Equating a Car Alternator with the Generated Voltage Equation

By

Ervin Carrillo

Senior Project

ELECTRICAL ENGINEERING DEPARTMENT

California Polytechnic State University

San Luis Obispo

2012

TABLE OF CONTENTS

LIST OF FIGURES AND TABLE

ACKNOWLEDGMENTS

This project would have not been possible without the help and support of various individuals. I would like to give special thanks to my advisor Dr. Taufik for all his advice and guidance. I would also like to thank the Electrical Engineering Department Faculty at Polytechnic State University, San Luis Obispo, who provided us with the knowledge and facilities to the fulfill this project. I would also like to acknowledge Yuri Carrillo, my senior project partner/sister, for all her help and contributing knowledge. Lastly, I would like to thank my father Crisanto Carrillo who helped us couple the car alternator to the dc motor coupling.

ABSTRACT

The following report presents the first key steps required in effectively retrofitting a car alternator into a low rpm generator for use in small-scale renewable energy sources. A car alternator is run through an open circuit test and taken apart in order to measure its physical dimensions. The data collected are then used to determine machine parameters required in the alternator's generated voltage equation. The appropriate number of stator windings for a given lowest rpm may then be determined using the equation. The alternator's stator is then rewound and remounted in the alternator to demonstrate whether the low rpm can be achieved. A Toyota alternator is retrofitted in this project which provides the step by step procedure on obtaining the alternator parameters to be laid out; hence, may serve as a guideline for anyone attempting to retrofit a car alternator for low speed rpm applications.

I. INTRODUCTION

There has been a growing interest in applying sustainable energy solutions to the needs of people living in developing countries. In remote areas, where there exists no electrical grid due to its great expense, small energy harvesting systems are desired. One example of such a system is a small scale hydro generation system. The main constrain faced by small scale hydro generation is the low rpm requirement of 200rpm – 600 rpm. Unfortunately, the generators that are designed to operate at these low rpm are relatively expensive. The price of these generators is usually no lower than 100 dollars. The proposed solution to this problem is to retrofit a car alternator into a low rpm generator in a cost-effective manner. The problem faced by current retrofitting methods is that they require that a car alternator's electromagnet rotor is replaced with a permanent magnet rotor [4]. Magnetic material can be difficult to find or expensive to buy in developing countries [4].

An alternative method to retrofitting a car alternator is to rewind the alternator's stator. This paper provides an easy to follow guide on how to equate a Toyota car alternator to an equation. The equation will allow a person to more accurately determine the number of stator windings needed to reduce the rpm requirement of the car alternator. This paper also introduces a possible way of rewinding the stator. The information provided in this document may serve as a key first step in the retrofitting process of a car alternator into a low rpm generator.

II. BACKGROUND

2.1 Importance of Relating Car Alternator to Equation

Presently, there is no clear and direct guide available that relates electromagnetic theory to the physical parameters of the commonly used AC machine known as the car alternator. The information that an individual, such as a college student, has access to through the internet or textbooks only provide the following: a basic understanding of AC machines concepts, or steps on how to change a component in a car alternator without a clear reason. There are various professors and students involved in renewable energy projects, where a clear correlation between a car alternator's physical components and electromagnetic theory would help them appropriately retrofit an alternator to their desired requirements. Therefore, this paper will provide a clear guide on how to relate a car alternator components, and dimensions to the parameters of the Generated Voltage Equation.

2.2 The Generated Voltage Equation

It is well known that a voltage can be induced by mechanically rotating a magnetic field past a set of wound coils. All ac machines that convert rotational energy into electrical energy make use of that concept. The equation below show the relation between the induced voltage in rms, number of windings, rotational speed, and flux of the rotating magnetic field.

$$E_{rms} \approx \left(\frac{1}{\sqrt{2}}\right) \omega_{me} k_w N_{ph} \varphi_p \qquad 2\text{-}1$$

E_{rms}
$\equiv$ *line to neutral rms voltage produced by ac machine*
$\omega_{me} \equiv$ *electrical frequancy*
$k_w \equiv$ *stator widing factor*
N_{ph}
$\equiv$ *number of turn widings per phase on stator*
$\varphi_p \equiv$ *air − gap flux per pole*[*Wb*]

It must be noted that the equation 2-1 is only valid when the given ac machine is operated in normal steady state. Since, the aim of this paper is to parameterize a car alternator that will be operated at steady state; equation 2-1 can be applied. Equation 2-1 is the basis of the whole paper.

2.3 The Key Components of a Car Alternator

All car alternators have various components, but for the purpose of this paper only the following will be explored: drive pulley, rotor, stator windings, and diode rectifier. The drive pulley is the component that is physically rotated by the prime mover to spin the rotor. The drive pulley is either bolted or pressed onto the rotors shaft.

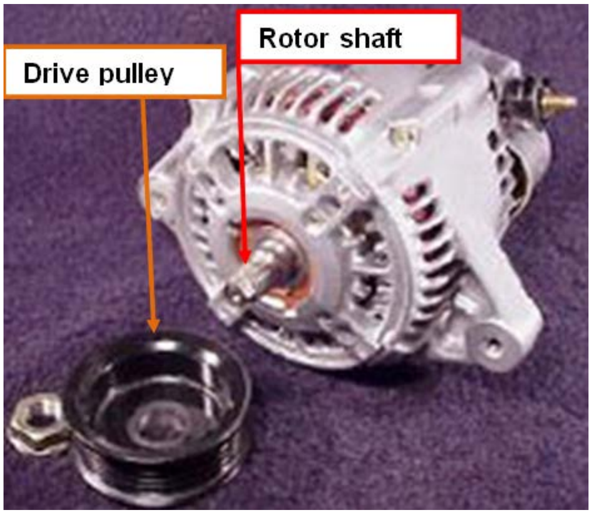

Figure 2-1: *Removed drive pulley from rotor shaft [3]*

The rotor is the electromagnet that will produce the magnetic field which will rotate across the stator to induce a voltage across it. The rotor's magnetic field is produced by applying current into the rotor winding. The amount of current determines the strength of the magnetic field. The current is applied with the use of two stationary carbon brushes that ride on two rotating slip rings located on one end of the rotor.

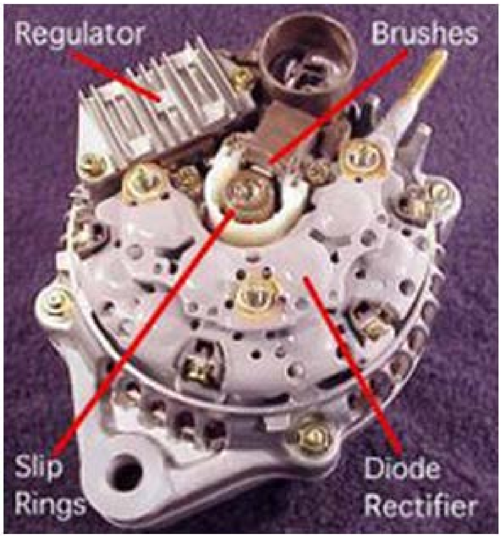

Figure 2-2: *Circuit components located under the cover of the alternator [3]*

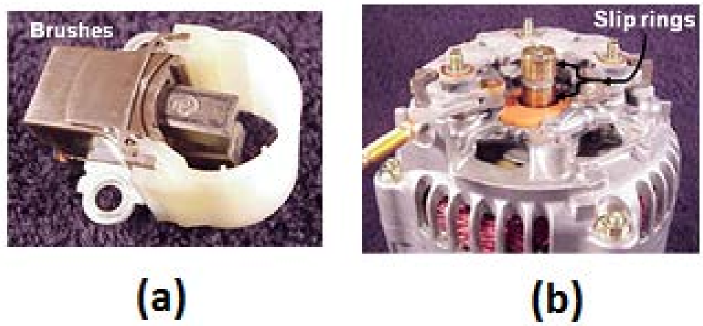

Figure 2-3: *(a) Stationary carbon brushes. (b) Rotating slip rings located on the end of the rotor [3]*

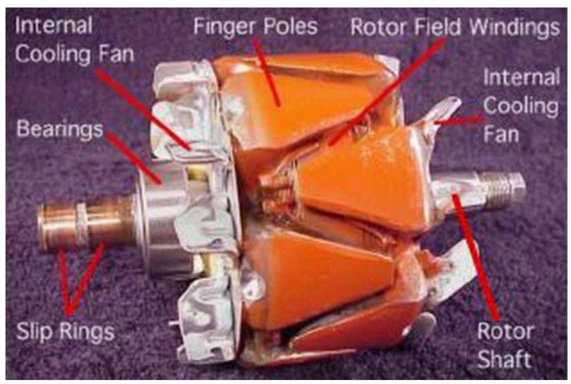

Figure 2-4: *Rotor removed from alternator [3]*

The stator winding is the stationary set of coils that experience the induced voltage produced by the rotating magnetic field (rotor). The voltage induced is affected by the strength of the magnetic field and the rotating speed of the rotor. The stronger the magnetic field, the bigger the induced voltage will be; the faster the rotor rotates the bigger the voltage will be. A car alternator stator is composed of three sets of windings connected in Wye configuration. The windings are wound in such a way as to produce 3-phase voltage 120 degrees out of phase.

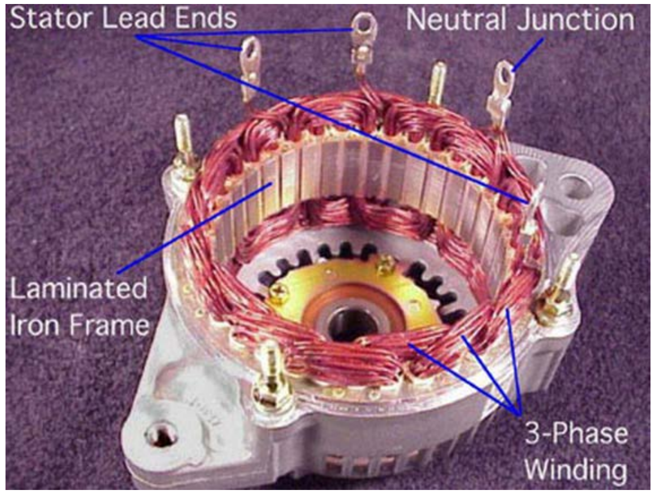

Figure 2-5: *Picture of Stator [3]*

The diode rectifier takes the AC 3-phase voltage induced in the stator coils and converts it into DC voltage. The diode rectifier is configured so that at any given time two of the three windings are in series.

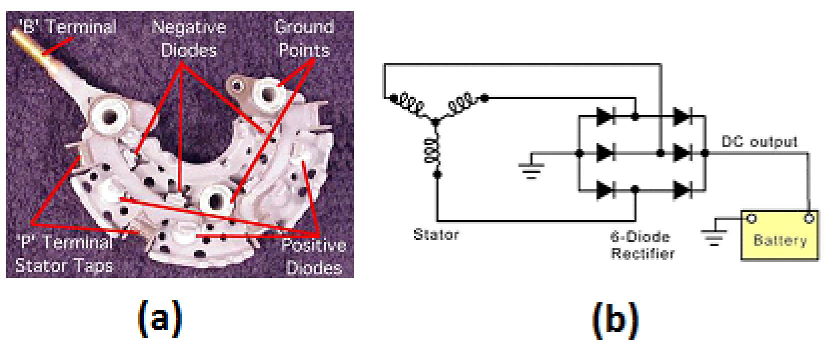

Figure 2-6: *(a) The alternator's diode rectifier. (b) Schematic of the rectifier circuit [3]*

III. Requirements

The main goal of this paper is to develop a method to modify a car alternator into a low rpm generator. This goal will be achieved by equating the car alternator to the Generated Voltage Equation. To achieve this, we will first purchase a Toyota car alternator at a junkyard; the reason for using a Toyota car alternator is because the Toyota car is one of the most common cars used in the world [5]. We will then take the Generated Voltage Equation and put it in terms of the following parameters: stator windings, stator winding factor, rotor winding, rotor winding factor, physical dimensions, current and voltage inputs and outputs. Next, we will run an Open-Circuit test to obtain data that will help us determine the values of parameters that cannot be directly measured, i.e., the rotor's winding factor and number of rotor winding turns. We will run the Open-Circuit test in the Cal Poly-San Luis Obispo Power Electronics Lab (Engineering East 20-Room 104) using an adjustable speed drive to run an AC motor that will be coupled with the car alternator; the AC motor will simulate the input rpm needed to turn the alternator's rotor. After running the test, we will take the car alternator apart and measure various physical dimensions including: stator internal diameter, rotor diameter, iron core length, air-gap length, and rotor radius to air-gap length. After equating the measured physical dimensions to the Generated Voltage Equation, we will take apart the alternator's stator to count its number of windings and measure its physical dimensions; we will use the stator physical dimensions to calculate the stator winding factor. After determining the stator winding factor, we will use the Generated Voltage Equation, the data collected in the Open-Circuit test, and the measured parameters to calculate the product of the rotor winding factor and number of rotor windings. Once reaching this point, the Generated Voltage Equation should be in terms of the car alternator's stator winding, stator winding factor, rotor winding, rotor winding factor, physical dimensions, and current and voltage inputs and outputs.

The new car alternator version of the Generated Voltage Equation should provide a key connection between desired electrical outputs, the field winding input, the rotational input speed, and the number of stator windings. The user of the equation will be able to plug in the desired rpm input, field current input, and phase-voltage output and be able to calculate the needed number of stator windings needed to achieve the desired parameters.

Ultimately, we will use the new Generated Voltage Equation to determine the number of stator windings needed to reduce a Toyota car alternator's input rpm from 1800 rpm to 200 rpm. We will then rewind the stator to meet the new winding requirement using 22-gauge wire rated at 7 amps. The reason we want to use 22-gauge wire is because it is the smallest wire that can handle at least 5 amps [6]. We want the alternator to produce at least 60 Watts at 12 volts DC.

IV. Obtaining the new Generated Voltage equation and Rewinding

4.1 Redefining the Generated Voltage Equation

Before the components and dimensions of the car alternator could be related to the Generated Voltage Equation, the equation itself must be rearranged to a form that contains elements that can be measured or calculated. From looking at equation 2-1 (the generated voltage equation) only three of the elements can be directly measured. The rms induced voltage can be measured with a voltmeter, the number of windings per phase can be measured by taking the stator out of the ac machine and counting the number of coil windings, and the winding factor can be calculated using the stator dimensions. The electrical frequency and air-gap flux can't be directly measured.

$$\boldsymbol{E_{rms} \approx \left(\frac{1}{\sqrt{2}}\right) \omega_{me} k_w N_p \varphi_p}$$

To put equation 1 in terms that could either be easily measured and calculated, the electric frequency and air-gap flux must be re-written.

$$\boldsymbol{\omega_{me} \approx \left(\frac{poles}{2}\right) \frac{2\pi n_s}{60}} \qquad \text{(4-1)}$$

$$\boldsymbol{poles \equiv number\ of\ poles\ on\ the\ rotor}$$
$$\boldsymbol{n_s \equiv rotational\ speed\ of\ the\ rotor\ in\ rpm}$$

$$\varphi_p = \left(\frac{2}{poles}\right) 2B_{peak} lr \tag{4-2}$$

$B_{peak} \equiv peak\ flux\ density\ [T]$
$l \equiv axial\ lenght\ of\ stator/rotor\ iron$
$r \equiv rotor\ radius$

Since the peak flux density cannot be directly measured, it must also be re-written into terms that can be measured directly.

$$B_{peak} = \frac{4\mu_0}{\pi g}\left(\frac{k_f N_f}{poles}\right) I_f \tag{4-3}$$

$g \equiv air\ gap\ lenght$
$I_f \equiv rotor\ field\ current$
$poles \equiv number\ of\ poles\ on\ the\ rotor$
$\mu_0 \equiv 4\pi \times 10^{-7}\ \mathrm{H \cdot m^{-1}\ or\ N \cdot A^{-2}}$
$k_f \equiv rotor\ field\ winding\ factor$
$N_f \equiv number\ winding\ turns\ on\ the\ rotor$
$I_f \equiv rotor\ field\ current$

All of the parameters in equation 4-3 can be measured with the exception of the rotor field winding and number of turns on the rotor's winding. The product of these two parameters can be calculated with the other measured parameters and data by running a test on the alternator. Now equation 4-1, 4-2 and 4-3 can be combined with equation 2-1 to make one that is in terms of elements that can either be measured or calculated.

$$\varphi_p = \left(\frac{2}{poles}\right)\frac{4\mu_0}{\pi g}\left(\frac{k_f N_f}{poles}\right) I_f 2lr = \left(\frac{2}{poles^2}\right)\frac{4\mu_0}{\pi g} k_f N_f I_f 2lr$$

$$E_{rms} \approx \left(\frac{1}{\sqrt{2}}\right)(poles)\frac{\pi n_s}{60} k_w N_{ph}\left(\frac{2}{poles^2}\right)\frac{4\mu_0}{\pi g} k_f N_f I_f 2lr$$

$$E_{rms} = \left(\frac{1}{\sqrt{2}}\right)\left(\frac{2}{poles}\right)\frac{\pi n_s}{60} k_w N_{ph} \frac{4\mu_0}{\pi g} k_f N_f I_f 2lr$$

Now the equation can be simplified and rearranged into sections that represent the different components and dimensions of the car alternator as seen in equation 4-4.

$$E_{rms} \approx \left[\left(\frac{\sqrt{2}}{poles}\right)\frac{\pi}{60}\frac{4\mu_0}{\pi g} 2lr\right]\left[n_s k_w N_{ph} k_f N_f I_f\right] \tag{4-4}$$

The black component is the output phase voltage in rms. The orange components of the equation represent the numerical constants and physical dimensions of the alternator. The red component simply represents the input rotational speed in rpm on the rotor's shaft. The purple components of the equation represent the parameters determined by the stator. Since the stator is the easiest component on the alternator to take apart, its number of windings is the parameter that will be retrofitted. The green components represent the parameters associated with the rotor. Since, taking apart the rotor is too difficult, the rotor components, except the field current, will remain constant.

4.2 Open circuit test

Before taking the alternator apart, it is important to run an open circuit on the machine. The data collected from the test will help parameterize the machine to equation 4-4. The test is simple and was run by coupling a DC motor to the alternator and running it at the alternator's rated speed of 1800 rpm. The rotor field current was then increased until the DC voltage output reached the alternator's rated DC output of 12 volts. The rotor's field current, line voltage, and DC output voltage where all measured during the test**.** The results of the test are shown on table 4-1.

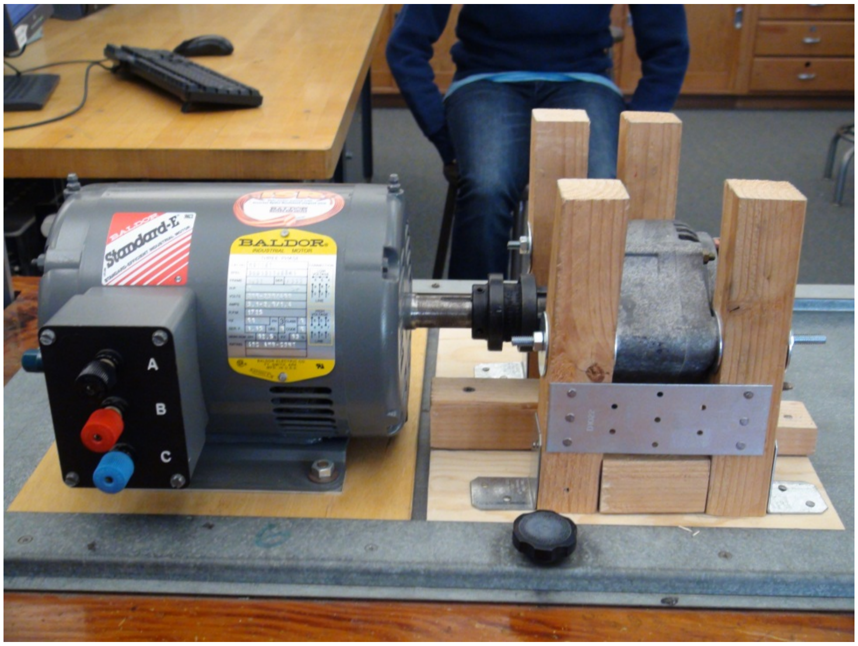

Figure 4-1: *DC motor coupled with car alternator*

Table 4-1: *Results of the Open Circuit Test*

I_f [A]	E_{L-L} [V]	E_{PH} [V]	$V_{out(DC)}$ [V]
0.123	0.921	0.53174	0.902
0.133	1.504	0.868335	1.718
0.17	1.952	1.126988	2.356
0.219	2.484	1.434138	3.12
0.263	2.952	1.704338	3.78
0.323	3.558	2.054212	4.66
0.374	4.23	2.442192	5.58
0.425	4.85	2.800149	6.42
0.473	5.38	3.106144	7.28
0.535	6.07	3.504516	8.22
0.641	7.16	4.133828	9.74
0.687	7.85	4.5322	10.71
0.745	8.44	4.872836	11.56
0.792	8.82	5.092229	12.13
0.862	9.56	5.519469	13.1
0.889	10.26	5.923614	13.93
0.955	10.62	6.13146	14.63
1.063	11.36	6.558699	15.67
1.332	13.7	7.909699	18.95

4.3 The Different Components of Equation 4-4

In this section all of the elements in equation 4-4 will be related to the car alternator. As already mentioned, equation 4-4 is divided into 5 different parts: output phase voltage in rms, physical dimensions, rotational speed input in rpm, stator parameters, and rotor parameter.

Table 4-2: *The Five Different Components of Equation 4-4*

Output Phase-Voltage in rms [V]	Physical Dimensions	Rotational Input speed [rpm]	Stator Parameters	Rotor Parameter
E_{rms}	$\left(\frac{\sqrt{2}}{poles}\right)\frac{\pi}{60}\frac{4\mu_0}{\pi g}2lr$	n_s	$k_w N_{ph}$	$k_f N_f I_f$

4.4 Obtaining the Alternator's Physical Dimensions

The goal of this section is to fill out Table 4-3. All the parameters in Table 4-3 can be either counted or measured with a ruler.

Table 4-3: *The Four Physical Dimensions of the Alternator that Need to be measured*

$poles$	$g\ [m]$	$l\ [m]$	$r\ [m]$

The number of poles can easily be obtained by counting the number of claws around the rotor. Each claw represents a north or south pole. Figure 4-2 illustrates the claw poles on the rotor. The Toyota car alternator we obtained has a total of 12 poles.

$$poles = 12$$

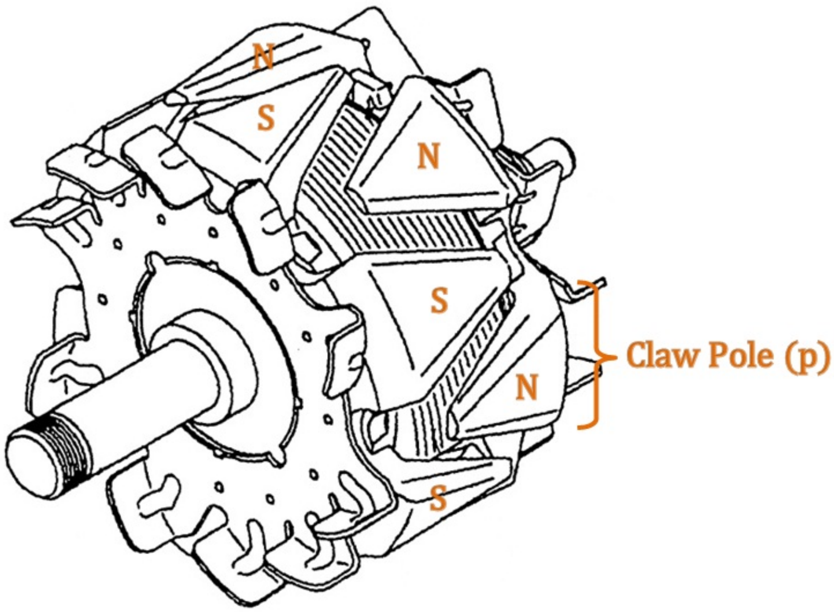

Figure 4-2: *Rotor with Marked North and South Poles*

Unlike the number poles, the air gap length is slightly more difficult to accurately obtain. The air gap length is obtained in three steps: measure the stator internal diameter (ID), measure the rotor diameter (D), and finally use equation 6 to calculate the air gap.

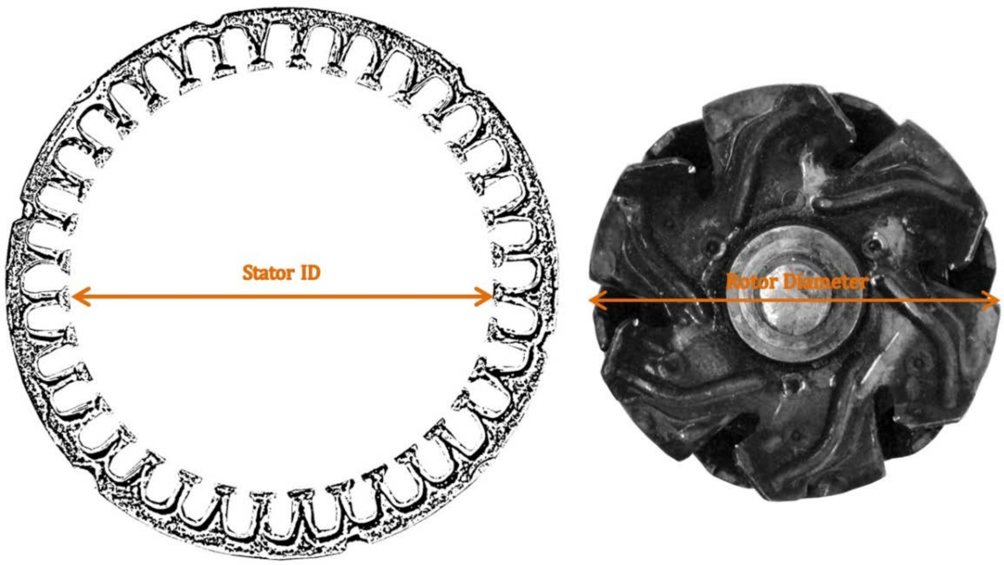

Figure 4-3: *Stator Internal Diameter (ID) and Rotor Diameter (D). Both are measured using a ruler; values computed in meters.*

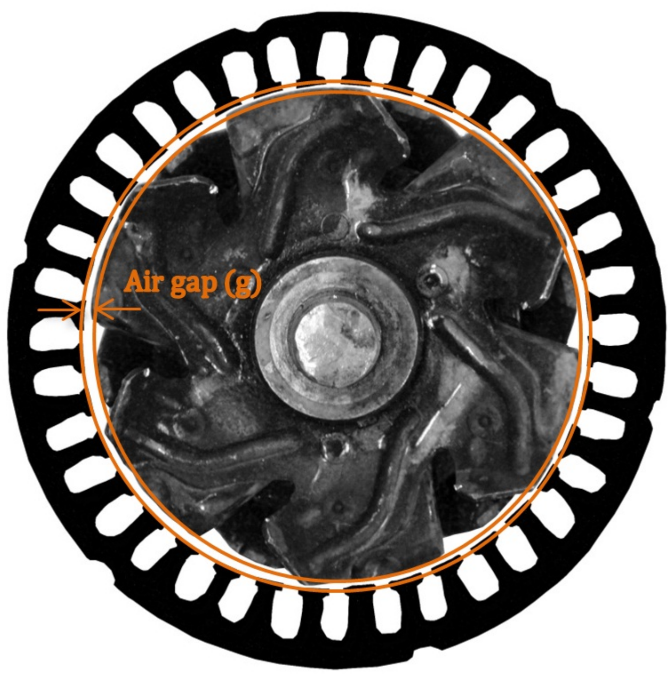

Figure 4-4: *Machine Air-gap*

$$g = \frac{Stator\ ID - Rotor\ D}{2} \tag{4-5}$$

The stator internal diameter of the Toyota alternator we purchased is 0.0895 meters and its rotor diameter is 0.087 meters. The air gap length was calculated using equation 4-5 to be 0.00125 meter.

$$g = \frac{(0.0895\,m) - (0.087m)}{2} = 0.00125m$$

The axial length of the stator/rotor iron is the length of the stator iron core. The length of the stator iron core can be easily measured with any ruler. The length of the rotor iron core was measured to be approximately 0.0258 meter.

$$l \approx 0.0258m$$

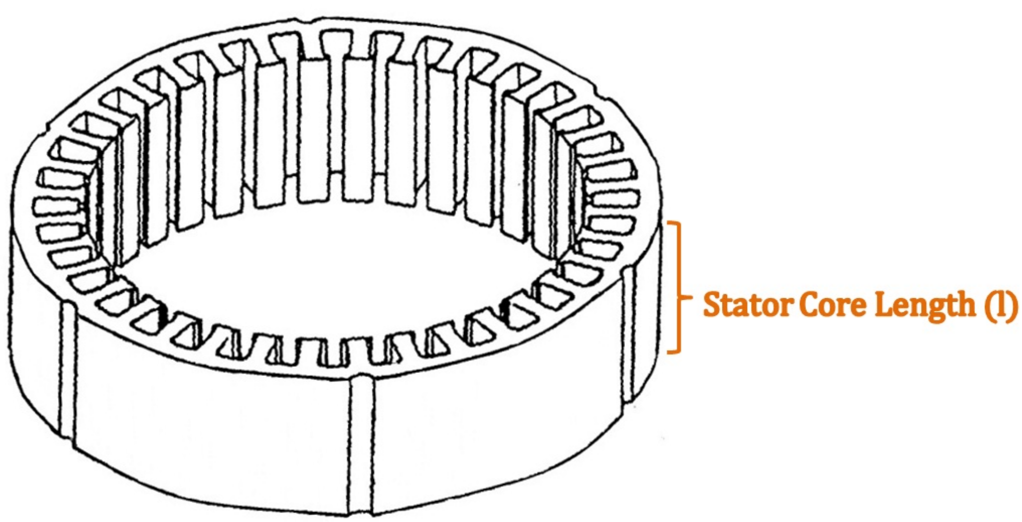

Figure 4-5: *Stator Core-Length.*

The rotor radius can also be easily measured with the use of any ruler. The rotor length was measured to be approximately 0.0435 meter.

$$r \approx 0.0435m$$

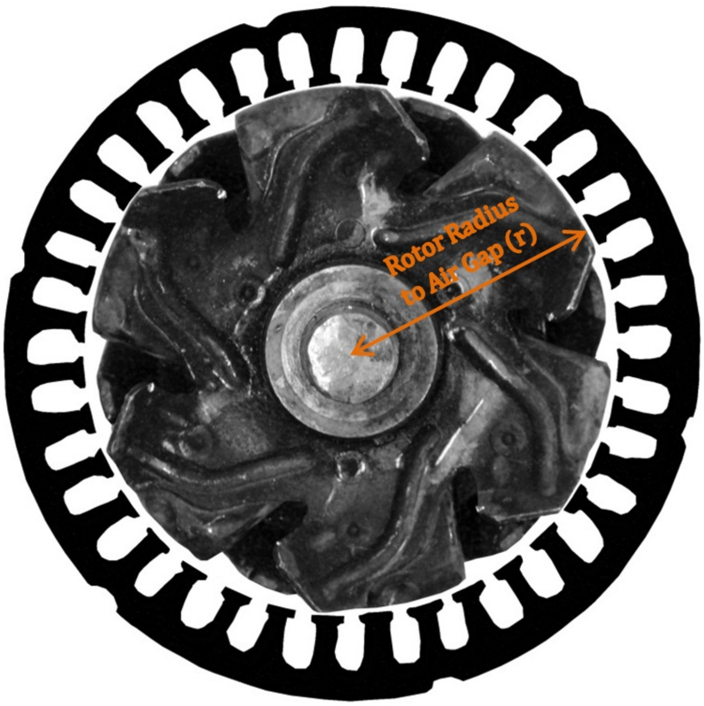

Figure 4-6: *Rotor Radius to Air-gap*

Table 4 contains all the measured physical parameter of the Toyota alternator we purchased.

Table 4-4: Measured physical parameters

$poles$	$g\ [m]$	$l\ [m]$	$r\ [m]$
12	$0.00125m$	$0.0258m$	$0.0435m$

4.5 The Rotational Input Speed

As already mentioned in the section 2.3, the input rotational speed is a determining factor in producing a desired voltage. All rotational AC machines have a rated rotational speed in which they are designed to work during normal operation. A car alternator normally operates at approximately.

$$n_s \approx 1800rpm$$

4.6 Stator Parameters

The stator has two parameters that must be obtained: the number of windings per phase, and the winding factor. The number of windings per phase can be obtained by counting the windings on the stator. The winding factor, on the other hand, has to be calculated using specific dimensions of the stator and rotor.

We first obtain the number of turns per phase by taking apart the stator windings and counting the number of windings. Our stator has approximately 42 windings per phase.

$$N_{ph} \approx 42$$

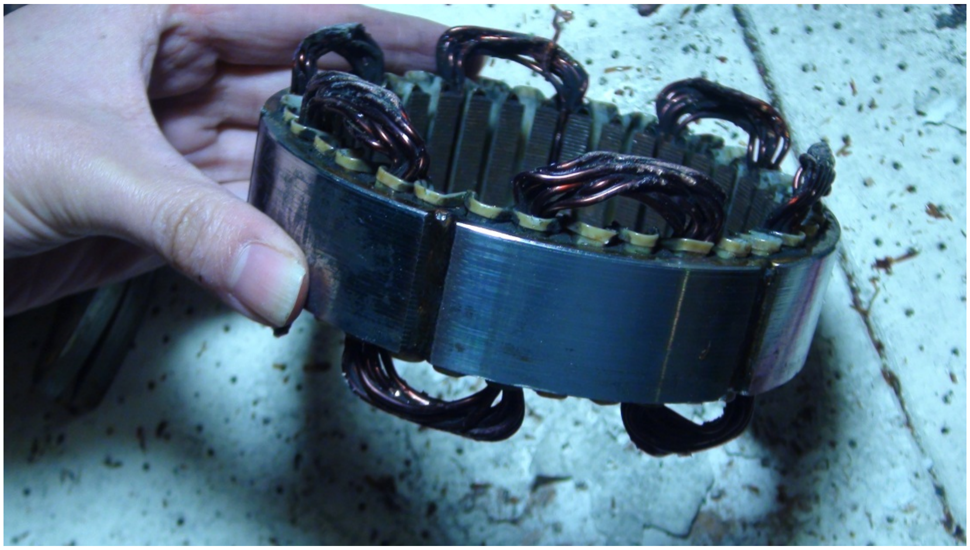

Figure 4-7: *One of the Three-phase Windings on the Rotor*

We begin to determine the rotor winding factor by calculating its pole pitch. The pole pitch is determined by equation 4-6.

$$\rho_p = \frac{360°}{poles} \tag{4-6}$$

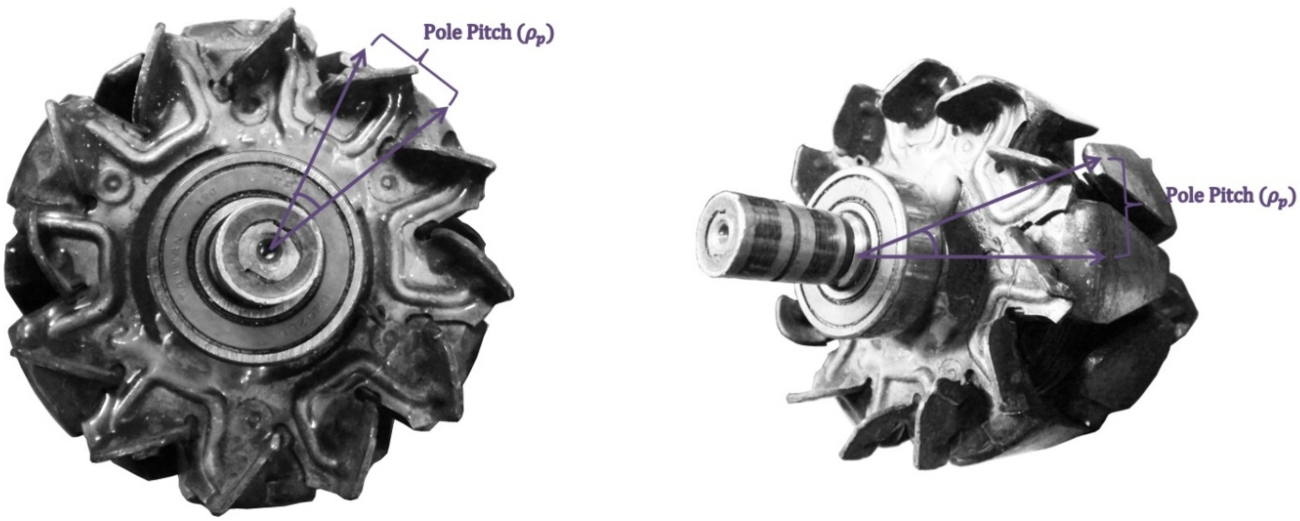

Figure 4-8: *Two different perspectives of the angular rotor Pole-pitch of a car alternator.*

The Pole-pitch in mechanical degrees is defined as the angular distance between two adjacent poles on a machine [1]. The pole pitch could be determined by using a circular protractor or calculated using the following formula: $\boldsymbol{\rho_p} = {}^{360^\circ}/_{\mathrm{P}}$, where P is the number of Poles. It must be noted that the pole-pitch is always 180 electrical degrees [1].

Once determining the pole-pitch and the stator-coil angle, we compared them to determine whether the machine's coil is a full-pitch coil or a fractional-pitch coil. If the stator coil spans the same angle as the pole-pitch, the coil is a full-pitch coil [1]. If the stator coil spans an angle smaller than the pole-pitch, the coil is a fractional-pitch coil [1]. Our machine's pole pitch ($\boldsymbol{\rho_p}$) is given by:

$$\boldsymbol{\rho_p = \frac{360^\circ}{12} = 30^\circ}$$

Next, we must measure the mechanical angle covered by a single coil as show by Figure 4-9. This can be measured using a protractor.

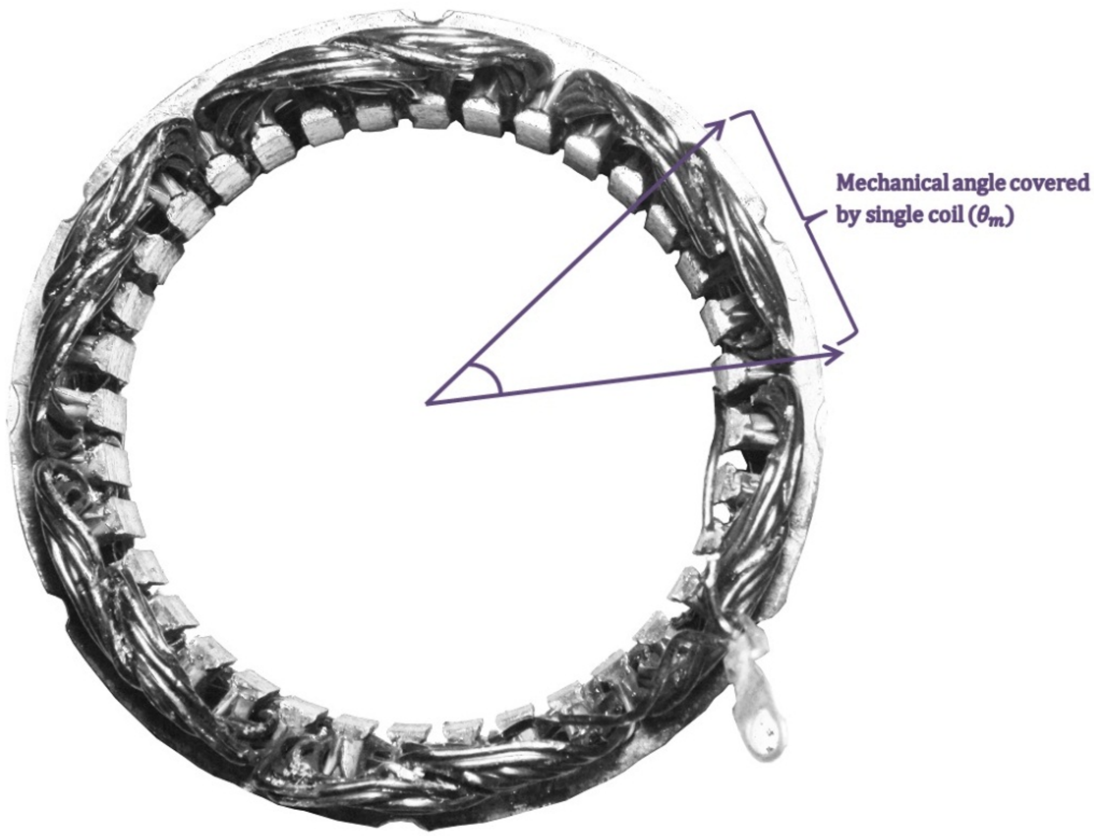

Figure 4-9: *The mechanical angle covered by a single coil, measured in degrees(θ_m). The coil-span angle could be measured using a circular protractor.*

Our machine's stator-coil angle($\boldsymbol{\theta_m}$) is given by:

(Measured with a protractor)

$$\boldsymbol{\theta_m = 20°}$$

Since our stator-coil angle is smaller than the pole pitch, our stator coil is a fractional-pitch coil.

The pitch of a fractional-pitch coil is calculated using equation 4-7 [1]:

$$\boldsymbol{\rho = \frac{\theta_m}{\rho_p} \times 180° = \rho = \frac{\theta_m P}{2} \times 180°} \tag{4-7}$$

Our machine's pitch is therefore:

$$\boldsymbol{\rho = \frac{20°}{30°} \times 180° = 120°}$$

The induced voltage in a single turn is given by equation 4-8 [1]:

$$\boldsymbol{e_{ind} = \emptyset\omega \sin\frac{\rho}{2} \cos\omega_m t} \tag{4-8}$$

The $\boldsymbol{\sin\frac{\rho}{2}}$ term is defined as the pitch-factor (k_p) of the coil [1]. Therefore, the pitch-factor of a coil is given by:

$$\boldsymbol{k_p = \sin\frac{\rho}{2}(\text{ electrical degrees})} \tag{4-9}$$

$$\boldsymbol{k_p = \sin\frac{\theta_m P}{2}(\text{ mechanical degrees})} \tag{4-10}$$

Our machine's pitch-factor is therefore:

$$\boldsymbol{k_p = \sin\frac{\theta_m P}{2} = \sin\frac{20° \cdot 12}{2} = \sin 120° = 0.866025404}$$

The distribution factor k_d as defined by Chapman, is the ratio of the actual voltage in a phase of a distributed winding to its expected value in a concentrated winding with the same number of turns [1]. In mechanical terms, the distribution factor is given by:

$$\boldsymbol{k_d = \frac{\sin(n\gamma/2)}{n\sin(\gamma/2)}} \tag{4-11}$$

Where *n* equals the number of slots per pole per phase and $\boldsymbol{\gamma}$ is the angular displacement between the slots [2]. Let Q equal the number of slots per pole, then:

$$\boldsymbol{n = \left(\frac{Q}{\varphi}\right)} \tag{4-12}$$

$$\boldsymbol{\gamma = \left(\frac{180^\circ}{Q}\right)} \tag{4-13}$$

For our machine:

$$\boldsymbol{Q = \frac{36 - slots}{12} = 3}$$

$$\boldsymbol{n = \left(\frac{3}{3 - phases}\right) = 1}$$

$$\boldsymbol{\gamma = \left(\frac{180^\circ}{3}\right) = 60^\circ}$$

Therefore, our distribution factor is:

$$\boldsymbol{k_d = \frac{\sin(n\gamma/2)}{n\sin(\gamma/2)} = \frac{\sin(1 \cdot 60^\circ/2)}{1 \cdot \sin(60^\circ/2)} = 1.000}$$

The pitch factor and distribution factor of a winding are combined into a single constant, called the *winding factor* k_w [1]. Therefore the winding of factor of a stator is given by:

$$\boldsymbol{k_w = k_p k_d} \tag{4-14}$$

Our machine's winding factor is thus:

$$\boldsymbol{k_w = k_p k_d = 0.866025404 \cdot 1 \approx 0.866}$$

4.7 Rotor Parameters

The rotor contributes three parameters: one input and two constants. The input parameter is the field winding current, whose value is subject to change. The other two parameters cannot be separately found, but their product, which will remain constant, can be calculated using the data from the OC test, the parameters already found, and equation 5.

Equation 5 rearranged to solve for $\boldsymbol{k_f N_f}$ product:

$$\boldsymbol{k_f N_f \approx \frac{E_{rms}}{\left[\left(\frac{\sqrt{2}}{poles}\right)\frac{\pi}{60}\frac{4\mu_0}{\pi g}2lr\right]\left[n_s k_w N_{ph} I_f\right]}} \tag{4-15}$$

Table 4-5: *Result of applying equation 4-15 at various input field currents.*

I_f [A]	V_{L-L} [V]	E_{PH} [V]	$V_{out(DC)}$ [V]	K_fN_f
0.123	0.921	0.53174	0.902	3702.854
0.133	1.504	0.868335	1.718	5592.143
0.17	1.952	1.126988	2.356	5678.23
0.219	2.484	1.434138	3.12	5609.053
0.263	2.952	1.704338	3.78	5550.635
0.323	3.558	2.054212	4.66	5447.353
0.374	4.23	2.442192	5.58	5593.077
0.425	4.85	2.800149	6.42	5643.322
0.473	5.38	3.106144	7.28	5624.75
0.535	6.07	3.504516	8.22	5610.699
0.641	7.16	4.133828	9.74	5523.789
0.687	7.85	4.5322	10.71	5650.605
0.745	8.44	4.872836	11.56	5602.324
0.792	8.82	5.092229	12.13	5507.132
0.862	9.56	5.519469	13.1	5484.445
0.889	10.26	5.923614	13.93	5707.26
0.955	10.62	6.13146	14.63	5499.247
1.063	11.36	6.558699	15.67	5284.783
1.332	13.7	7.909699	18.95	5086.258

After calculating the $k_f N_f$ product at various input filed currents, we used excel to calculate the mean of the various $k_f N_f$ products. We will use the calculated mean as the input constant. Note that the $k_f N_f$ stays very close to the same value except at the first point where no field current is applied and at points significantly above the rated DC output voltage of 12 volts.

Chosen field winding factor and field winding product:

$$k_f N_f \approx 5538$$

At this point, all the parameters of the car alternator have been equated with the equation 4-4.

4.8 Rewinding the stator

Now that the car alternator has been equated to equation 4-4, the equation can be used to determine the appropriate number of windings needed to reduce the alternator rpm requirement from 1800 rpm to 200 rpm. First, take equation 4-4 and solve for stator winding per phase.

$$N_{ph} \approx \frac{E_{rms}}{\left[\left(\frac{\sqrt{2}}{poles}\right)\frac{\pi}{60}\frac{4\mu_0}{\pi g}2lr\right]\left[n_s k_w k_f N_f I_f\right]} \qquad (4\text{-}16)$$

Now plug in the desired input rpm, input field current, and output phase voltage. Since we want a desired voltage of DC of 12 volts, we need to plug in the phase voltage that will produce 12 volts DC through the rectifier. We can determine that by looking at Table 4-1:

Table 4-6: *Phase-Voltage at 12 volts DC output*

E_{PH} [V]	$V_{out(DC)}$ [V]
5.0922294	12.13

The desired rpm input is 200 rpm:

$$n_s = 200rpm$$

We also want the minimum field current needed to produce 12 volts; this value is also obtained from Table 4-1:

Table 4-7: *Field current at 12 volts dc output*

I_f [A]	$V_{out(DC)}$ [V]
0.792	12.13

$$N_{ph} \approx \frac{5.09V}{\left[\left(\frac{\sqrt{2}}{12}\right)\frac{\pi}{60}\frac{4\mu_0}{\pi(0.00125m)}2(0.025832m)(0.0435m)\right][(200rpm)(0.87)(5538)(0.792A)]}$$

$$N_{ph} \approx 376\ windings\ per\ phase$$

To reduce the rpm requirement of a Toyota car alternator from 1800 rpm to 200 rpm you need about 376 windings per phase. This translates to approximately 6 distributed coil-windings each containing 63 turns.

Unfortunately, when attempting to fit 63 windings of 22 gauge magnet wire into the stator slots, they did not fit. The most windings that could fit in the slots with 22 gauge wire were 50, which translate to 300 windings per phase. By rearranging Equation 4-4 to solve for input rpm using the new winding requirement, we find that the alternator can be ran at about 251 rpm and still produce 12 volts DC.

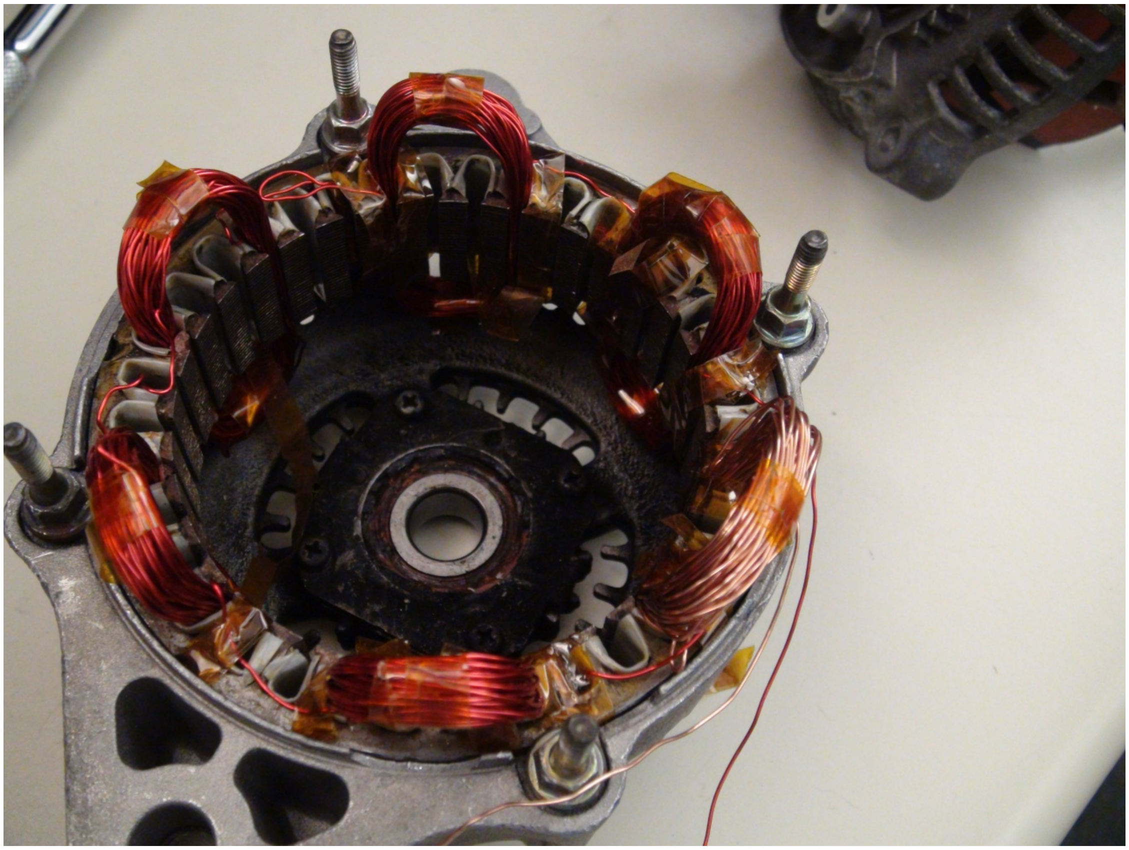

Figure 4-10: *Re-wounded single-phase of Stator.*

Figure 4-1- shows the rewound stator with the maximum number of windings that fit in its slots; 50 windings per slot with 22 gauge wire, which translates to 300 windings per-phase.

V. CONLUSION AND RECOMMENDATIONS

The investigation into developing a method to retrofit a car alternator through the equating the car alternator with the General Voltage Equation produced a good learning curve. One key lesson we learned during this project was how to properly operate a car alternator. This was important because, without a practical understanding of how the alternator works, it is impossible to figure out how a structural change in the stator affects the alternator's output voltage. The other key lesson we learned during this project is how to calculate the stator winding factor using physical measurements obtained with the use of a ruler and protractor. This was particularly important because readily available alternator specifications do not include the stator winding factor; if the stator winding factor is not calculated, there would be too many unknown variables in the Generated Voltage equation, making it impossible to use as a guide to solve our desired stator winding number.

The lessons learned through this project allowed us to develop an easy-to-follow guide on how to equate a car alternator to the Generated Voltage Equation. However, it must be mentioned that, even though the guide is straightforward, the process of taking apart the alternator is significantly difficult. Namely, removing the alternator's drive pulley with a hand wrench is nearly impossible. We had to go to an automobile shop and have them remove the drive pulley with a high torque power wrench. Another practical difficulty we encountered was the limited number of windings that can actually fit in ea ch stator slot. Using the derived Generated Voltage Equation, we determined that the number of rotor windings per-phase needed to reduce our alternator's rmp requirement from 1800 rpm to 200 rpm is 376, which translates to approximately 6 distributed coils of 63 windings per-phase. When we attempted to rewind the stator using this winding requirement, the most windings we were able to fit into a slot were 50 windings per coil, which translated to 300 windings per-phase. Due to the small area of the stator slots, we had to limit our machine to this new winding requirement. With 300 windings per-phase, we determined that the minimum rpm the alternator can be operated with and still produce 12 Volts DC is approximately 251 rpm.

We eventually plan to post an instructional video on the internet showing how to reproduce the work we did for this project. The video will contain a more detailed illustration of how to obtain each parameter. The video will also provide the viewer with a better perspective into the limiting factors associated with taking apart the alternator and rewinding the stator.

We recommend that a student continues to work on this project to test the quality of the rewound alternator. Also, we encourage the student to develop a way to remove the drive pulley without the use of a high torque power wrench. Furthermore, if the same 12 Volt DC Toyota alternator model is used, the student should use the same equation derived in this report to make needed calculations in order to remain consistent with the findings of this project.

VI. BIBLIOGRAPHY

[1] S. J. Chapman, "Appendix B-Coil Pitch and Distributed Windings," in *Electric Machinery Fundamentals,* Fourth Edition, USA: McGraw-Hill, 2004.

[2] S.I.Shahl, "Electrical Machines II", [Online]. Available: http://www.uotechnology.edu.iq/dep-eee/lectures/3rd/Electrical/Machines%202/I_Introduction.pdf

[3] K. R. Sullivan, "Understanding the Alternator," San Bruno, CA, USA, [Online]. Available: http://www.autoshop101.com/trainmodules/alternator/alt101.html

[4] Picohydro Generator, [online]. Available: http://www.appropedia.org/Picohydro_generator

[5] C. Laine, "Sam Redfield on Pico-hydro at La Florida," in AIDG Blog [Appropriate Technology, Development, Environment], [Online]. Available: http://www.aidg.org/dugg/redfield_picohydro.htm

[6] D. G. Fink and H. W. Beaty, Standard Handbook for Electrical Engineers, Eleventh Edition, McGraw-Hill, New York, 1978, ISBN 0-07-020974-X, page 4-18 and table 4-11.

APPENDIX A

Project Costs

Parts	Cost [$]
Car Alternator	**30**
22 gauge wire	24
Total	54