subsystem reaches its maximum efficiency of 80.54% at 500RPM, which means the system will perform well at low loads given low wind or water speeds.

Table 5-5: Complete System Characteristics Given a 1A Load

Rotational Speed (RPM)	Vin (Volts)	Iin (Amps)	Pin (Watts)	Vout (Volts)	Iout (Amps)	Pout (Watts)	Efficiency (%)
400	12.2	0.86	10.5	7.00	1.00	7.00	66.67
500	13.1	1.91	25.0	22.0	1.00	22.0	88.00
600	15.1	1.83	27.6	24.0	1.00	24.0	86.96
700	20.9	1.35	28.2	24.0	1.00	24.0	85.11
800	24.5	1.17	28.6	24.0	1.00	24.0	83.92
900	28.2	1.03	29.1	24.0	1.00	24.0	82.47
1000	30.3	0.97	29.4	24.0	1.00	24.0	81.63
1100	35.0	0.86	30.1	24.0	1.00	24.0	79.73
1200	37.6	0.81	30.4	24.0	1.00	24.0	78.95

Given a 1A load, the system begins to output 24V at 500-600RPM. Similar to the results for a 0.5A load, the generator output voltage increases steadily with rotational speed while the DC-DC converter regulates the system output voltage to 24V. Also, the efficiency is boosted by about 10% compared to the 0.5A load.

Table 5-6: Complete System Characteristics Given a 1.5A Load

Rotational Speed (RPM)	Vin (Volts)	Iin (Amps)	Pin (Watts)	Vout (Volts)	Iout (Amps)	Pout (Watts)	Efficiency (%)
400	11.5	1.44	16.6	8.00	1.50	12.0	72.29
500	13.0	2.54	33.0	18.5	1.50	27.8	84.09
600	n/a	n/a	n/a	n/a	n/a	n/a	n/a
700	n/a	n/a	n/a	n/a	n/a	n/a	n/a
800	23.0	1.79	41.1	23.95	1.50	35.93	87.41
900	26.9	1.55	41.6	23.95	1.50	35.93	86.36
1000	28.3	1.47	41.7	23.95	1.50	35.93	86.15
1100	33.8	1.26	42.6	23.95	1.50	35.93	84.33
1200	37.1	1.16	43.1	23.95	1.50	35.93	83.35

Given a 1.5A load, the system begins to output 24V at approximately 800RPM. However, data was difficult to obtain at lower speeds due to the increased load. We discovered during testing at higher loads that the motor shaft speed remains constant even as the voltage applied to the motor increases. This happens until the voltage reaches a certain point in which the rotational speed quickly jumps to ~1000RPM. From there, the voltage can be slowly lowered in order to achieve lower speeds. The following tables indicate that as the load increases, the gap the motor input voltage must overcome also increases, making it difficult to obtain certain rotational speeds. Once this gap is surpassed though, the system outputs a constant 24V.

Table 5-7: Complete System Characteristics Given a 2A Load

Rotational Speed (RPM)	Vin (Volts)	Iin (Amps)	Pin (Watts)	Vout (Volts)	Iout (Amps)	Pout (Watts)	Efficiency (%)
400	11.4	1.60	18.2	6.00	2.00	12.0	65.93
500	12.8	2.93	37.5	14.5	2.00	29.0	77.33
600	13.6	3.31	45.0	19.0	2.00	38.0	84.44
700	n/a	n/a	n/a	n/a	n/a	n/a	n/a
800	n/a	n/a	n/a	n/a	n/a	n/a	n/a
900	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1000	29.3	1.86	54.6	23.92	2.00	47.84	87.62
1100	33.3	1.65	55.1	23.92	2.00	47.84	86.82
1200	36.7	1.51	55.6	23.92	2.00	47.84	86.04

Table 5-8: Complete System Characteristics Given a 2.5A Load

Rotational Speed (RPM)	Vin (Volts)	Iin (Amps)	Pin (Watts)	Vout (Volts)	Iout (Amps)	Pout (Watts)	Efficiency (%)
400	11.4	1.86	21.2	6.00	2.40	14.4	67.92
500	12.7	3.07	39.0	13.0	2.50	32.5	83.33
600	13.7	3.87	53.0	18.0	2.50	45.0	84.91
700	n/a	n/a	n/a	n/a	n/a	n/a	n/a
800	n/a	n/a	n/a	n/a	n/a	n/a	n/a
900	24.2	2.75	66.6	23.85	2.50	59.63	89.53
1000	29.7	2.26	67.2	23.85	2.50	59.63	88.73
1100	33.3	2.03	67.6	23.85	2.50	59.63	88.20
1200	35.8	1.91	68.4	23.85	2.50	59.63	87.17

Table 5-9: Complete System Characteristics Given a 3A Load

Rotational Speed (RPM)	Vin (Volts)	Iin (Amps)	Pin (Watts)	Vout (Volts)	Iout (Amps)	Pout (Watts)	Efficiency (%)
400	11.4	1.87	21.3	5.00	2.50	12.5	58.69
500	12.5	2.98	37.3	9.00	3.00	27.0	72.39
600	13.9	4.32	60.0	17.0	3.00	51.0	85.00
700	n/a	n/a	n/a	n/a	n/a	n/a	n/a
800	n/a	n/a	n/a	n/a	n/a	n/a	n/a
900	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1000	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1100	31.5	2.55	80.2	23.82	3.00	71.46	89.10
1200	34.6	2.34	80.8	23.82	3.00	71.46	88.44

According to Table 5-9, the system cannot output 24V until the generator shaft is spinning at speeds greater than 1000RPM. We discovered that when loads above 3A were connected, the generator needed a large amount of mechanical power to produce the needed electrical power. This required its shaft to spin at speeds above those outlined in the requirements. For this reason, measurements were not taken at loads above 3A.

Efficiency refers to the power output by the converter compared to the power consumed. This is a crucial value because one of the goals of the DC House is to be as sustainable as possible and minimize wasteful power consumption. As Figure 5-7 shows, the efficiency of the converter increases with the load as long as the generator is spinning fast enough to produce the necessary power. The efficiency can reach 90% at loads above 2.5A.

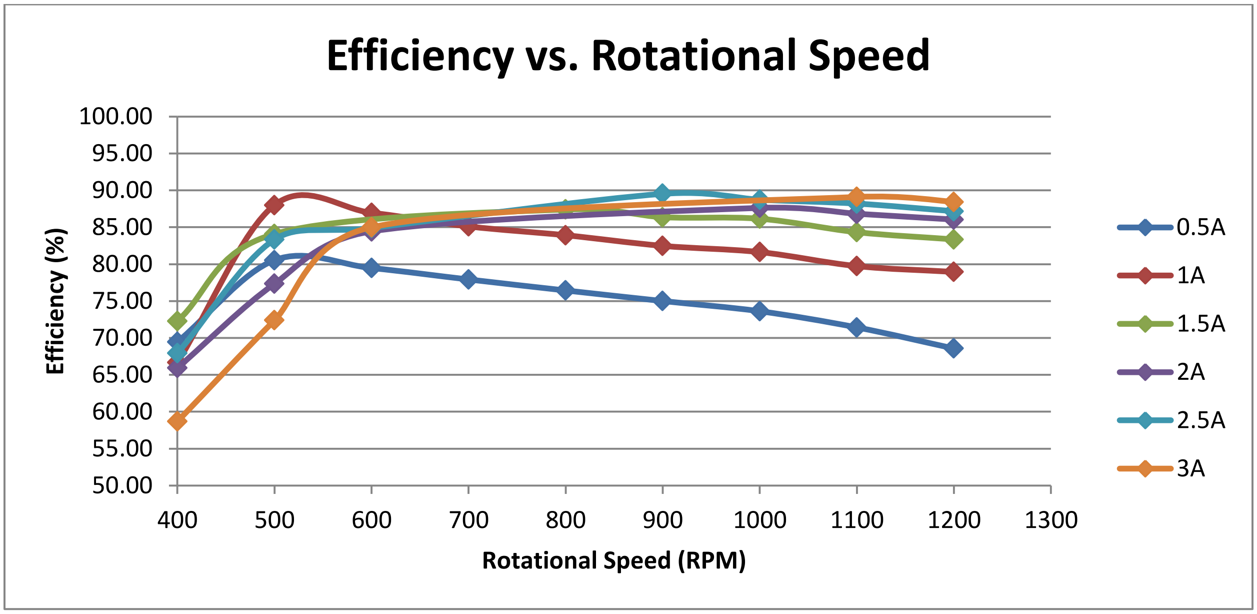


Figure 5-14: Complete System Efficiency vs. Rotational Speed

The results indicate that the system is performing consistently at different loads and speeds, and the measured values are relatively similar to our initial performance expectations. The DC generator output voltage is directly correlated to the shaft speed, increasing at a rate of roughly 4V/100RPM. This means the user can consistently adjust the output power at low loads using the variable speed drive. Given a low load, the overall system produced 24V at the desired speeds and the converter efficiency remains between 70% and 90%. The highest output power achieved during testing was 71.46W at 1100RPM. Although the system could not produce 150W at low speeds, the project should be sufficient when testing other portions of the DC House. According to the specifications of the MISO converter currently being used, when there are multiple inputs, no more than 3.5A is required by a single source while the converter is operating at full load [8]. Our project is capable of producing this power from both systems even if the required rotational speed is beyond what was specified in the initial requirements. Both systems were tested to insure that they share the same characteristics and that they could simultaneously output power to the same load. Final testing was executed on both systems after they had been fully wired and mounted within the housing structure. Both systems successfully output results similar to those produced when testing with the laboratory equipment.

VI. Conclusion

The main project objective was to create a user-friendly system that simulates both wind and hydroelectric power generation. The final test results show that our project is able to supply two 24V outputs at varying loads. This allows the user to quickly and easily provide a specific amount of power to the DC house with the turn of a knob. This control over the specific output power of both systems enables the user to simulate the theoretical power available from multiple sources in a certain geographic region.

To illustrate this fact, let us consider that a hypothetical wind turbine is placed in San Luis Obispo for use with the DC House. Using an appropriate wind model allows us to estimate the power available in the wind. More accurate results can be obtained by performing a wind study over an extended period of time, but making a few assumptions is sufficient for this example.

First and foremost, the amount of power available in the wind follows the equation:

$$Pw = \frac{1}{2}\rho A v^3$$

ρ = air density (kg/m^3)
A = $(\pi/4)D^2$; D = blade diameter
v = wind speed (m/s) at the center of the rotor

Air density is affected by both temperature and altitude, but for the purposes of this example we will assume 15˚C (59˚F) and 1 atmosphere of pressure, where:

$\boldsymbol{\rho = 1.225\ kg/m^3}$

Area refers to the cross sectional area of the rotor blades. Increasing the length of the rotor blades increases the maximum power that can be obtained from the wind. For simplicity, we will assume 1 meter blades, or a 2 meter diameter.

$A = (\pi/4)D^2 = (\pi/4)2^2 = \mathbf{A = \pi = {\sim}3.14\ m^2}$

Wind speed is dependent upon a multitude of factors including tower height and friction coefficient, all of which are beyond the scope of this example. For simplicity, we will assume that the average wind speed in San Luis Obispo is measured at the center of the rotor and that it is constant at the top and bottom of the blades. Since the original wind power equation uses instantaneous wind speed, we must change the model to utilize average wind speed.

Assuming a Rayleigh distribution, which is often done when estimating wind power [9], the equation changes to:

$$Pw = \left(\frac{1}{2}\right)\left(\frac{6}{\pi}\right)\rho A vavg^3$$

According to [10] the average wind speed in San Luis Obispo was 8 mph for seven out of twelve months in the last year. Converting this value to meters per second allows us to estimate the amount of power available in the wind.

$$vavg = 8\,mph * \left[\frac{1\frac{m}{s}}{2.237\,mph}\right] = 3.5762\,m/s$$

$$Pw = \left(\frac{1}{2}\right)\left(\frac{6}{\pi}\right)\rho A vavg^3 = \left(\frac{1}{2}\right)\left(\frac{6}{\pi}\right)(1.225\frac{kg^3}{m})(\pi m^3)(3.5762\left(\frac{m}{s}\right)^3)$$

$\boldsymbol{Pw =}$ **168.08 Watts**

Unfortunately this is not the amount of power that is converted into electricity. We must also account for electrical and mechanical losses. The highest efficiency possible for a rotor is 59.3%, which is known as Betz' law [9]. It makes sense that all the energy can't be taken out of the wind, otherwise after hitting the rotor the wind would stop and prevent any more wind from passing through. A reasonable estimation for the efficiency of converting wind power to electricity is 30% [9]. Using this efficiency we obtain:

Electrical Power Output = 168.08W * .30 = **56.03 Watts**

This example estimates that a wind turbine in San Luis Obispo with 1m blades might expect to produce about 56.03 Watts of power. Hydropower operates under many of the same principles, but runs off water flow instead of air flow. Our system can easily provide the 56 Watts of power assumed in this example and lets the user see how fast the generator must be spinning to produce this power. The user can also quickly adjust the input settings to simulate the power expected in a different region or simulate the wind speed in San Luis Obispo suddenly changing. This is valuable when testing how other elements of the DC House will react to varying energy sources. It also tells if implementation of the DC House in certain areas will be viable based on the amount of wind and water resources available. The wide power output settings and ease of use show that the project has fulfilled all of the original requirements and is therefore beneficial to the advancement and eventual completion of the DC House Project.

VII. Bibliography

[1] Taufik. (2010, September 13). *The DC House Project* [Online]. Available: http://www.calpoly.edu/~taufik/dchouse/

[2] D. Elzinga et al., “Advantage Energy: Emerging economies, developing countries and the private-public sector interface.” International Energy Agency, Paris, France, Int. Global Compact, 2011, pp. 10-31.

[3] F. Birol et al., “Energy for cooking in developing countries,” in *World Energy Outlook*, 2nd ed. Paris, France: IEA Publications, 2006, ch. 15, pp. 419-445.

[4] R. Rapier, “Renewable Energy,” in *Power Plays: Energy options in the age of peak oil*. New York: Apress, 2012, ch. 3, pp. 25-40.

[5] *Adjustable Speed DC Control Data Manual*, Dart Controls, Inc., Zionsville, IN.

[6] Mean Well, “150W Railway Single Output DC-DC Converter,” RSD-150 series datasheet, [Revised Apr. 26, 2013].

[7] M. Lund. (2013). Wire Gauge and Current Limits Including Skin Depth and Strength [Online]. Available: http://www.powerstream.com/Wire_Size.htm

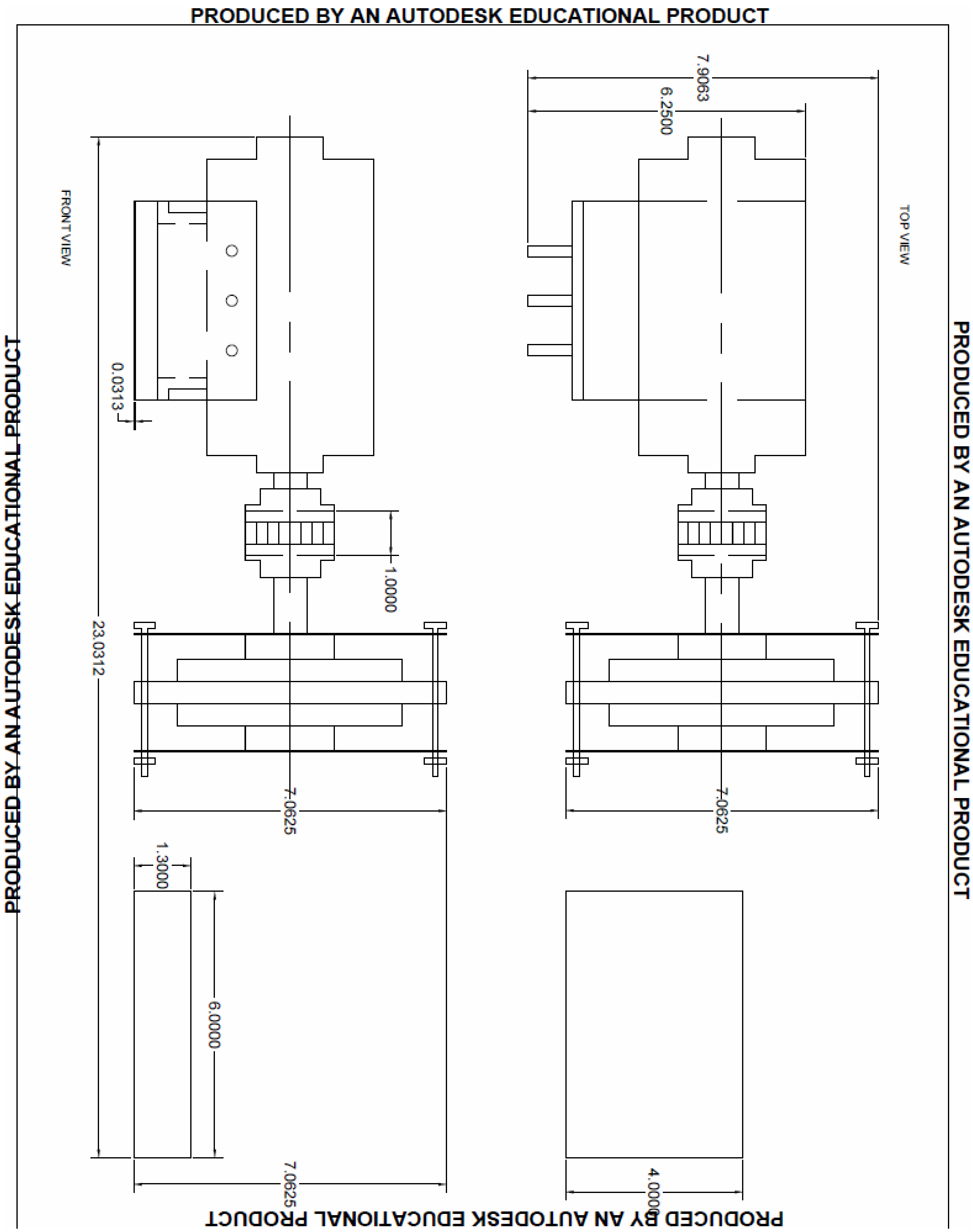
[8] O. Jong, “Multiple Input Single Output (MISO) DC-DC Converter for the DC House Project,” California Polytechnic University, Dept. of Elect Eng., 2012.

[9] G. M. Masters, “Wind Power Systems,” in *Renewable and Efficient Electric Power Systems*, 1st Ed. New Jersey: Wiley, 2004, Ch. 6, pp. 307-351.

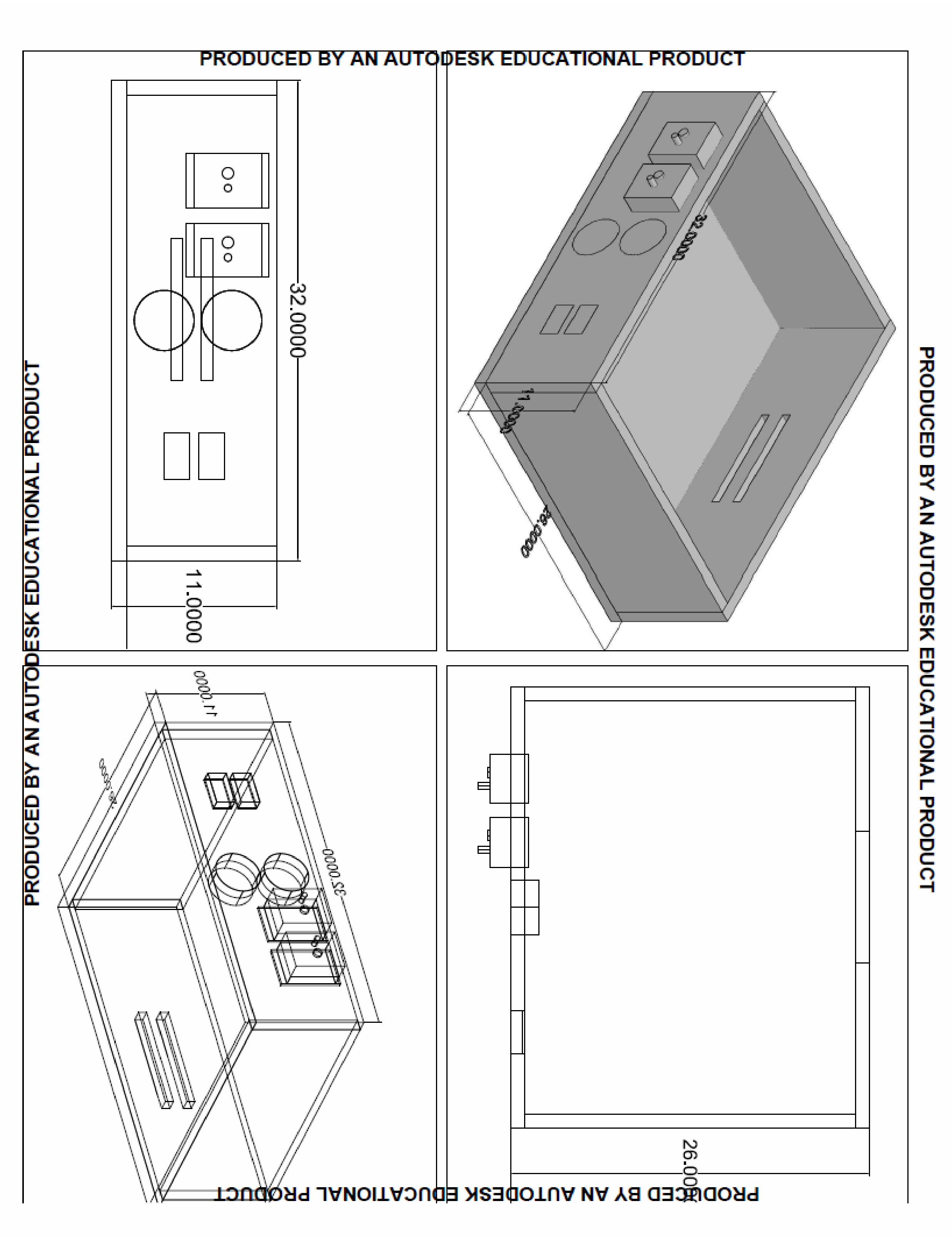
[10] “Wind and Weather Statistics San Luis Obispo,” Windfinder [Online]. Available: http://www.windfinder.com/windstats/windstatistic_san_luis_obispo.htm

X. Appendices

Appendix A – Initial CAD Design



Appendix A – Initial CAD Design



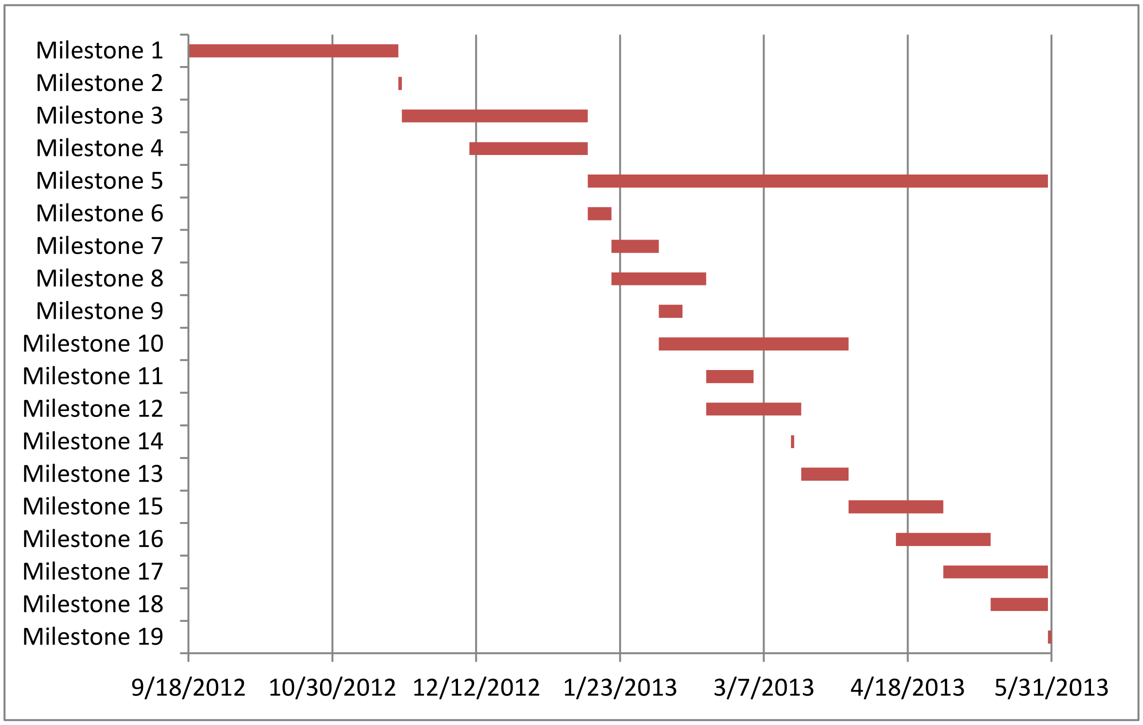
Appendix B – Parts List and Costs

Parts Used in Design

	Part	$/piece	Sales Tax	Price w/Tax	# used	Final Cost
1	Ametek 50V Generator	131.29	0.00	131.29	1	131.29
2	Ametek 50V Generator	141.29	0.00	141.29	1	141.29
3	1x12x4 Pine Wood Sheet	7.29	0.58	7.87	1	7.87
4	2x3x8 Wood Stud	1.96	0.16	2.12	1	2.12
5	1-1/2"x1-3/8" Framing Anchor	0.67	0.05	0.72	8	5.79
6	#8x5/8" Wood Screws	1.18	0.09	1.27	2	2.55
7	10A 125V White Blade Plug	1.48	0.12	1.60	2	3.20
8	Digital Photo Laser Tachometer	16.22	0.00	16.22	2	32.44
9	16-14 AWG Ring Terminals	2.18	0.17	2.35	1	2.35
10	Standard Wire Connector 25pk	1.97	0.16	2.13	1	2.13
11	14 Gauge Stranded Red Wire - 1FT	0.27	0.02	0.29	30	8.75
12	14 Gauge Stranded Black Wire - 1FT	0.27	0.02	0.29	30	8.75
13	Boston Gear BF37/8X1/2 Shaft Coupling	19.56	1.57	21.13	1	21.13
14	16-14 AWG Spade Terminals	6.97	0.56	7.53	1	7.53
15	2" Rubber Wheel Plate Caster	3.96	0.32	4.28	4	17.11
16	VAM9020 Amp Volt Meter	13.99	0.00	13.99	4	55.96
17	RSD-150B-24 DC/DC Converter	80.68	5.78	86.46	2	172.92
18	APV-25-12 LED Power Supply	15.19	0.84	16.03	2	32.06
19	3/8" Round Vinyl Pads	2.48	0.19	2.67	1	2.67
20	Plexiglass Acrylic Sheet	14.98	1.12	16.10	1	16.10
21	Engraved Metal Plates	34.58	0	34.58	1	34.58
22	3/8"X1/2" Lovejoy Motor Coupling	16.48	0	16.48	1	16.48
					Total	$725.06

Appendix C – Schedule/Time Estimates

The Gantt timeline below outlines the schedule that must be followed in order to complete the project. Each bar represents a milestone that is described below along with possible deliverables for that milestone.



Milestone 1: Choose senior project and define requirements.
Deliverables: Senior project definition rough draft

Milestone 2: Submit final project report definition.
Deliverables: Completed senior project definition

Milestone 3: Order initial parts and devices. (**High Risk** – parts and devices must be compatible with the variable speed controllers and generators provided)
Deliverables: Parts list along with prices.

Milestone 4: Brainstorm system design and plan testing procedures.

Milestone 5: Document progress and write project report.

Milestone 6: Create detailed design of overall system.
Deliverables: Schematic and layout of system

Milestone 7: Test and determine properties of variable speed drive and DC generator.
Deliverables: Speed drive and generator test results

Milestone 8: Select and purchase DC-DC converter. (**High Risk** – compatibility)
Deliverables: Parts list along with prices.

Milestone 9: Test and determine properties of DC motor and DC-DC converter.
Deliverables: Motor and converter test results

Milestone 10: Design case to house the project and prevent user injury.
Deliverables: Layout of housing structure.

Milestone 11: Build and test single system to determine behavior.

Milestone 12: Analyze system test results and debug to achieve proper functionality.
Deliverables: Functioning wind power generation simulation system.

Milestone 13: Submit interim progress report at the end of EE463.
Deliverables: EE463 interim report

Milestone 14: Build and test second system and make any necessary alterations.
Deliverables: Functioning hydroelectric power generation simulation system.

Milestone 15: Build case based on component properties and final design specifications.

Milestone 16: Implement system within case and test to ensure consistent results.
Deliverables: Both systems housed in completed case

Milestone 17: Create display to showcase project.
Deliverables: Display board describing project

Milestone 18: Complete final testing and make any final adjustments before demoing.

Milestone 19: Demo completed project at Senior Project Expo and submit final report.
Deliverables: Completed senior project and report

WIND AND HYDROELECTRIC POWER SIMULATOR USER'S GUIDE

Safety Concerns (PLEASE READ!):

1. Always verify that loads are connected properly and that the Variable Speed Drives attached to the front of the case are turned off before operating the simulator.

2. To prevent damage to the simulator, it is recommended that the knob on the Variable Speed Drives is placed below the #5 tick on the dial before powering on the device. This will insure that the motors don't start spinning rapidly as soon as the simulator is powered on.

3. When varying the input to the Variable Speed Drives, it is recommended that changes be made slowly. This applies to both increases and decreases in speed. Doing so will help protect the equipment and prevent it from overheating.

4. Variable Speed Drive #1 (Drive on the left when looking at the front of the case) has a maximum output of 92V. It drives a Baldor motor with a rated input of 90V. For this reason, it is recommended that the dial of drive #1 is not turned to its maximum value. If the maximum output of the drive is required for testing, it is recommended that the test be performed as quickly as possible to prevent damage to the motor. Drive #2 has a maximum output of only 79V and can therefore be safely operated at maximum capacity. Note that because the drives output different values, placing the knobs in identical positions will not make the output of the two systems the same.

5. Care should be taken not to exceed 5.9A of current out of the generator. The system is wired using 14 Gauge wire and AWG (American Wire Gauge) standards indicate a maximum current of approximately 5.9A for power transmission. This is a conservative estimate, but it is recommended to stay either below or as close to 5.9A as possible and only exceed that value for a short duration.

6. Finally, always be sure to keep hands, feet, hair, and any other loose equipment away from the motors and generators while the simulator is operational and open. If something gets tangled in the motor or generator it can cause serious harm to both the system and the people around it. If this does happen, unplug the simulator from the wall socket immediately; do not attempt to turn off the device from the internal power strip.

BASIC OPERATION:

1. Connect the power strip inside the case to a wall socket. If the fans turn on, the power strip has already been activated. If not, open the lid and press the switch on the side of the power strip to apply power to the case.

2. Connect the output banana cables of each system to separate test loads (5.9A or less recommended). If only one system is needed, insure that the system not being used remains off.

3. Once the system has been loaded, turn on the variable speed drive on the front of the box. Slowly increase the speed of rotation by turning the dial on the speed drive.

4. Continue increasing or decreasing the speed of rotation until the desired output of either the generator or the DC-DC converters is displayed on the meters.

5. Use the digital tachometer to measure the speed of rotation of the shaft. If the shaft does not already have a small piece of reflective tape on it, turn off the system and place a small piece of reflective tape (about a half inch) on the shaft. Once the tape is in place, point the laser on the tachometer directly at the tape while the system is powered and rotating the shaft.

6. After testing has been completed, slowly decrease the speed of rotation down to the #5 mark on the dial and then turn the speed drive/s off. It is also recommended to turn off the internal power strip switch.

7. Unplug the simulator from the wall and disconnect the load/s.