EE 221L Circuits II Final Project Report
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Section 1002

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Final Project

EE 221L - Circuits II (Lab)

PWM Frequency Regulated AC/DC Rotary Convertor

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
UNIVERSITY OF NEVADA, LAS VEGAS

Final Project
PWM Frequency Regulated AC/DC Rotary Convertor

1. Introduction

The following is a brief description on the objective of the project.

Motivation

1. Since this project encompasses a large amount of the EE221 subject material, it allows the team to apply these concepts to a single project to demonstrate overall competency in the calculation of AC/DC steady state measurements, filter design techniques, integration of electromagnetic induction principles, and soldering. The key motivation is to successfully apply this array of skills in a creative way to build a functioning electro-mechanical machine with basic electronic control.

2. The machine consists of a prime mover section driven by a microcontroller Correct PWM (Pulse Width Modulation) control scheme which drives a fixed PM (Permanent Magnet) within a induction generator coil assembly. The AC generator section is comprised of a two pole single phase winding with 56 turns per coil and 6 coil groups wound at #24AWG. Control of the rotary field is accomplished by sampling the generator RMS terminal voltage and adjusting the DC duty cycle to maintain frequency as it relates to output voltage.

3. The prime mover is rated at 8.2^{VDC} at 0.25^{ADC} and the generator is rated at 200^{mVDC} RMS.

Background Theory

The following is a brief description on the theoretical concepts used in the design.

Electromagnetic Induction

1. Electromagnetic induction is the production of an electromotive force across a conductor when it is exposed to a varying magnetic field. It is described mathematically by Faraday's law of induction.

$$\mathcal{E}_{\text{coil}} = N\left|\frac{d\Phi_{\text{per turn}}}{dt}\right| = \left|\frac{d\Phi_{\text{m}}}{dt}\right| \qquad \mathcal{E}_{\text{coil}} = L\left|\frac{dI}{dt}\right|$$

AC Time Domain Analysis

1. Time domain analysis gives the behavior of the signal over time. This allows predictions and regression models for the signal. In a time domain analysis, the variable is always measured against time and provides the instantaneous value at that time.

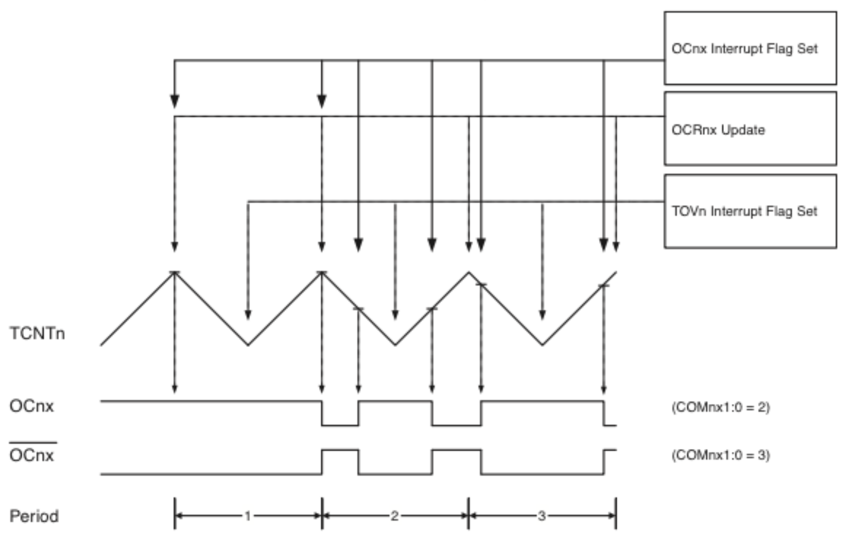
DC Motor Applications

1. Since the DC motor has a higher starting torque over the stepper and servo motors, it is preferred when driving low speed high torque loads, and traction type applications with high inertial loading.

PWM - Pulse Width Modulation (ATmega328P Microcontroller)

1. The phase correct PWM mode provides a high resolution phase correct PWM waveform generation option. The phase correct PWM mode is based on a dual-slope operation. The counter counts repeatedly from BOTTOM to TOP and then from TOP to BOTTOM. TOP is defined as 0xFF when WGM2:0 = 1, and OCR0A when WGM2:0 = 5. In non- inverting Compare Output mode, the Output Compare (OC0x) is cleared on the compare match between TCNT0 and OCR0x while up counting, and set on the compare match while down counting. Due to the symmetric feature of the dual-slope PWM modes, these modes are preferred for motor control applications.

Figure 14-7. Phase Correct PWM Mode, Timing Diagram



TIP120 PWM Amplifier

1. The TIP120 is an NPN Epitaxial Darlington Transistor sized for medium power linear switching applications. Since DC motors draw large starting and locked rotor currents, an amplifier must be used to avoid having the ATmega328P source these currents.

ATmega328P 8-bit Microcontroller

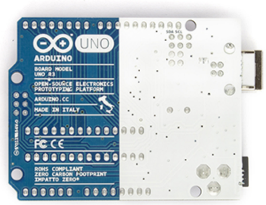
1. The ATmega328P Microcontroller features an Analog/Digital Converter (ADC) with 10 bit resolution using a successive approximation algorithm. A Sample and Hold circuit allows measurement of the input voltage at a constant level. The converted measurement is stored in dedicated registers as an integer value that ranges from 0 to 1023. Thus, the reference voltage would be represented by 1023.

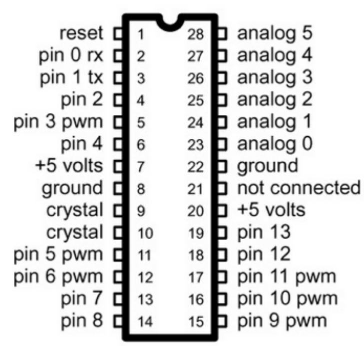
2. For project purposes, an internal reference voltage of 1.1 V was used. Because the focus of the project was not on microprogramming, we utilized an Arduino Uno and called higher level language library functions such as analogRead() to access the ADC register values. The ADC takes approximately 100 us to read an analog input (10,000 times per second), which is more than enough for our project purposes.

Arduino - Uno

1. In order to regulate the induced voltage generated from the transformer we needed to control the motor with extreme accuracy and precision. Our group decided to use the Arduino Uno microcontroller. The Arduino Uno is a general purpose microcontroller based on the ATmega328p datasheet that can serve as an amazing tool for engineers, hobbyists, or anyone else who desires an interfacing solution for their project.

2. For our project we specifically took advantage of the input and output pins and the additional functionalities that operate with them. By using a 5 volt input signal as a reference voltage, we were able to use the onboard analog to digital converter to read the voltage produced from the transformer. Once the voltage was read in we were able to generate an output pulse signal to the motor that was connected to a rotating magnet. The duty cycle of the pulse signal is then regulated by code written in the C language and implemented by the Arduino Uno. This process continues autonomously until the user ceases the circuit's operation. In the end, the Arduino Uno was an invaluable solution used to control our transformer. The extensive options functions it provides through the use of high level machine language instructions made this portion of the project highly enjoyable.



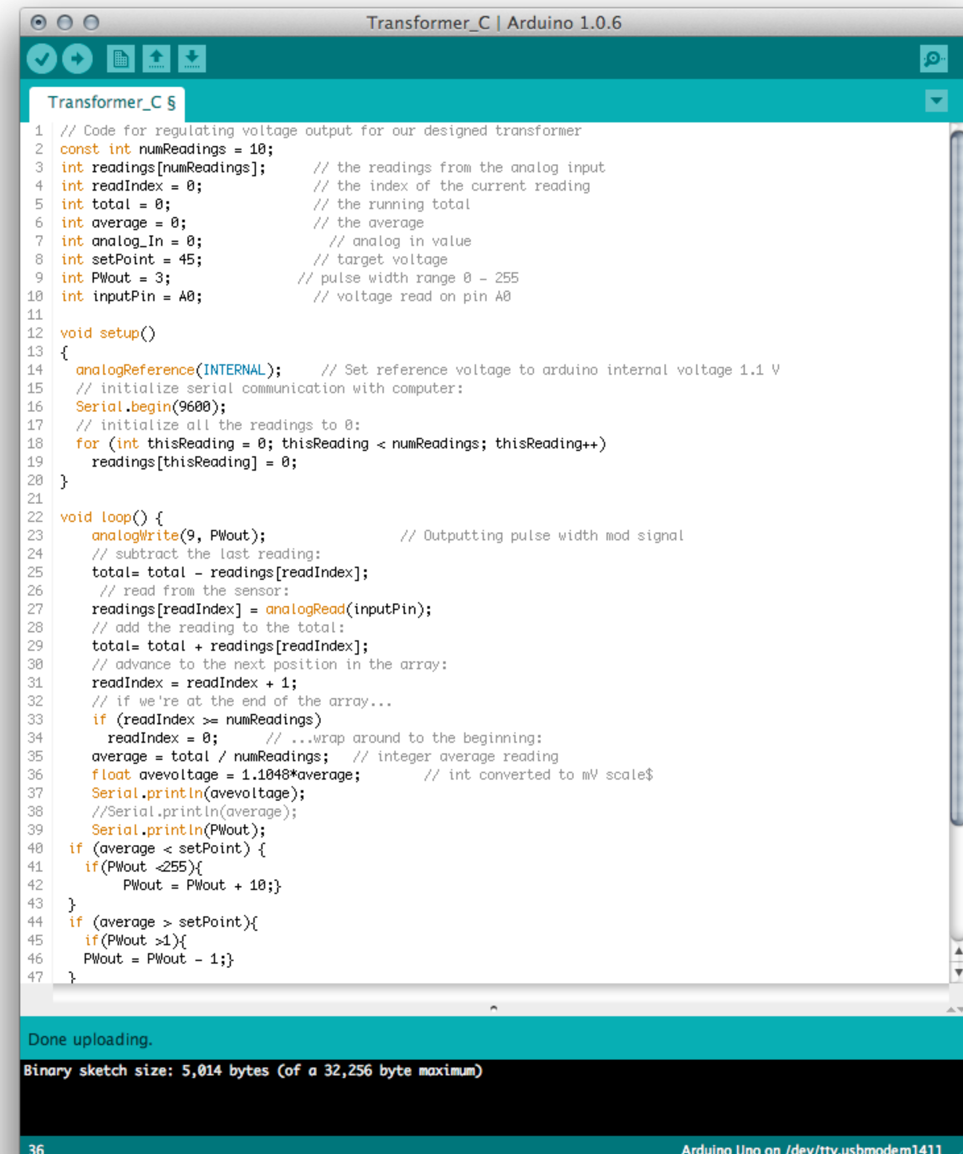


3. Experimental Data

The following information relates to the experimental outcomes and/or results.

Image of C implementation Code:

1. After the provided DC motor code was modified with the right duty cycle and speed control requirements, it was debugged with the virtual simulator and yielded a successful project build. It was further verified by the correct pulse width and timing using a DMM. The circuit was then constructed with the appropriate semiconductor components and the ATmega328P chip was programmed. To test, the analog input voltage was adjusted to demonstrate the different “under” and “over” voltage operating modes. The prime mover performed as expected.




```
// Code for regulating voltage output for our designed transformer
const int numReadings = 10;
int readings[numReadings];      // the readings from the analog input
int readIndex = 0;              // the index of the current reading
int total = 0;                  // the running total
int average = 0;                // the average
int analog_In = 0;                // analog in value
int setPoint = 45;              // target voltage
int PWout = 3;                // pulse width range 0 - 255
int inputPin = A0;              // voltage read on pin A0

void setup()
{
  analogReference(INTERNAL);     // Set reference voltage to arduino internal voltage 1.1 V
  // initialize serial communication with computer:
  Serial.begin(9600);
  // initialize all the readings to 0:
  for (int thisReading = 0; thisReading < numReadings; thisReading++)
    readings[thisReading] = 0;
}

void loop() {
    analogWrite(9, PWout);                   // Outputting pulse width mod signal
    // subtract the last reading:
    total= total - readings[readIndex];
     // read from the sensor:
    readings[readIndex] = analogRead(inputPin);
    // add the reading to the total:
    total= total + readings[readIndex];
    // advance to the next position in the array:
    readIndex = readIndex + 1;
    // if we're at the end of the array...
    if (readIndex >= numReadings)
      readIndex = 0;      // ...wrap around to the beginning:
    average = total / numReadings;   // integer average reading
    float avevoltage = 1.1048*average;        // int converted to mV scale$
    Serial.println(avevoltage);
    //Serial.println(average);
    Serial.println(PWout);
 if (average < setPoint) {
   if(PWout <255){
       PWout = PWout + 10;}
 }
 if (average > setPoint){
   if(PWout >1){
   PWout = PWout - 1;}
 }
```

Captured Measurements Testing 1

1. The following measurements were taken with the machine at rated-speed:

AC Output Waveform	Measured		Theoretical	
	Magnitude	Phase	Magnitude	Phase
V_T (Generator Terminal Voltage)	848 mVAC (PP)	0°	1 VAC (PP)	0°
Crest Factor	1.74	-	1.414	-

Captured Measurements Testing 2

Operational Range	Measured			
	PWM Duty	I DC RMS	$V_{T\ AVG}$	$V_{T\ RMS}$
Lower Limit	50%	223 mADC	143 mVAC	153 mVAC
Upper Limit	100%	288 mADC	251 mVAC	282 mVAC

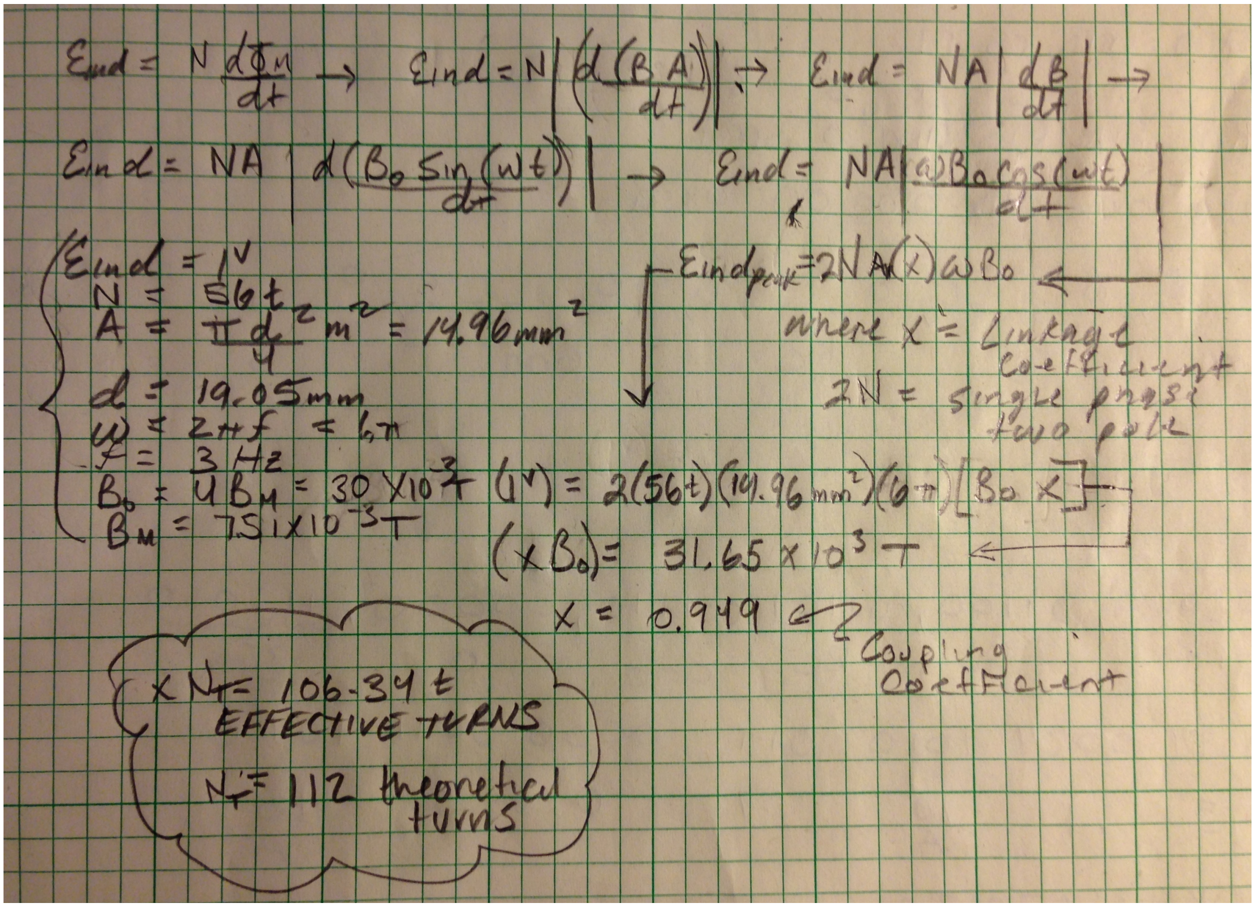
4. Analysis/ Comparisons with Simulation Data and Hand Calculations

The following are hand calculations relating effective turns to theoretical turns which correlates to induced voltage in the testing 1 table.

Analysis/Data Comparison

The following is a demonstration that induction principles apply to the experiment. As can be seen, the measured values correlate very well with the theoretical ones. Any variation can be explained by circuit noise influence, equipment error, measurement non-repeatability, and external systematic factors such as generator inductance. The theoretical values were calculated based on empirical data.

To account for error, the calculation introduces a factor x that acts to decrease the flux linkage. This number was calculated to be 0.949, which suggests a tightly coupled field to the three 56 turn coils.



$$\mathcal{E}_{ind} = N\frac{d\Phi_M}{dt} \rightarrow \mathcal{E}_{ind} = N\left|\frac{d(B\,A)}{dt}\right| \rightarrow \mathcal{E}_{ind} = NA\left|\frac{dB}{dt}\right| \rightarrow$$

$$\mathcal{E}_{ind} = NA\left|\frac{d(B_0 \sin(\omega t))}{dt}\right| \rightarrow \mathcal{E}_{ind} = NA\left|\frac{\omega B_0 \cos(\omega t)}{dt}\right|$$

$$\mathcal{E}_{ind\,peak} = 2NA(x)\omega B_0$$

where x = Linkage coefficient

$2N$ = single phase two pole

$$\begin{cases} \mathcal{E}_{ind} = 1^V \\ N = 56t \\ A = \frac{\pi d^2}{4}\,m^2 = 14.96\,mm^2 \\ d = 19.05\,mm \\ \omega = 2\pi f = 6\pi \\ f = 3\,Hz \\ B_0 = 4B_M = 30\times10^{-3}\,T \\ B_M = 7.51\times10^{-3}\,T \end{cases}$$

$$(1^V) = 2(56t)(14.96\,mm^2)(6\pi)[B_0\,x]$$

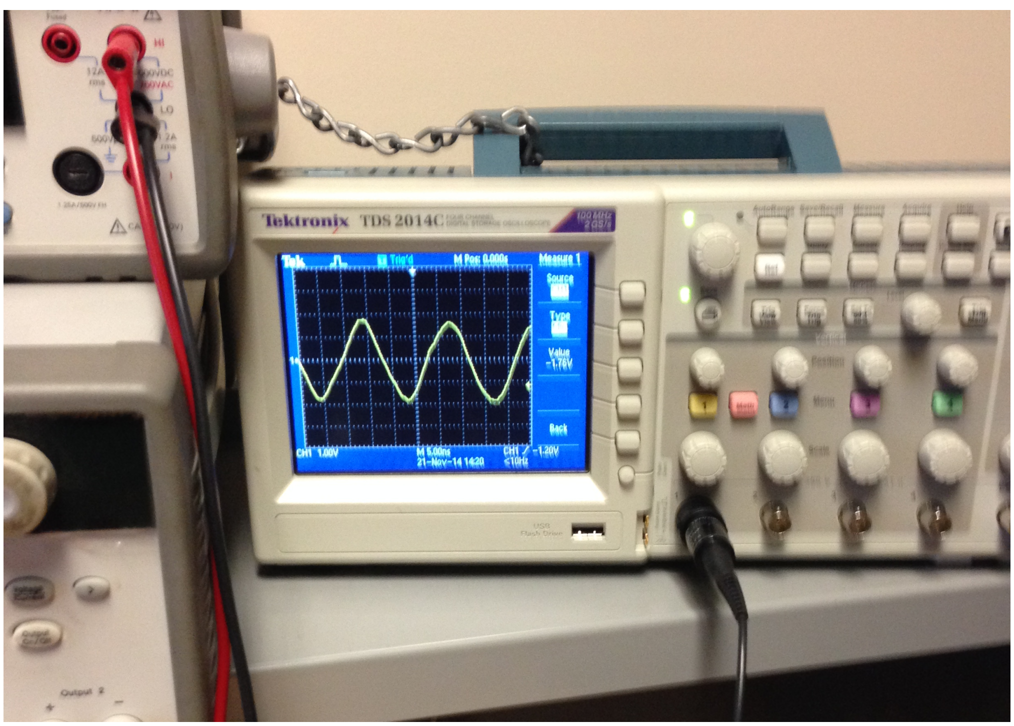
$$(x B_0) = 31.65\times10^{3}\,T$$

$$x = 0.949$$ ← Coupling coefficient

$x N_T = 106.34\,t$ EFFECTIVE TURNS

$N_T = 112$ theoretical turns

Induced Voltage Magnitude Calculation



Induced AC Voltage at Full-Speed Operation

5.Altium Design

For the Altium design footprints, schematics and net lists, refer to the end of this report. All preliminary design specifications and simulation data are included.

6. Conclusion

The following are the teams conclusions.

Lessons Learned

In conclusion, since this project encompassed a large amount of the EE221 subject material, it allowed the team to apply these concepts to a single project to demonstrate overall competency in the calculation of AC/DC steady state measurements, filter design techniques, integration of electromagnetic induction principles, and soldering. The key motivation was to successfully apply this array of skills in a creative way to build a functioning electro-mechanical machine with basic electronic control. The cross-discipline teamwork enriched our troubleshooting and problem solving skills in both a theoretical and practical hands-on way.

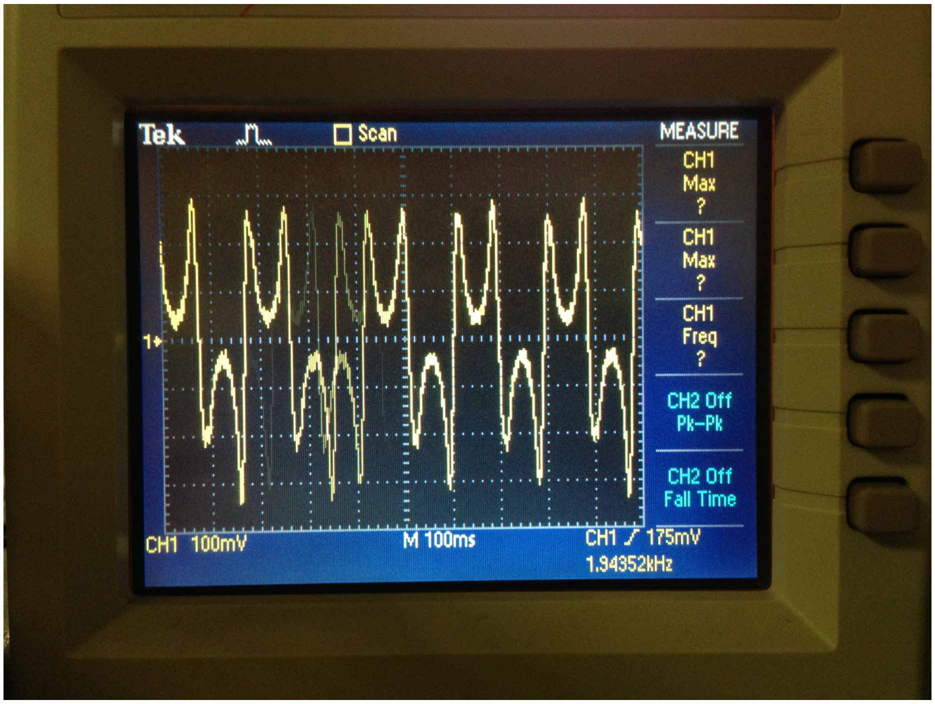
During this lab it was confirmed that a large majority of the analysis principles used are reliable both in circuit analysis and in experimental measurement. Any discrepancies can be explained by systematic and experimental errors in equipment limitations. External factors are also present that will cause variation in the circuit quantities. For one, the resistors used had variances in their allowable tolerances, as well as temperature influence, all of which will introduce deviations from expected values. Non-repeatability and extended time between measurements may cause alterations or disturbances in the initial circuit condition and thus cause measurements to not add up perfectly. All in all, the experiment helped build experience in testing and measurement of single-phase equipment.

Problems Encountered

1. Timing and Generator Prime Mover Response: We successfully were able to maintain a desired voltage, although there was some lag in system response. This can be attributed to latency in the software as well as other experimental and code implantation factors.

2. Weak Flux Linkage and High Magnetic Reluctance Path: Because the design was of the salient pole type, the magnetic circuit path inherently had high levels of flux reluctance and thus required more turns to compensate for the weak flux linkage in the AC coils.

3. Harmonics (3^{rd}) Distorted MMF: Along with having an innate weak flux linkage, the PM rotor also had a distorted field due to the combination of magnets used. This caused a third harmonic to be reflected into the induction process and thus modified the expected sinusoidal voltage. As a result the waveform still appears as a sine wave but with a higher than normal crest factor.



Third Harmonic Superimposed Signal

4. PWM Code and Speed Regulation Over Full Voltage Range: One problem encountered dealt with defining the machine upper and lower operating voltage limits and correlating this range to the applied PWM signal. The problem was resolved by running the machine at both “over” and “under” speed conditions then setting up a proportion with the corresponding induced voltage to derive the incremental scaling factor.

7.Group Members

The following is the proposed group members for this project.

Tone Pondaharn, Clinton Bess, Dane Gentry, and Octavio Gonzalez

8. Roles

The following is a brief description on the technical roles for the group members.

Tone Pondaharn- Microcontroller application and integration engineer

1. Tone's roles will include defining the microcontroller specifications, operation modes, I/O, pin-out, and CpE Altium design requirements.

Clinton Bess- Microcontroller programing and feedback controls engineer.

1. Clinton's roles will include writing the algorithms and necessary C code for the analog feedback control to be used in regulating the output frequency of the AC generator via PWM.

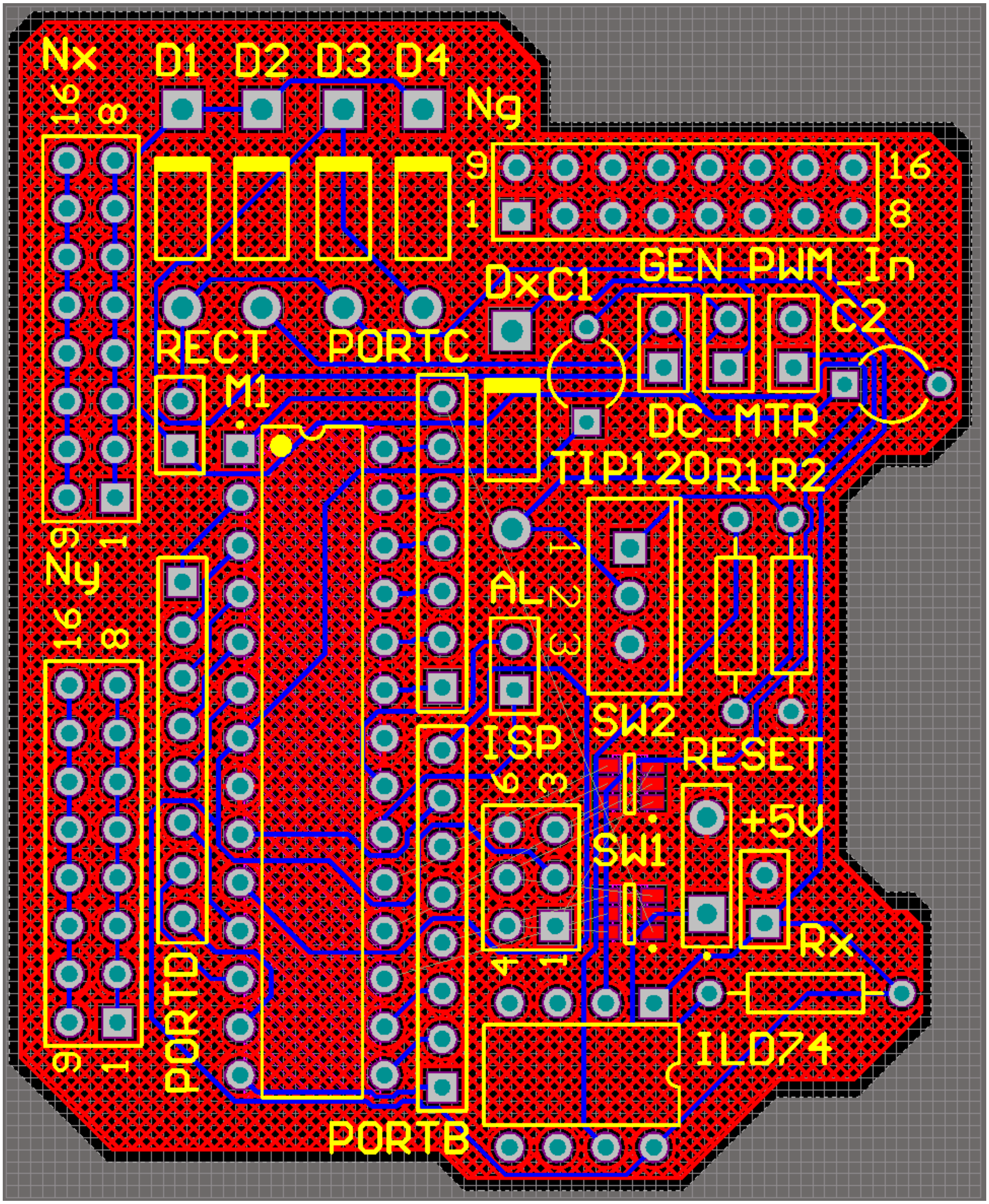
Dane Gentry- Electronic solid state design and controls engineer.

1. Dane's roles will include designing the power circuity for the DC controlled prime mover, semiconductor applications, protection, filtering, and associated Altium design requirements.

Octavio Gonzalez- Electro-mechanical machine const/design and test engineer.

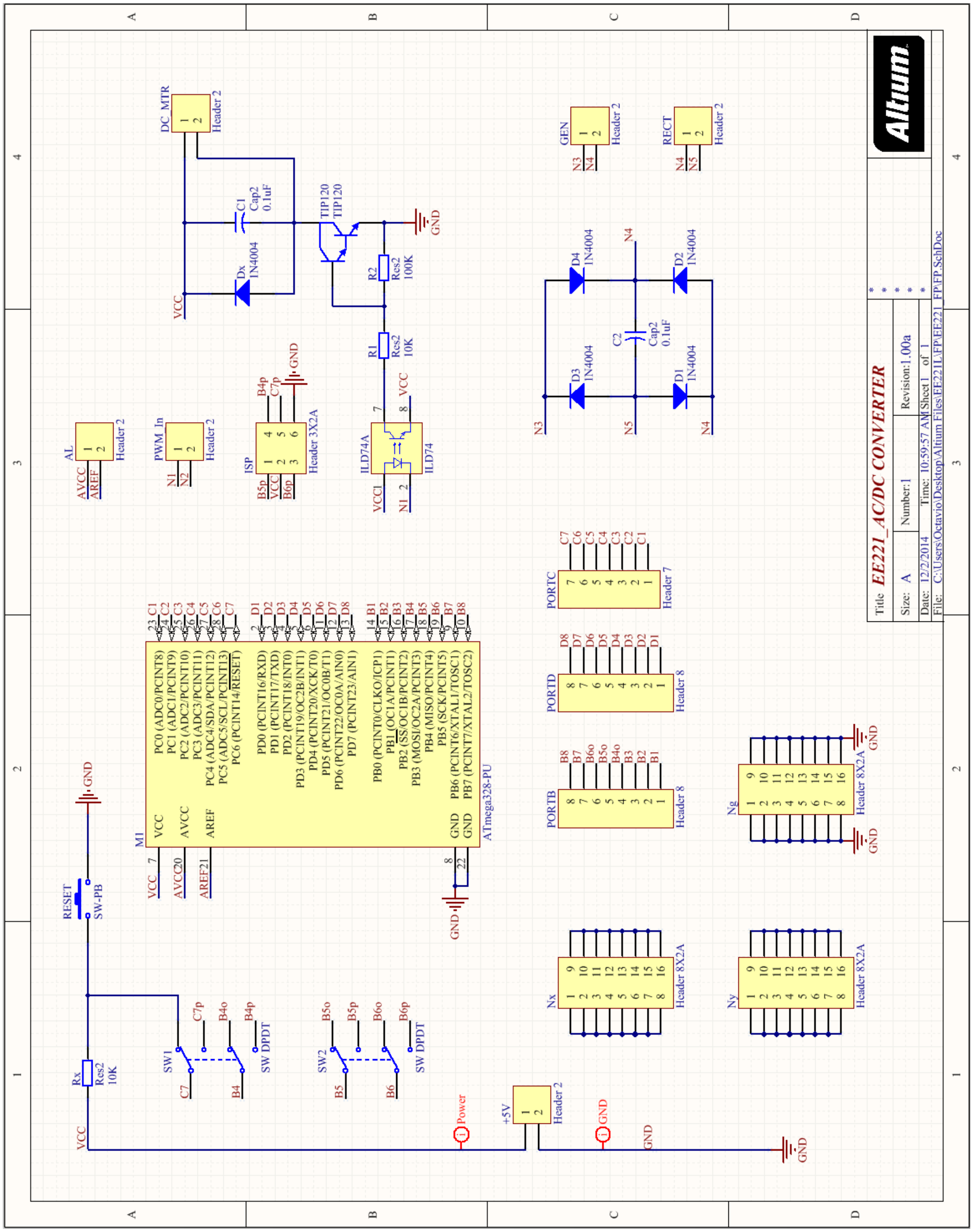
1. Octavio's roles will include designing the rotary converter, testing of the machine, project oversight as well as documentation.

Altium PCB Footprint:



AC/DC Rotary Converter PWM and AVC PCB Footprint

Altium Schematic:



AC/DC Rotary Converter PWM and AVC Combined Schematic

<u>Altium Netlist:</u>

AC/DC Rotary Converter PWM and AVC PCB Project Netlist

```
[
Dx
DO-41
1N4004

[
Nx
HDR2X8_
CEN
Header
8X2A

]
[
C2
CAPR5-4X
5
Cap2

]
[
AL
HDR1X2
Header 2

]
[
TIP120
221A-02
TIP120

]
[
SW2
SOT23-6_
N
SW DPDT

]
[
SW1
SOT23-6_
N
SW DPDT

]
[
Rx
AXIAL-0.4
Res2

]
[
RESET
SPST-2
SW-PB

]
[
R2
AXIAL-0.4
Res2

]
[
R1
AXIAL-0.4
Res2

]
[
PORTD
HDR1X8
Header 8

]
[
PORTC
HDR1X7
Header 7

]
[
PORTB
HDR1X8
Header 8

]
[
M1
28P3
ATmega32
8-PU

]
[
ISP
HDR2X3_
CEN
Header
3X2A

]
[
ILD74
DIP8
ILD74

]
[
C1
CAPR5-4X
5
Cap2

]
[
+5V
HDR1X2
Header 2

]
[
RECT
HDR1X2
Header 2



]
[
PWM_In
HDR1X2
Header 2

]
[
Ny
HDR2X8_
CEN
Header
8X2A

]
[
Ng
HDR2X8_
CEN
Header
8X2A

]
[
GEN
HDR1X2
Header 2

]
[
D3
DO-41
1N4004

]
[
D4
DO-41
1N4004

]
[
D1
DO-41
1N4004

]
[
D2
DO-41
1N4004

]
[
DC_MTR
HDR1X2
Header 2

]
(
VCC
M1-7
Dx-2
ILD74-8
ILD74-1
ISP-2
Rx-1
+5V-1
C1-1
DC_MTR-
1
)
(
NetRESET
_1
SW1-2
Rx-2
RESET-1
)
(
NetR1_2
TIP120-1
R1-2
R2-1
)
(
NetNy_9
Ny-12
Ny-9
Ny-11
Ny-15
Ny-16
Ny-13
Ny-14
Ny-10
)
(
NetNy_1
Ny-4
Ny-1
Ny-3
Ny-7
Ny-8
Ny-5
Ny-6
Ny-2
)
(
NetNx_9
Nx-12
Nx-9
Nx-11
Nx-15
Nx-16
Nx-13
Nx-14
Nx-10
)
(
NetNx_1
Nx-4
Nx-1
Nx-3
Nx-7
Nx-8
Nx-5
Nx-6
Nx-2
)
(
NetILD74_
7
ILD74-7
R1-1
)
(
NetC1_2
Dx-1
TIP120-2
C1-2
DC_MTR-
2
)
(
N5
RECT-2
D1-1
C2-2
D3-1
)
(
N4
RECT-1
D1-2
D2-2
D2-1
C2-1
D4-2
GEN-2
)
(
N3
GEN-1
D3-2
D4-1
)
(
N2
PWM_In-2
)
(
N1
ILD74-2
PWM_In-1
)
(
GND
M1-8
M1-22
ISP-6
Ng-1
TIP120-3
Ng-2
Ng-9
Ng-10
Ng-3
Ng-11
Ng-4
RESET-2
Ng-5
Ng-6
+5V-2
R2-2
Ng-8
Ng-14
Ng-12
Ng-13
Ng-7
Ng-15
Ng-16
)
(
D8
PORTD-8
M1-13
)
(
D7
M1-12
PORTD-7
)
(
D6
PORTD-6
M1-11
)
(
D5
PORTD-5
M1-6
)
(
D4
PORTD-4
M1-5
)
(
D3
PORTD-3
M1-4
)
(
D2
PORTD-2
M1-3
)
(
D1
PORTD-1
M1-2
)
(
C7
M1-1
SW1-1
PORTC-7
)
(
C7P
ISP-5
SW1-3
)
(
C6
M1-28
PORTC-6
)
(
C5
M1-27
PORTC-5
)
(
C4
M1-26
PORTC-4
)
(
C3
M1-25
PORTC-3
)
(
C2
M1-24
PORTC-2
)
(
C1
M1-23
PORTC-1
)
(
B8
M1-10
PORTB-8
)
(
B7
M1-9
PORTB-7
)
(
B6
M1-19
SW2-5
)
(
B6P
ISP-3
SW2-6
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B6O
PORTB-6
SW2-4
)
(
B5
M1-18
SW2-1
)
(
B5P
ISP-1
SW2-3
)
(
B5O
PORTB-5
SW2-2
)
(
B4
M1-17
SW1-5
)
(
B4P
ISP-4
SW1-6
)
(
B4O
PORTB-4
SW1-4
)
(
B3
M1-16
PORTB-3
)
(
B2
M1-15
PORTB-2
)
(
B1
M1-14
PORTB-1
)
(
AVCC
M1-20
AL-1
)
(
AREF
M1-21
AL-2
)
```
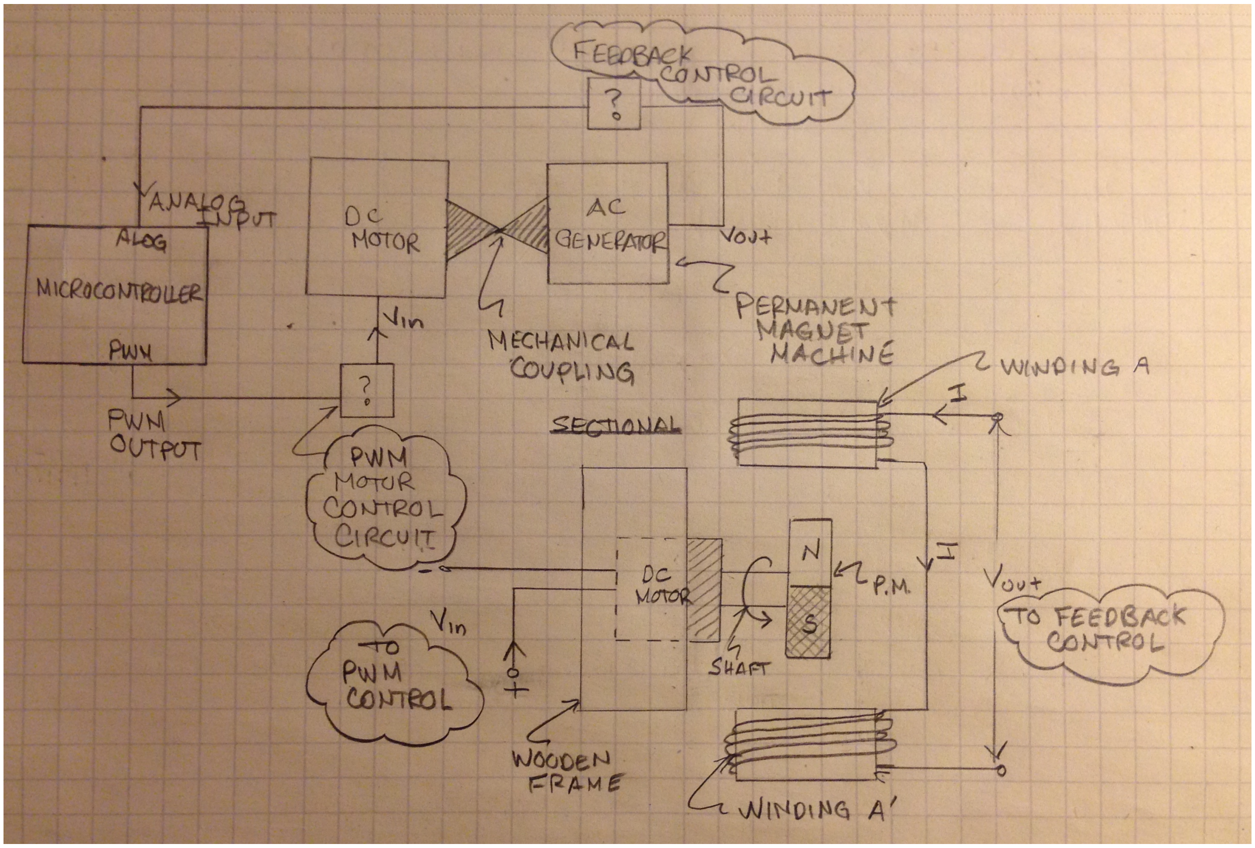
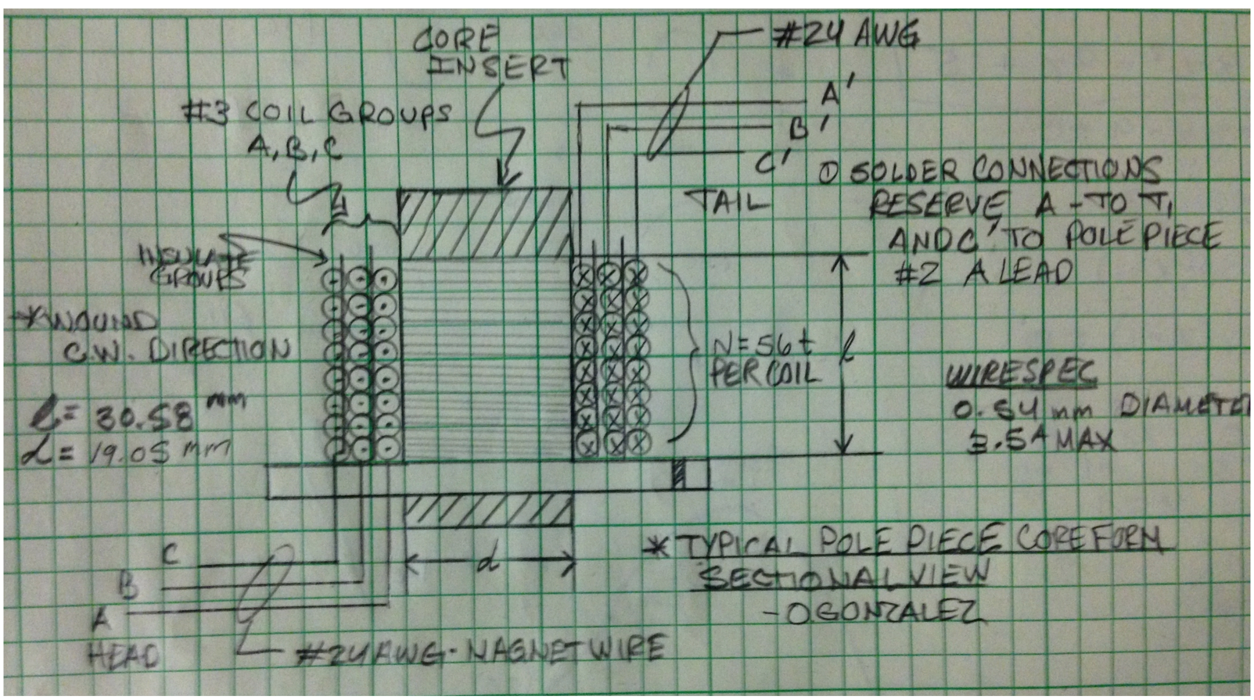

Diagrams:

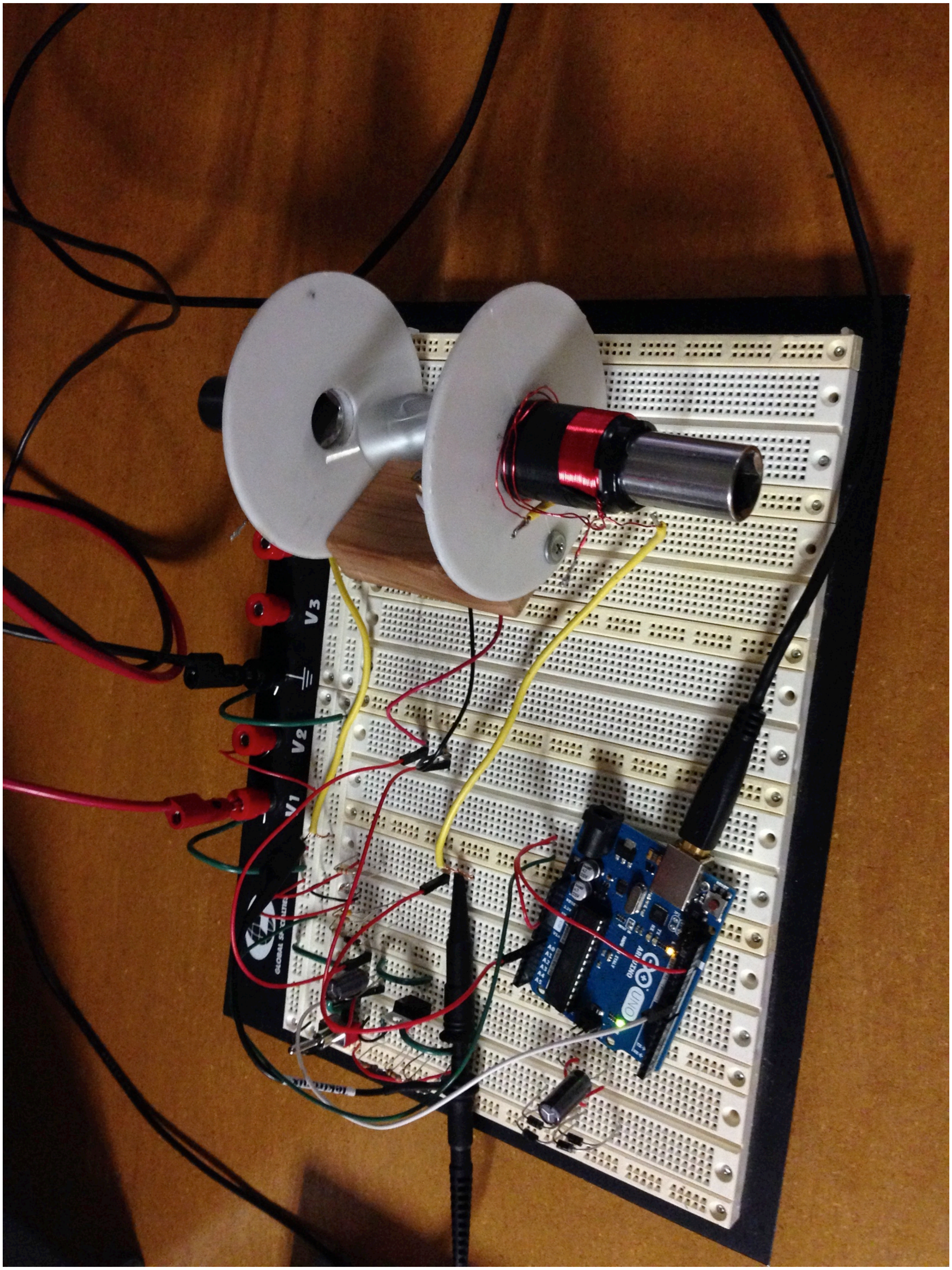


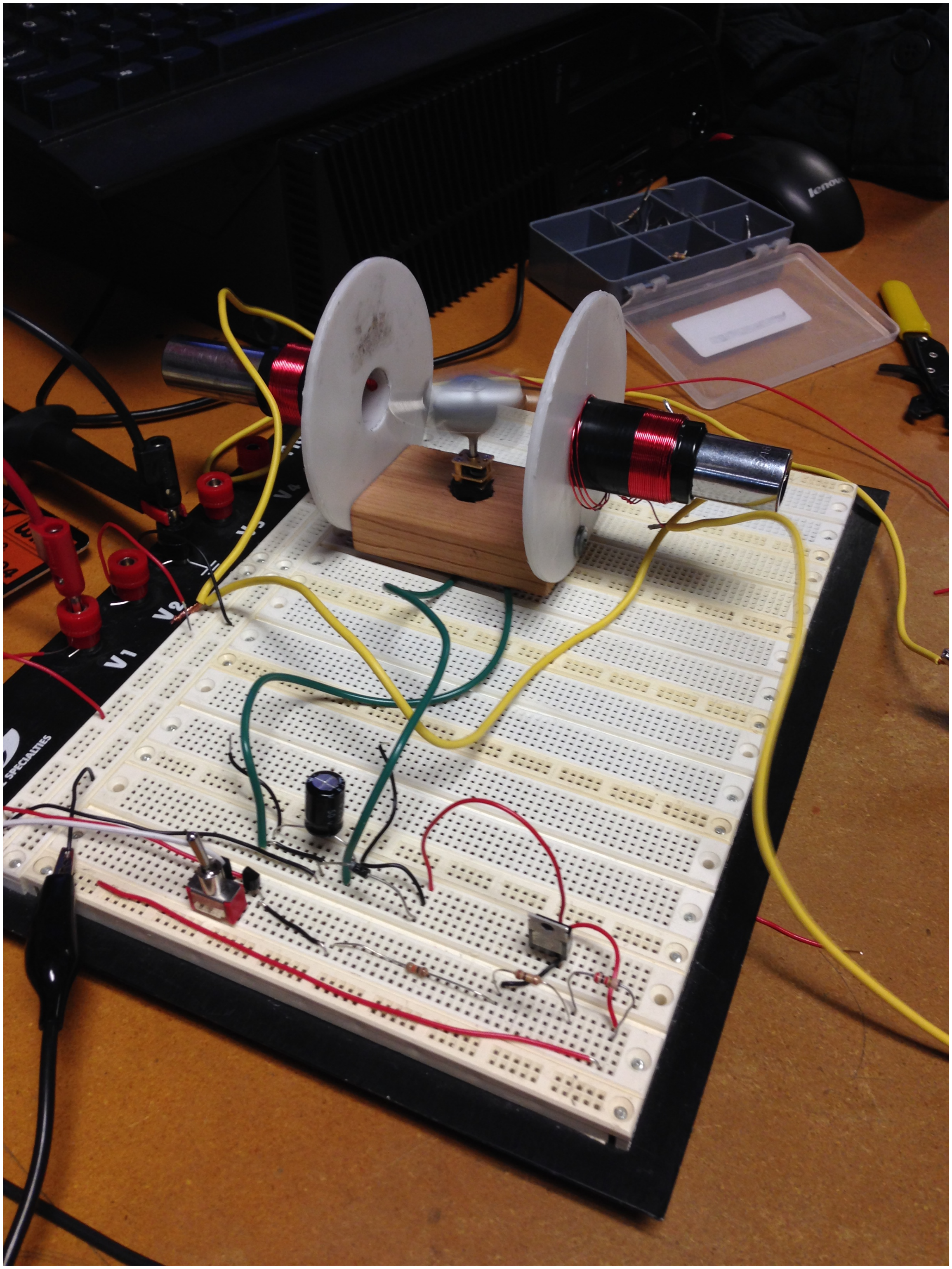
AC/DC Rotary Converter PWM and AVC Proposal Block Diagram



Winding Construction Diagram

<u>Assembled Project:</u>




V1
V2