Low Speed Alternator Design

Senior Project

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Abstract

The following report builds upon Erin Carrillo's equations used in his senior project to retrofit a cars alternator into a low speed generator[2]. Through the use of his results the alternator will be taken apart and turned into a low speed generator by changing the turns ratio in the stator. Once done the generator will be tested to determine the operational power output for multiple.

The second part of this project consists of creating a "do it yourself" video that will allow others to replicate this design. The video will use laments terms and no power tools; that way anyone without advanced knowledge or access to such tools will be able to implement this design. The goal of this video is to simultaneously help anyone who wants to build on these tests in the future and allow citizens of developing nations instructions on how to produce their own electricity.

I.0 Introduction

With the world's CO_2 levels steadilyincreasing,and the limited amount of fossil fuels there is no doubt that we need to look into renewable sources for energy production. Fossil fuels might be easier to use and cheaper to deal with but that is only because the time and research has already been done to put the system in place. The only thing fossil fuels have going for them is their high energy density which makes them very transportable and their domination of the market. These benefits are greatly outweighed by the negative aspects they have. For instance, fossil fuels released 8749 million metric tons of carbon into the atmosphere in 2008[1], and our energy consumption has only increase in the last 5 years. Not only do we create copious amounts of carbon gas with fossil fuels, but the dependence we have obtained will cause a worldwide panic when we run out unless something is done now. Luckily people have started to research renewable energies (which range from nuclear fusion to using the kinetic energy from streams) in hopes that they can sustain our energy demands. Among the most prominent renewable energy sources are nuclear fission, and using energy from the wind, sun, and water[3]. Since many people do not like the idea of having a power plant using radioactive material near their homes nuclear fission has lost much support since it started. Now we mostly view photovoltaic cells, hydropower, and wind turbines as the future of renewable energy.

Photovoltaic, or PV, cells use the energy in the sun to stimulate current flow through semiconductors in order to create energy. PV cells have had some major advances in the last decade and can now be purchased for under $1/Watt. This means that they are very affordable and could be put to use by a large portion of the population. The major problem with these devices is that they cannot produce energy if there are no solar rays, thus they can only be effectively used during the day time on sunny days. The cells can be coupled with batteries in order to keep energy available even when there is

no sun light, but the cost of batteries and the charging units greatly increases the cost of the system and thus solar cells cannot be effectively used by much of the world.

Both wind and hydroelectric power use the same principle to produce energy. They take the kinetic energy available in either running water or the wind and turn it into electric energy. This is done by spinning a turbine that is connected to a generator. As the turbine spins the generator turns and it creates useable energy. As with solar energy, wind turbines can only be used a portion of the time. That is when the wind is blowing. However, hydroelectric power can be used as long as there is a current in a stream. The main problem with these two forms of energy is the cost is takes to convert the kinetic energy into electric energy. Most low speed generators cost too much money to be used by much of the world, and thus this form of energy isn’t readily available.

2.0 Background

Low speed generators are in use all over the world today. From large hydro projects to wind turbines, they are used to create energy from slow moving objects. The problem with this technology is the cost for the retail consumer. Most low speed generators cost over $100. While this might not be the biggest problem for someone in a first world country, how is someone in a developing nation supposed to buy the generator? Most likely they would not be able to and thus they could not attain the natural energy available in streams or wind. If however, there was an affordable option they would be able to have a constant flow of energy available just by putting a turbine in a nearby stream. This project is going to do exactly that. The low speed alternator design will take an alternator, and through a few tweaks of the generator, will be usable for low speed applications.

2.1 Key Alternator Components

The main components of an alternator are the rotor, the stator, and the rectifying circuit. In order to finish this project one must be familiar with all three components. First, the stator, as shown in figure 2-1. The stator is located inside the housing of the alternator and stays stationary (hence the name). The one that is being worked with consists of 3 sets of 6 loops per wire.

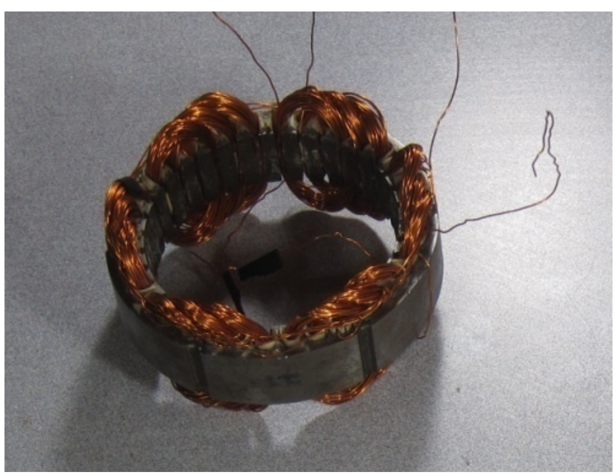

Figure 2-1:The stator

The rotor, as shown in figure 2-2, is also located inside the alternator housing and it spins inside the stator (as the name suggests). The rotor is composed of 6 magnets which induce an electromagnetic field inside the stator windings when the rotor spins.

Figure 2-2:The rotor

The rectifying circuit is used to turn the generated AC voltage into a steady DC voltage which is important because that is the form of energy storage batteries use. A rectifying circuit is shown in figure 2-3 below.

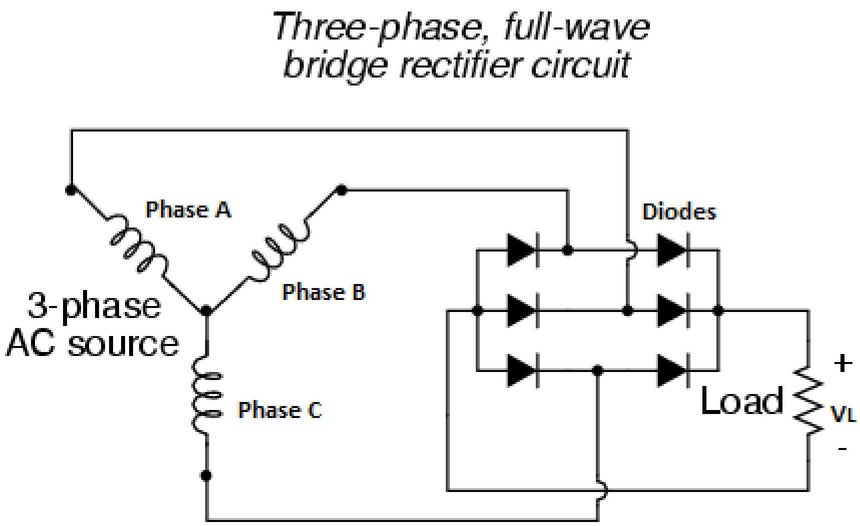

Figure 2-3:Circuit diagram for a rectifier[6]

2.2 How it Works

Generators work by using rotational energy to spin a magnet across a loop of wire, or vice versa. This produces an Electromagnetic Field in the wire that is proportional to both the number of loops (n) and change in magnetic flux (dΦ/dt).

$$EMF = n * \frac{d\Phi}{dt} \quad (2.1)$$

From equation 2.1 it is easy to see that if there was already a generator either changing the speed it rotats at (dΦ/dt) or the number of loops (n) would change the EMF. Now if there was a desired speed then adding loops of wire would cancel out the change in the EMF that came from changing the operational speed of the motor. In this project that is exactly what will happen. The original stator windings will be taken out and replaced with more wires composed of a thinner gauge. This will allow for the alternator to run at a lower speed and be used for energy generation in developing nations.

2.3 The Big Picture

While working on this project videos will be taken at each step, allowing for a Do-it-Yourself video to be made and put on a public domain, such as YouTube. Throughout the project only easily accessible tools will be used so that the process can be copied by anyone who has access to an alternator and some wire.

The newly created low speed generator will also be used on Dr. Taufik's DC house project. The DC House is a project that aims to prove the usefulness of DC power storage in developing nations using only renewable energy. This will also allow for future students to work with the generator and report any problems they encountered and how they fixed the problems, thus providing a variety of tests that might be encountered by others trying to simulate this experiment.

3.0 Requirements

There are 2 major goals of this project. The first is to build a low speed generator using a Toyota alternator, and the second is to make a video of the process that way others can replicate the results. In order to turn the alternator into a low speed generator all of the original alternator specifications will need to be measured. This was already done in Ervin Carrillo's senior project and can be located in the Bibliography section of this report. Once the alternator' physical parameters are measured the number of turns required to produce the desired voltage can be calculated and the building phase of the project can begin.

3.1 Low Speed Generator

The reason a Toyota alternator was chosen is that there are an abundance of these cars across the globe[2]and thus would make the most sense to use for this project. In order to turn the alternator into a low speed generator it will first have to be taken apart to remove the stator. Once the stator is taken out the turns ratio will be changed and the alternator will act as a low speed generator. After the building phase of this project is complete the generator will be tested in the Cal Poly-San Luis Obispo Power Electronics Lab (Engineering East 20- room 104). Here the generator will run through a load test at multiple operational speeds in order to see the maximum power output for a variety of speeds. An open and short circuit test will then be run at the desired speed of 300rpm. With this information the operational parameters of the generator can be found. The power output goal of the generator is 60 watts at 300 rpm.

3.2 Do-It-Yourself Video

The second major part of this project consists of making a video that will explain how to replicate the results in this project. This video will be available on a public domain in hopes thatanyone with access to the internet will have the capability to change an alternator into a low speed generator.

The video will need to be made entirely in laments terms that way people with any form of background knowledge will be able to recreate the results, as well as use only very common tools. Since it cannot be assumed that everyone has access to power tools, the video must be made completely without these tools. The final portion of the video will explain how to set up the alternator for low speed generation and well be available on a public domain.

4.0 Design and Construction

Most alternators are synchronous generators. A synchronous generator creates an EMF through changing the magnetic flux around a coil of multiple wires. Equation 2.1 explains that the EMF produced is proportional to the number of windings in the coil, and the change in magnetic flux[Gönen 320]. This means that increasing the flux density of the magnet, increasing the speed in which the flux rotates, or increasing the number of windings in each coil will produce a higher EMF. In this design the number of windings will be increased and the speed will be decreased. This change will enable the alternator to perform at lower speeds while still delivering a useable voltage.

4.1 Design

As with any construction project, the first step is to design what will be made. In this case the first step of designing the low speed generator will be to measure the characteristics of the alternator and use these characteristics to find the optimal turns ratio for the generator. Since Ervin already did this using the generated voltage equation his paper can be referenced to find that using 22ga wire the motor need to be run at 251 rpm with a field current of 0.792A to produce the desired 12V[2]. His original goal was an operational speed of 200rpm, but this could not be achieved since only 300 or the desired 376 windings could fit in one phase of the stator.A table of Ervin's findings is shown in Table 3-1 below.

ρ_p	Θ_m	n_s (rpm)	k_w	N_{ph}	Poles	Air Gap	Rotor core length	Rotor radius
30˚	20˚	1800	0.866	42	12	1.25mm	25.8mm	43.5mm

Table 3-1:Physical parameters of this Toyota alternator

4.2 Construction

Using these results we can now take apart the alternator and re-wind the stator. Before this can be done the alternator must be taken apart. The first step will be to unscrew the wires connecting the stator to the rectifier as shown in figure 3-1 below.

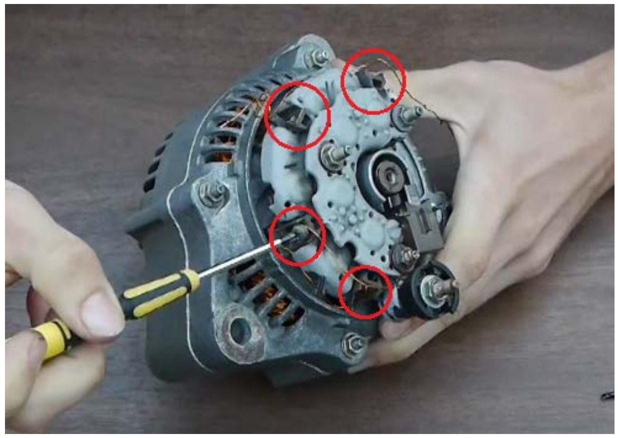
Figure 3-1:4 screws connecting to phases to the rectifier

Once these screws are removed the nuts holding the rectifier to the chassis and the nuts holding the chassis together will need to be removed. This step is shown in figure 3-2 below.

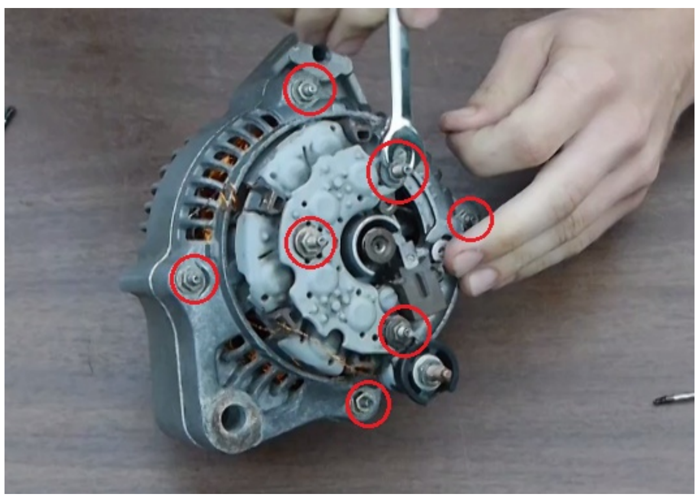
Figure 3-2: Location of nuts to unscrew

Once these 7 screws are removed it is time to disassemble the alternator. The rectifier will slide right off the 3 bolts connecting it to the chassis. Removing the two sides of the chassis can prove to be very difficult to do by hand and thus a screwdriver is needed to pry it apart. When prying the alternator apart it is helpful to do it from multiple angles so the seam is completely broken. Figure 3-3 shows where to pry the alternator apart using a flat head screw driver.

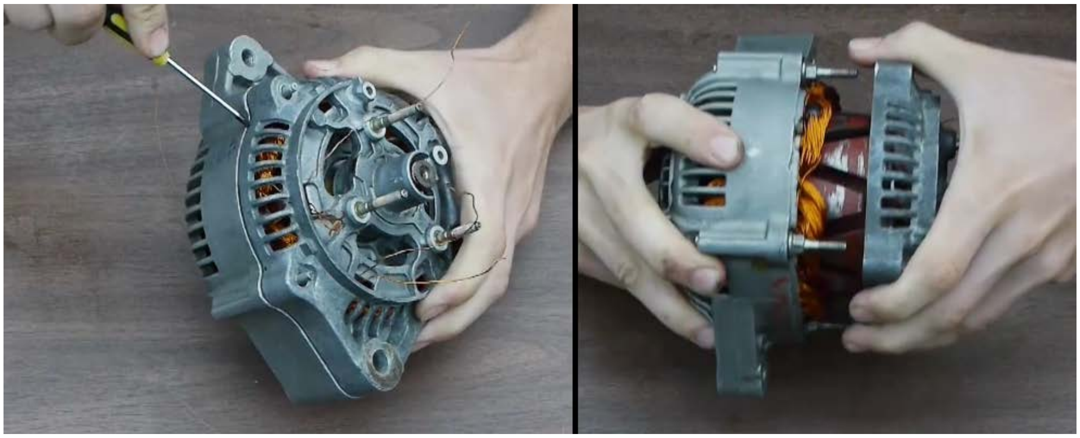
Figure 3-3:Separation of the chassis

Once the two side of the chassis are disconnected, the screws holding the stator in place must be loosened. At this point they should not be taken out all the way since they will be used to help remove the stator by creating a slightly raised surface that can be hit with a screw driver. It is best to only unscrew them for roughly 1cm so the surface will be raised, but the threads of the bolt will still be useable when it is time to put the alternator back together. Figure 3-4 shows a reference for how far to unscrew the bolts.


Figure 3-4:Bolt location for stator removal

Once the bolts are unscrewed this half of the chassis will be flipped over so the unscrewed bolts are supporting the alternator. Using a small screwdriver and something to hit it with, place the screwdriver inside the slits and pound on the stator. Since there is not much room for the stator to

move it will need to be hit from multiple angles to be successfully removed.Be careful to only make contact with the stator and not to damage the insulative slits between the wire and the stator. This step is shown in figure 3-5 below.

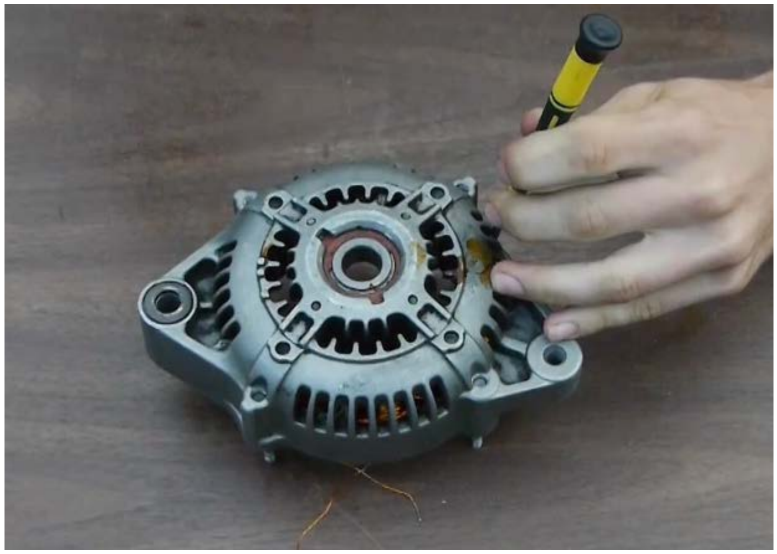

Figure 3-5:Removing the stator

Once the stator is taken out it is time to remove the existing windings. In order to do this, use a hammer to break the glue holding the windings together and wire cutters to cut the wires. Make sure to cut both ends of the loop that way they can be removed by pulling on either end. Giving the stator and windings an acetone bath can be very helpful since it will eat away the glue, but it is not absolutely necessary.

Now that the old windings are removed from the stator the winding process can begin. This stage is the most important so make sure to pay very close attention to the winding orientation. Since the electric angle between phases relates directly to the physical location of the windings it is important to note the winding direction of each phase. In order to create a 120˚ phase difference between each waveform wind phases one and three in the same direction and wind phase two in the opposite direction. Figure 3-6 shows the re-wound stator and the wires corresponding to each phase.

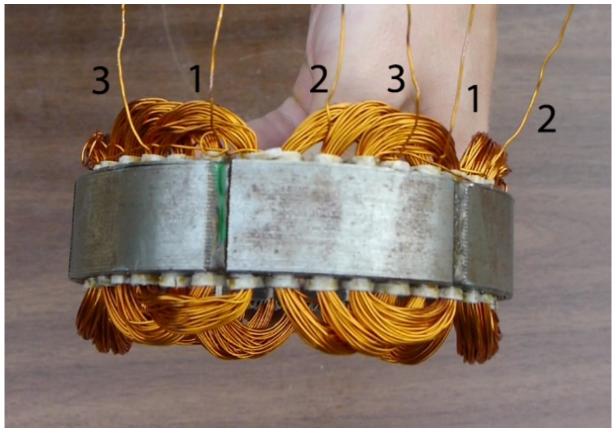

Figure 3-6: Wires of each phase

When winding the stator it is important to know how many loops there are in each phase. In this specific case, we will wind the stator with as many loops as possible since Ervin's findings explain that there are spatial limitations in the stator. When doing this roughly 37 loops per winding were obtained, and there are 6 windings per phase. This equates to a low speed generator with 224 loops per phase.

Now that the stator is re-wound and we know how many windings are in each phase, there is only one more step before everything can be put back together. The outside of the windings must be wrapped in electrical tape. This is done to increase in insulation layer between the windings and the stator. Without this tape the windings will grind against the chassis when it is put back into place and there will be a chassis – phase short. Figure 3-7 shows the outside of the windings being wrapped in electrical tape.


Figure 3-7: Wrapping the wire in electrical tape

Now it is time to put the alternator back together. Although this is almost the exact same process as taking it apart in reverse there are nuances that must be explained the first is to attach the rectifier first. Once the rectifier is back in place, reconnect the chassis. With the rectifier now on the chassis the wires can be lined up to the rectifier and the stator can be oriented to match the holes show by red circles in figure 3-8.

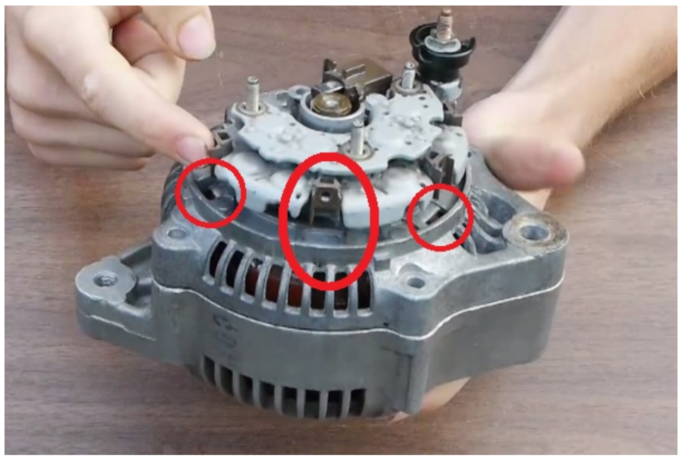

Figure 3-8: Location of the holes for wires

For the generator to be effective it would be optimal to obtain as high of a current as possible. Therefore the alternator will be connected in Wye configuration. To do this one end of phases 1, 2, and 3 must be connected to a single node while the other end of the phases are connected to their corresponding locations on the rectifier. Figure 3-8 also shows the location of the neutral node denoted by the larger red oval in the center of the picture. Once the wires are connected to their corresponding connecting plates, the building process is complete.

5.0 Testing

Before any testing take place, it is a good idea to become familiar with the high level system setup. Figure 5-1 shows the box diagram for the testing of the synchronous generator. It is apparent from the figure that the left side of the diagram is needed to spin the generator, while the right side of the diagram is the system that will be under test.

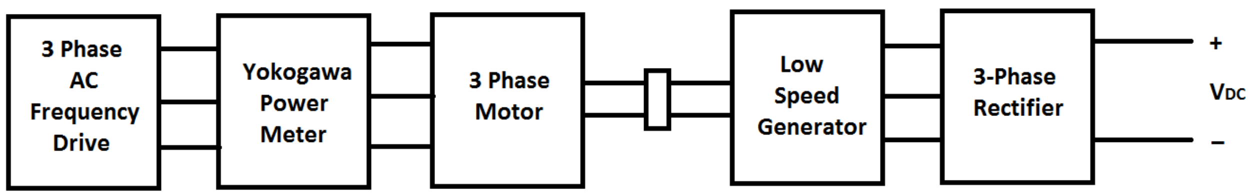

Figure 5-1: Black Box Diagram for the synchronous generator test setup

5.1 Continuity Check

The first step in testing the alternator is to make sure that all of the connections are actually connected, and that nothing is shorted to the chassis. In order to do this, use a multimeter and check the resistance between each phase and the neutral point (all of which should be less than 5Ω) and the resistance between each phase and the chassis (all of which should be greater than 1KΩ). Please note the phase resistances since they will be used to calculate the rating of the generator. If either of these two criteria are not met the generator is not connected correctly and the construction process needs to be completed before any testing takes place. If all of these criteria are met, the generator is ready to be tested.

5.2 Waveform Verification

Before connecting the generator to a load it is a good idea to view the waveforms on an oscilloscope. This will allow for verification that all the waveforms have the correct phase angle between them and that they differ a minimal amount in voltage amplitude. The first step to this setup will be supplying power to the variable frequency AC drive. Figure 5-2 shows the bench setup to power the AC

drive. Once all of thenodes are connected as in figure 5-2 flip the switch circled in red. Next measure the Variacvoltage and adjust it until it reaches 208V and flip the switch circled in blue`. Now connect the Red, Black, Blue, and green terminals of the AC drive the Red, Black, Blue, and green terminals of the motor as shown in figure 5-3. The red, black, and blue terminals represent phases A, B, and C while the green terminal represents ground. Once the voltage output is set,connect the motor to the generator and set the AC Drive to operate at 10Hz in the forward direction.

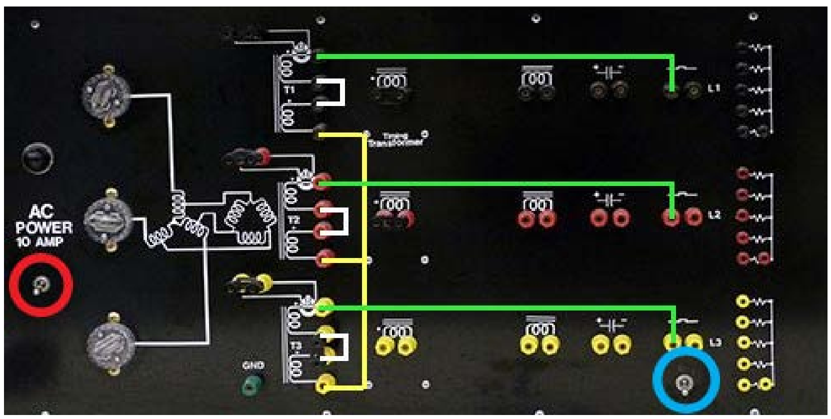

Figure 5-2: Test Bench Setup for AC Frequency Drive

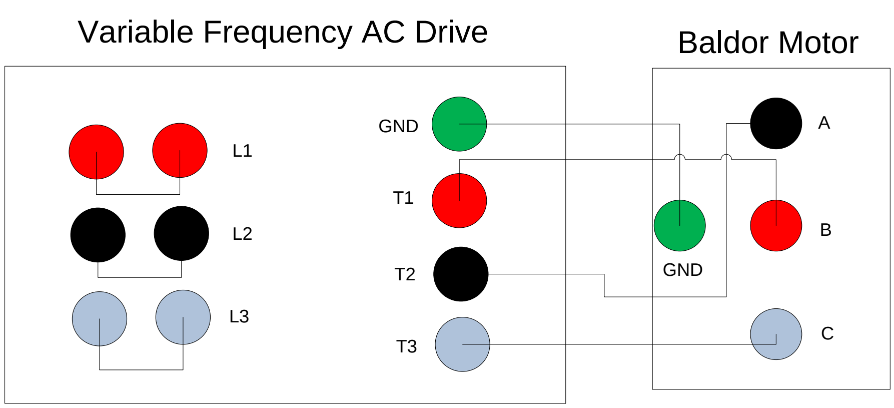

Figure 5-3: 3 Phase Motor Setup

The generator needs a field current in order to create a magnetic field. The field current will be supplied through a DC power supply and a 100Ω, 3Arheostat. Set the power supply to supply 1A max current at 12V, and connect the DC outputs to the rheostat. Next connect the output of the rheostat to an ammeter and make sure that it is supplying 0.792A to the generator’s field windings. Figure 5-4shows where to supply the field current on the generator.

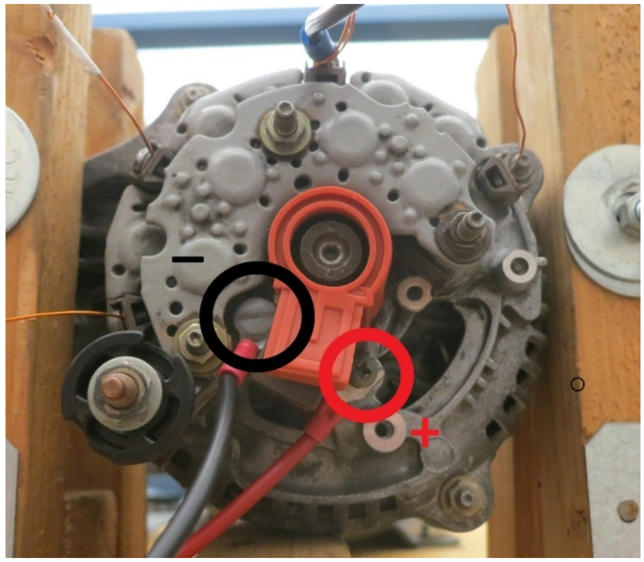

Figure 5-4: Positive and Negative Terminals of Field Windings

Now that everything is connected and the generator is running, connect phases A, B, and C to the oscilloscope. Once connected check to see that the waveforms look similar to those shown in figure 5-5. It is important to note that if one of the waveforms appear to be 180˚ out of phase, switch the terminals of the oscilloscope and the waveforms phase should be correct. Once the phase angle of the waveforms are correct take a screen capture with the V_{PP} of at least one phase as this will be used to calculate the magnetic flux of the rotor at a field current of 0.792A. Finally, connect all the ground terminals of the oscilloscope to the neutral point of the rectifier and the 3 remaining wires to their nodes on the rectifier.

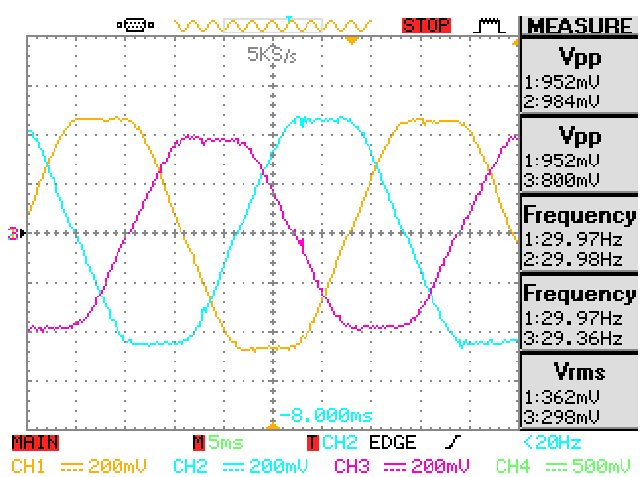

Figure 5-5: Generated 3 Phase Voltage Waveforms

5.3 Open and Short Circuit Test

Normally the open and short circuit tests are used to find the internal parameters of a motor or generator at rated voltage[5]. However in this project the goal is to maximize output power with as small a field current as possible, hopefully one that could be produced by a normal battery. This means that the generator rating will be calculated using the smallest field current that produces a useable voltage. To find these values, the machine will be set to the desired operational speed and the field current will bevaried from 0A to 1A in 0.05A steps. This will produce data at a high enough resolution between a current that is both too low to use, and too high to supply.

The open circuit test is performed by the setting the generator to the desired operational speed and adjusting the field current. In this case the motor will spin the generator at 300rpm and the field current will vary between 0A and 1A in 0.05A steps. At each step the voltage will be measured by connecting the output of the rectifier directly to a multimeter and measuring the open circuit voltage. The open circuit test bench setup is the same as the waveform verification test except the measurements will now be taken from the alternator output (shown in figure 5-6). The data collected from the test is shown in the Results section of this report.

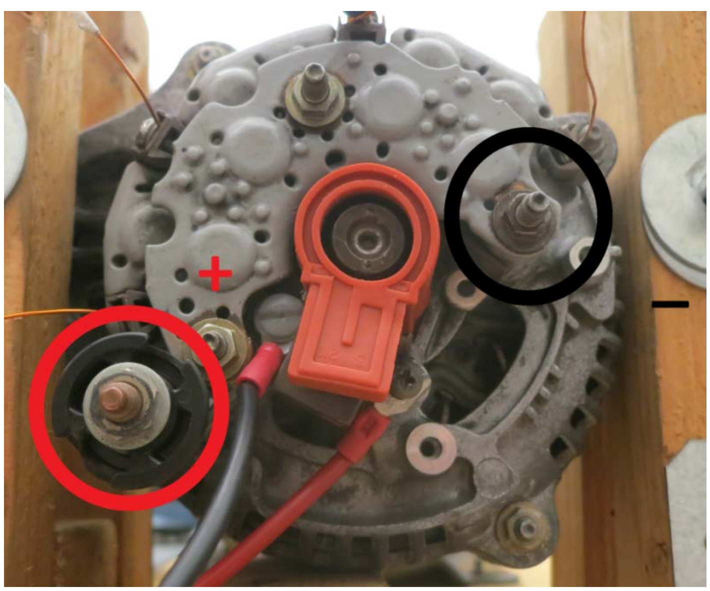

Figure 5-6: Output Terminals of the Rectifier

Likewise, the short circuit test is performed with the same bench setup and the same variation of the field current. The only difference in this step is that the output will be shorted through an ammeter to calculate the short circuit voltage. The short circuit data is shown in the Results section of this report.

5.4 Variable Load Test

The variable load test will find both the internal resistance of the system and the maximum power that the generator can supply at a field current of 0.792A. To perform this test the field current will be set to 0.792A, the generator will spin at 300rpm and theload resistance will be varied from 0Ω to .5MΩ (although most of the data points should be taken between 0Ω and 10Ω). Before running the test, disconnect the generator from the motor and measure the input power of the motor at 300rpm with no load attached. Subtracting this power from the loaded input power of the motor will give the input power of the generator and from this the efficiency and rating of the machine can be calculated.

Once the no-load input power is measured, connect the motor to the generator and the output of the generator to the variable resistor. When performing this step it is important to use a resistor that has a current rating high enough for this application. At each resistance measurement, measure the resistance of the load when disconnected from the generator, the voltage across the load, and the power supplied from the variable frequency drive. Using these values the current, power, and efficiency of the load can be calculated. The bench setup for this step is the same as the of the open or short circuit test (shown in figure 5-6) except there will now be a variable resistance load across the output of the generator and the 3 phase input power will be measured. Figure 5-7 shows the new setup for the input of the 3 phase motor.

Since the output of the rectifier is a dc voltage, the maximum power transfer will happen when the load and source impedances are matched. This means that the resistance that gives the highest output power will also represent the internal resistance of the generator and rectifier. The internal

impedance of the system will also change with the rotor speed, so this test will need to be implemented when the internal impedance is desired at any rotational speed. Perform this test for 100rpm, 200rpm, 300rpm, 400rpm, and 500 rpm. Once again, the data for this test is shown in the Results section of this report.

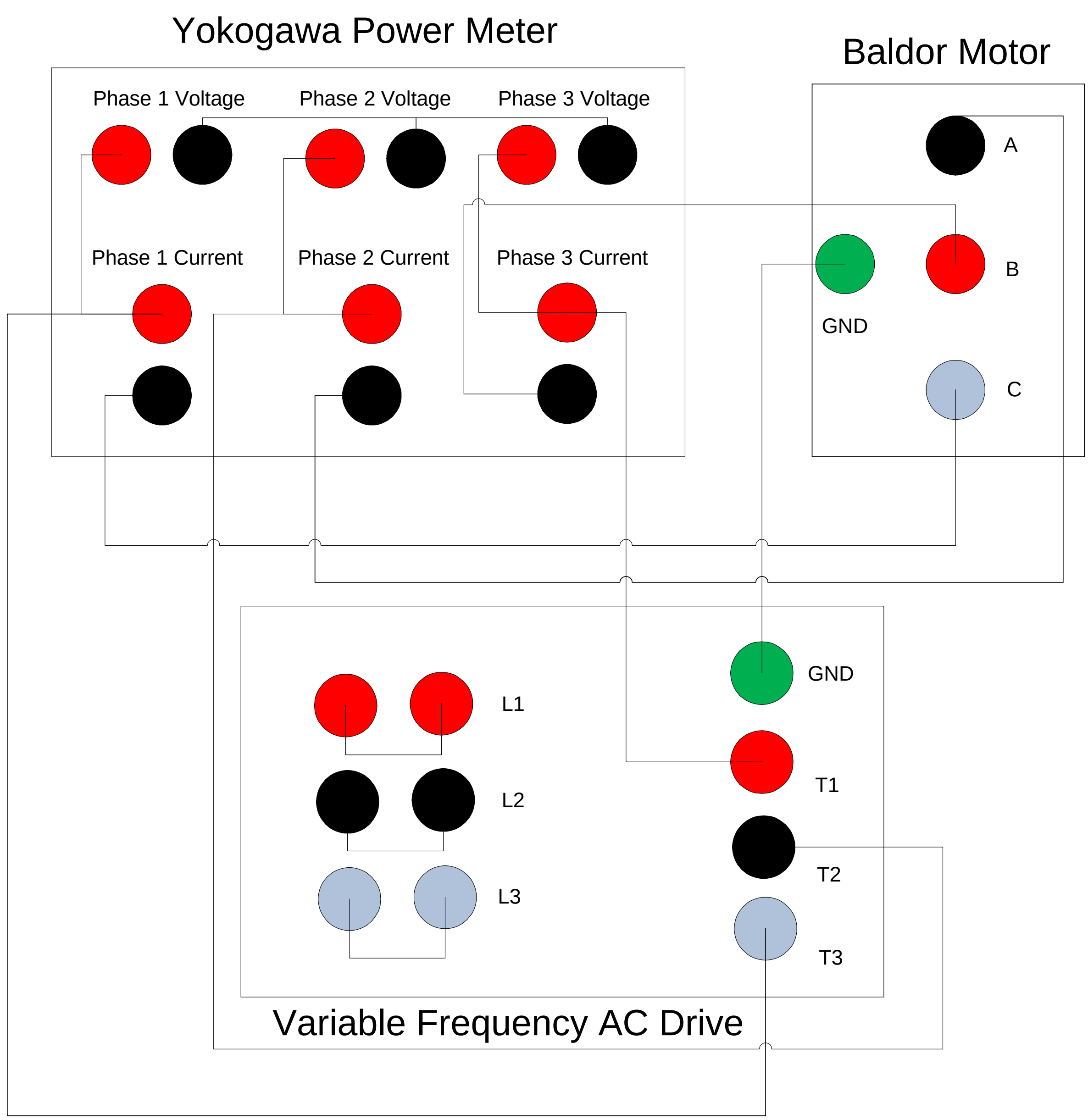

Figure 5-7: Motor Setup for Variable Load Test

6.0 Results

6.1 Waveform Verification

When combining the results from Ervin's report, the construction phase, and the waveform verification it is possible to calculate the magnetic flux intensity of the rotor for a given field current. The equation for EMF generation from a rotating magnetic field is given in eq. 6.1below, will be modified to calculate the magnetic flux intensity of the rotor.

$$EMF = n\omega\Phi K_{\omega} \quad (6.1)$$

From Ervin's findings the winding factor (K_{ω}) is known to be 0.866, and the number of turns per phase was measured to be 224. Since the test was run at 300rpm, the rotational frequency can be calculated from equation 6.2.

$$\omega = 2\pi f = 2\pi \frac{Rotational \quad Speed}{60} = 2\pi \frac{300}{60} = 31.41\ rad/s \quad (6.2)$$

From the oscilloscope screen capture the EMF produced can be found to be 0.984V_{PP}. Now that all of the variables have been found, equation 6.1 can be rearranged to give the magnetic flux intensity of the rotor for a field current of 0.792A[4].

$$EMF = n\omega\Phi K_{\omega}$$

$$\Phi = \frac{EMF}{\omega n K_{\omega}} = \frac{0.984}{31.41 * 224 * 0.866} = 161.5\mu Wb$$

6.2 Open and Short Circuit Test

Performing the open and short circuit test on a synchronous generator can find the per-phase synchronous reactance, full load current and reactive power supplied by the generator. However, to perform these calculations the ratings of the system are needed, and since this generator was built for this project the ratings are not known. Since the ratings are not known none of these parameters can be found, and thus the tests cannot be used as they normally are.

Although the parameters cannot be calculated with the open and short circuit test, that does not mean that the tests provide no useful information. Since the generators desired operational speed is 300rpm and a field current of 0.792A was only chosen because of Ervin's calculations the open and short circuit tests will provide very useful information of the voltage and current relationship at different field currents. This information will come in handy later when attacking the topic of what the optimal field current is for implementing this design in rural areas. Table 6-1 shows the information gathered from performing the open and short circuit tests of this generator.

Open Circuit (300rpm)		SHORT Circuit (300rpm)	
Field Current (A)	O.C. Voltage (V)	Field Current (A)	S.C. Current (A)
0	0.32	0	0.01
0.06	0.631	0.05	0.01
0.1	0.904	0.1	0.01
0.15	1.41	0.156	0.11
0.2	1.685	0.205	0.2
0.25	2.157	0.255	0.31
0.3	2.6	0.305	0.49
0.35	3.17	0.367	0.62
0.4	3.54	0.401	0.72
0.45	4.03	0.45	0.89
0.5	4.5	0.5	1.01
0.55	5	0.561	1.18
0.6	5.47	0.605	1.29
0.65	5.94	0.651	1.4
0.7	6.3	0.72	1.57
0.75	6.71	0.777	1.72
0.8	7.03	0.8	1.77
0.85	7.46	0.84	1.87
0.9	7.9	0.902	2.03
0.95	8.32	0.95	2.14
1	8.74	1	2.25

Table 6-1: Open and Short Circuit Data

Figure 6-1 shows the data from table 6-1 in graphical form. It is worthy to note that the open circuit voltage does not reach the saturation point. This is due to the fact that the rotor magnets are designed for use in automotive applications where the voltage should saturate at 14.4V with less windings per phase than what the stator currently has. This means that voltage saturation should occur at a much higher potential than what the generator can currently reach.

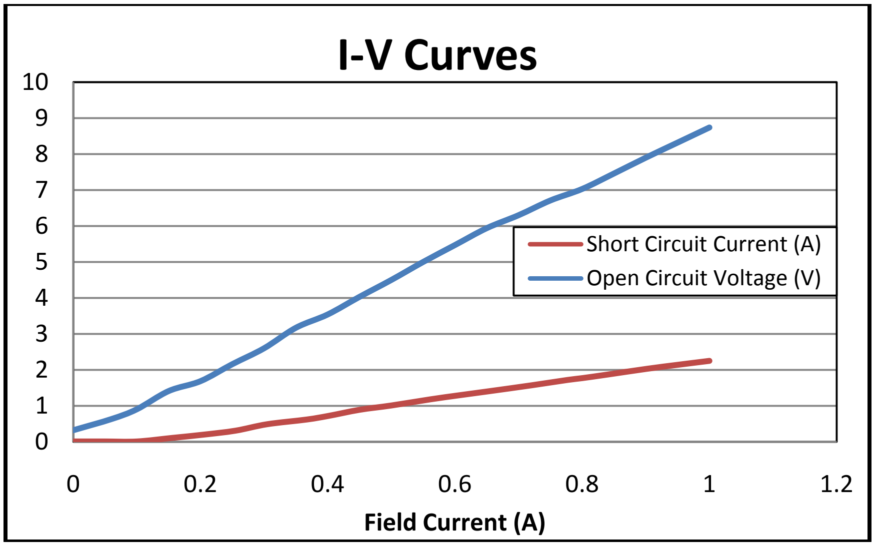

Figure 6-1: I-V Curves for the Open and Short Circuit Test

6.3 Variable Load Test

The variable load test will provide the most information about the constructed synchronous generator. With the data from this test, we will calculate the following values: Internal resistance of the generator, maximum output power, the efficiency of the generator, the generators ratings at a field current of 0.792A, and show how the generated power changed with operational speed. Figure 6-2 shows the graphical form of the data from the variable load test, and the table of this data is given in AppendixA.

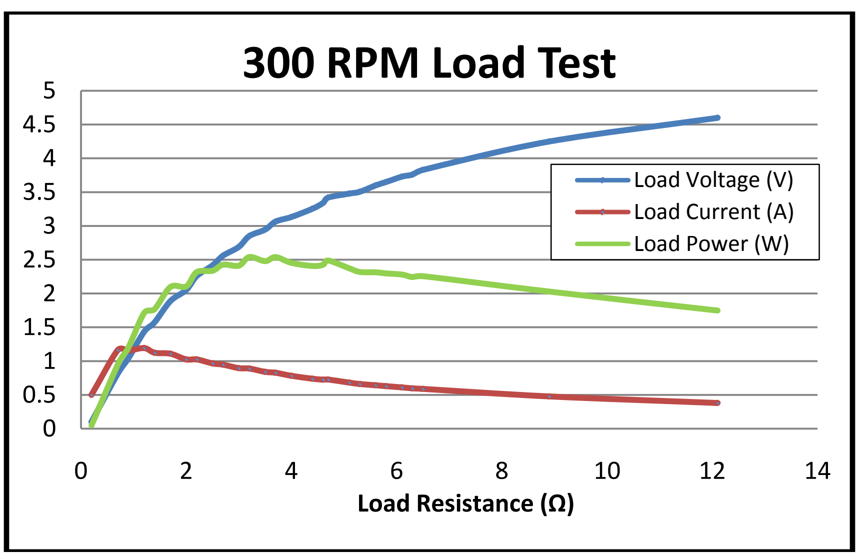

Figure 6-2: Output Voltage, Current, and Power Vs. Load Resistance

6.3.1 Internal Resistance and Maximum Output Power

From Figure 6-2 it is apparent that the maximum power generated happens at a load resistance of 3.7Ω and has a magnitude of 2.539W. Since the output of the system is a DC voltage the thevenin maximum power transfer theory can be applied to this system. It is known that the maximum power transfer occurs when the load resistance is equal to the magnitude of the source impedance. From this we can say that the internal resistance of the generator is 3.7Ω. This resistance includes all components of the system, not just the stator windings, but the rectifier circuitry as well.

6.3.2 Generator Efficiency

When running the variable load test the no load input power of the motor and loaded input power to the motor was measured.Using these two measurements we can find the input power to the generator by subtracting the no-load input power from the loaded input power. The output power of the generator can also be found by measuring the voltage across the load and using equation 6.3. Figure 6-3 shows how the efficiency of the generator changes as the load resistance varies, and the tabular data of this graph is shown in Appendix A.

$$P_{Load} = \frac{{V_{Load}}^2}{R_{Load}} \quad (6.3)$$

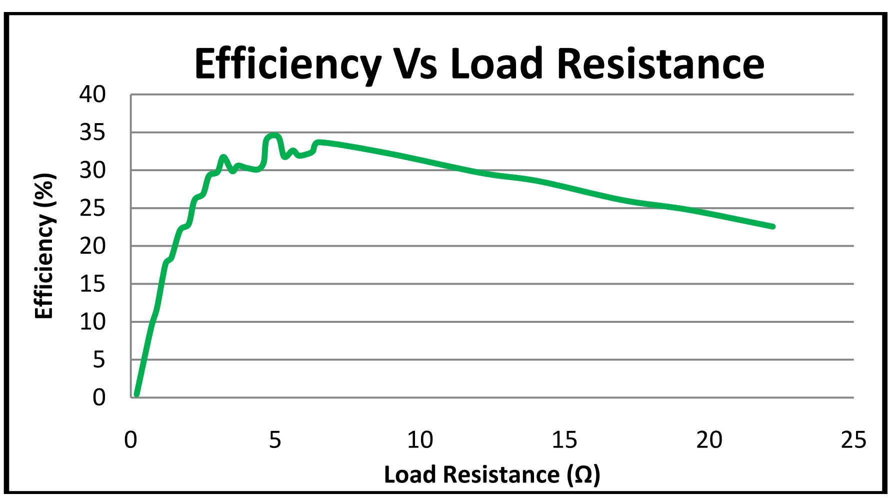

Figure 6-3: Efficiency Vs. Load Resistance

6.3.3 Generator Ratings

In order to define the generator ratings the first thing that must be done is pick a point of data to use. For this application the data point of that will be chosen corresponds to the highest efficiency and is shown below. The stator phase resistances from the continuity check will also be needed to find the generator ratings

R_L	V_L	$P_{In, Motor}$	$P_{No Load, Motor}$	$P_{In, Generator}$	I_L	P_L	Efficiency
5.1Ω	3.479V	31.6W	24.7W	6.9W	0.682A	2.373W	34.395

$$R_A = 1.513\Omega$$
$$R_B = 1.513\,\Omega$$
$$R_C = 1.237\,\Omega$$
$$R_{Total} = R_{Stator} = R_A + R_B + R_C = 4.263\,\Omega$$

Before finding the ratings, we will now look into the generator losses at this point.

$$P_{Out} = P_{In} - P_{Losses}$$
$$P_{In} = 6.9W$$
$$P_{Out} = 2.373W$$

$$P_{Stator} = {I_L}^2 * R_{Stator} = 0.682^2 * 4.263 = 1.983W$$

From this we know that there are 2.54W of other losses in the system for this load value. This is the sum of the air gap losses, eddy current losses, frictional losses, core losses and many other less significant losses.

Finding Machine Rating:

$$I_{Total} = \frac{VA_{Rated}}{V_{Rated}} = 0.682A$$

$$V_{Rated} = V_{O.C.} @ I_f = 0.792A$$

$$VA_{Rated} = V_{Rated} * I_{Total} = 6.65V * 0.682A = 4.535\text{VA}$$

Now it is known that this is a 3 Phase, 300rpm, 12 pole, 4.5VA, 6.65V Synchronous Generator.

6.3.4 Power at Different Operational Speeds

With the data from the variable load test performed at different speeds, a chart was created the produced a visual representation of how the power changed with respect to operational speed and load values. The chart is shown in figure 6-4 and behaves exactly as expected. The power output increases as the change in magnetic flux across the stator windings increase.

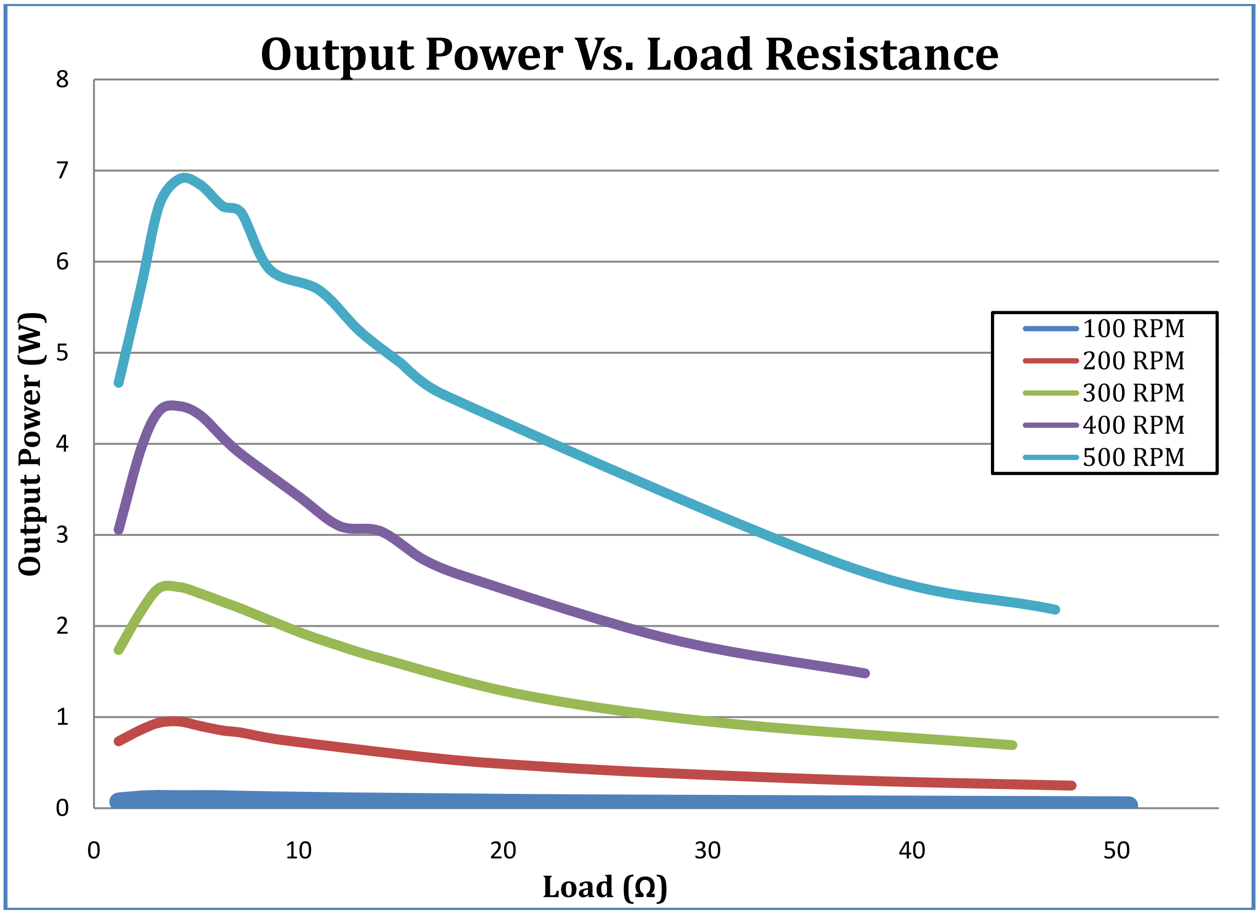

Figure 6-4: Output Power at Different Rotor Speeds

7.0 Conclusion

Since this project was mainly to test a product that has already been designed, all testing was performed for Ervin's designs. This means that with the exception of the open and short circuit tests all tests were performed at a field current of 0.792A. From these tests the generator ratings were found. Now we look into the feasibility of supplying 0.792A in a remote area. Since the resistance of the field winding is 2.87Ω Ohms Law states that a 2.27V battery would be needed to create this current. The easiest way to supply this would be with 2 AA batteries and have a voltage of 3V across the field. This would equate to a 1.04A field current. This field current would produce a field power loss of $P_f = I_F^2 * R_f$ = 3.1W. Since the capacity of Duracell rechargeable AA batteries ranges from 1700mAh to 2450mAhthe longest the generator could run on the batteries is 2.35 hours and that the input field losses would be 1W less than the maximum power generated with a 1A field current (measured to be 4.160W)[7]. Considering that this generator costs $54 to build and it produces 1W at maximum efficiency it is not recommended to choose this method over other renewable energy sources.

Using the same process above the power output of a single AA battery was found. To do this another measurement at a field current of 0.523A had to be taken. Since it was already shown that maximum power transfer happened at 3.7Ω, the field current, and load resistance were changed and the output power of the generator was measured at that to be 0.851W. With this field current P_f = 0.7838W, meaning that this setup only produced 67.2mW.

Overall the design and testing of this synchronous generator proved that the modification will not produce a low speed generator that is feasible for use in the CD House Project. The generator could only produce 1W, and it could only do so for 2.35 hours (not taking into account voltage drop as the battery loses charge). Considering that solar cells are starting to less than $1/W it is very inadvisable to ever implement this system. Although these tests did not produce the desired results, they did prove

that the idea works and I would recommend another to run these tests with an alternator that uses a permanent magnet. Since they can not only have more magnetic flux but they also eliminate the need for field windings a permanent magnet would increase the output power and efficiency of the machine.

Bibliography

[1] *Boden, T.A., G. Marland, and R.J. Andres. 2010. Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2010*

[2] E. Carrillo, "Equating a Car Alternator with the Generated Voltage Equation," Cal Poly State University, San Luis Obispo, Ca, 2012.

[3] "Global Fossil-Fuel CO2 Emissions." *Global Fossil-Fuel CO2 Emissions*.Listverse, 1 May 2001. Web. 18 Mar. 2013.

http://listverse.com/2009/05/01/top-10-renewable-energy-sources/

[4] Gönen, Turan. *Electrical machines*. Carmichael, Calif: Power International Press, 1998. Print.

[5] Slemon, Gordon R., and A Straughen. *Electric machines*. Reading, Mass: Addison-Wesley Pub. Co, 1980. Print.

[6] Parekh, Alan. "3 Phase Rectifier Basics - Hacked Gadgets – DIY Tech Blog." 3 Phase Rectifier Basics - Hacked Gadgets – DIY Tech Blog. 2 Oct. 2010. 05 June 2013 <http://hackedgadgets.com/2010/10/05/3-phase-rectifier-basics/>.

[7] "Product Data Sheets." Duracell.Duracell. 04 June 2013 <http://www.duracell.com/en-US/Global-Technical-Content-Library/Product-Data-Sheets.jspx>.

Appendix A

100RPM		200RPM		300RPM		400RPM		500RPM	
R_L (Ω)	P_L (W)	R_L (Ω)	P_L (W)	R_L (Ω)	P_L (W)	R_L (Ω)	P_L (W)	R_L (Ω)	P_L (W)
1.2	0.070	1.2	0.735	1.2	1.737	1.2	3.056	1.2	4.669
2.3	0.090	2.3	0.861	2.3	2.162	2.3	3.944	2.3	5.720
3.2	0.098	3.2	0.939	3.2	2.419	3.2	4.364	3.2	6.627
4.2	0.095	4.2	0.950	4.2	2.426	4.2	4.413	4.2	6.909
5.2	0.096	5.2	0.901	5.2	2.357	5.2	4.313	5.2	6.843
6.3	0.095	6.3	0.852	6.3	2.264	6.3	4.069	6.3	6.608
7.2	0.089	7.2	0.829	7.2	2.190	7.2	3.885	7.2	6.536
11	0.076	9.2	0.748	10.1	1.927	10	3.426	8.6	5.911
14.8	0.067	16.8	0.545	12	1.783	12	3.098	11	5.688
24.8	0.049	22	0.456	13.9	1.651	14	3.041	13	5.236
50.6	0.028	27.8	0.387	21	1.243	16.1	2.730	15	4.885
60.9	0.024	37.6	0.301	30.7	0.937	18	2.554	17.1	4.539
189.5	0.009	47.8	0.247	44.9	0.692	28.1	1.860	36.8	2.658
1.48E+03	0.001	5.06E+03	0.003	245.9	0.147	37.7	1.480	47	2.179
9.32E+05	0.000	9.83E+05	0.000	1.10E+06	0.000	9.57E+05	0.000	1.04E+06	0.000

Table A-1: Multiple Speed, Variable Load Test

Load test								
Speed (rpm)	**R_L (Ω)**	**V_L (V)**	**P_{In} (W)**	**$P_{No-Load}$ (W)**	**P_{In-Gen}(W)**	**I_L (A)**	**P_L**	**Efficiency**
300	0.2	0.1	36.2	24.7	11.5	0.500	0.050	0.435
300	0.7	0.815	35	24.7	10.3	1.164	0.949	9.213
300	0.9	1.039	34.9	24.7	10.2	1.154	1.199	11.759
300	1.2	1.433	34.4	24.7	9.7	1.194	1.711	17.642
300	1.4	1.574	34.3	24.7	9.6	1.124	1.770	18.434
300	1.7	1.888	34.2	24.7	9.5	1.111	2.097	22.071
300	2	2.052	33.9	24.7	9.2	1.026	2.105	22.884
300	2.2	2.258	33.6	24.7	8.9	1.026	2.318	26.040
300	2.5	2.417	33.4	24.7	8.7	0.967	2.337	26.859
300	2.7	2.56	33	24.7	8.3	0.948	2.427	29.244
300	3	2.69	32.8	24.7	8.1	0.897	2.412	29.778
300	3.2	2.851	32.7	24.7	8	0.891	2.540	31.751
300	3.5	2.946	33	24.7	8.3	0.842	2.480	29.876
300	3.7	3.065	33	24.7	8.3	0.828	2.539	30.590
300	4	3.133	32.8	24.7	8.1	0.783	2.454	30.295
300	4.4	3.255	32.7	24.7	8	0.740	2.408	30.100
300	4.6	3.34	32.5	24.7	7.8	0.726	2.425	31.091
300	4.7	3.42	32	24.7	7.3	0.728	2.489	34.090
300	5.1	3.479	31.6	24.7	6.9	0.682	2.373	34.395
300	5.3	3.506	32	24.7	7.3	0.662	2.319	31.771
300	5.6	3.6	31.8	24.7	7.1	0.643	2.314	32.596
300	5.8	3.651	31.9	24.7	7.2	0.629	2.298	31.920
300	6.1	3.73	31.8	24.7	7.1	0.611	2.281	32.124
300	6.3	3.76	31.6	24.7	6.9	0.597	2.244	32.523
300	6.5	3.83	31.4	24.7	6.7	0.589	2.257	33.683
300	8.9	4.25	31	24.7	6.3	0.478	2.029	32.214
300	12.1	4.6	30.6	24.7	5.9	0.380	1.749	29.640
300	14.1	4.79	30.4	24.7	5.7	0.340	1.627	28.548
300	17	4.98	30.3	24.7	5.6	0.293	1.459	26.051
300	19.3	5.08	30.1	24.7	5.4	0.263	1.337	24.761
300	22.2	5.2	30.1	24.7	5.4	0.234	1.218	22.556
300	24.4	5.28	30.1	24.7	5.4	0.216	1.143	21.158
300	29.5	5.38	29.9	24.7	5.2	0.182	0.981	18.869
300	34.4	5.48	29.9	24.7	5.2	0.159	0.873	16.788
300	44.5	5.63	29.83	24.7	5.13	0.127	0.712	13.885
300	63.3	5.77	29.5	24.7	4.8	0.091	0.526	10.957
300	96.8	5.9	29.5	24.7	4.8	0.061	0.360	7.492
300	116.9	5.95	29.5	24.7	4.8	0.051	0.303	6.309
300	219.2	6.07	29.2	24.7	4.5	0.028	0.168	3.735
300	311.6	6.11	29.3	24.7	4.6	0.020	0.120	2.605
300	718	6.22	29	24.7	4.3	0.009	0.054	1.253
300	2951	6.33	29	24.7	4.3	0.002	0.014	0.316
300	12636	6.44	29	24.7	4.3	0.001	0.003	0.076
300	131800	6.56	29.3	24.7	4.6	0.000	0.000	0.007
300	495000	6.65	29.1	24.7	4.4	0.000	0.000	0.002

Table A-2: Variable Load Test