

COMPARATIVE MOTOR DESIGN

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Abstract

In recent years, there has been an interest in using copper rotors in induction machines instead of aluminum rotors. This project compares the performance of one commercially available aluminum induction machine and one fabricated copper machine. In order to protect users' safety, an overcurrent protection circuit is included in this project in addition to the rotor design.

Contents

1. Introduction	1
1.1 Purpose	1
1.2 Project Functions	1
1.3 Blocks	1
2 Design	3
2.1 General Design Alternatives	3
2.2 Equations and Simulations	4
2.3 Detailed Description of Design	8
2.4 Schematics and Flow Diagram of Protection Circuit.....	10
3. Design Verification.....	12
3.1Current Sensor Functionality	12
3.2 Final Circuit	13
3.3 Rotor Testing	13
4. Costs	16
5. Conclusion	17
5.1 Accomplishments	17
5.2 Uncertainties	17
5.3 Ethical considerations.....	18
5.4 Future work	18
References	19
Appendix A Requirement and Verification Table.....	20
Appendix B Sample Motor Parameter Calculation (Motor 1).....	22
Appendix C Current Sensor Data Analysis.....	25
Appendix D Motor Load Test Data	26
Appendix E Microcontroller Code.....	27

1. Introduction

1.1 Purpose

According to the material properties, copper rotors are theoretically more efficient than aluminum rotors. However, there needs to be a balance between cost and efficiency for induction motor manufacturers. The project's results will provide an industrial reference on induction motor material selection.

To ensure a safe testing environment, we will also design and implement an over current protection circuit to complement our motor. The circuit would warn users when the current is higher than expected, and it would cut the power source to the motor when the current gets to a magnitude that is harmful to the human body.

1.2 Project Functions

Our project begins with two small commercial AC induction motors (1/4 HP, Grainger #3N843). After obtaining testing data and measurements for both original motors, we etched away one of the rotors' conducting material by using sodium hydroxide (NaOH) solution, then filled the rotor slots with copper bars. The performances and testing data for both the original and fabricated rotors were analyzed. A finite element analysis software—JMAG was used to run simulation for both rotors. In addition, the rotor lamination was changed in JMAG to obtain an optimized performance result.

The output of the protection circuit depends on the magnitude of current. There are different levels of warnings. When the detected current is above the rated current but still relatively low, the circuit should give some warnings to get users attention to let them know the situation. When the current is large enough to be harmful, the circuit should immediately trip the circuit.

1.3 Blocks

The design was broken into different modules. The modules we decided to implement and their functions are listed below.

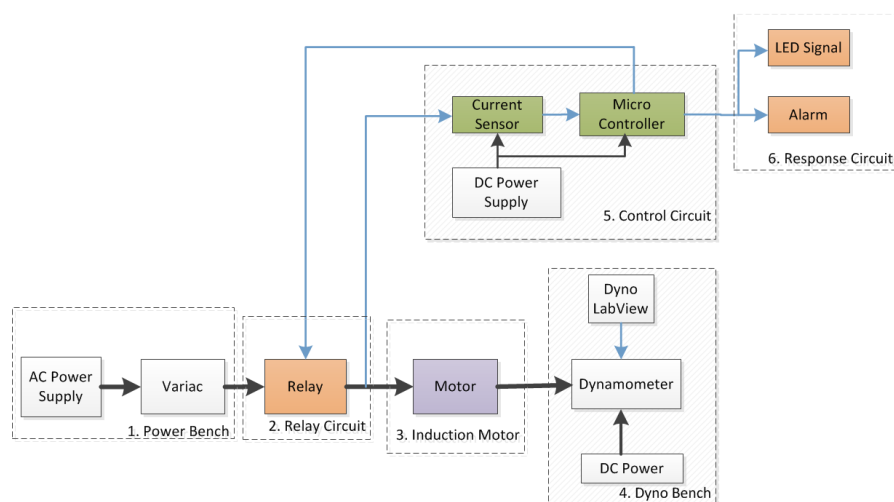


Figure 1. Block Diagram

1.3.1. Power Bench

This module provides 0-230 V AC power to the induction motor through Variac, which can adjust the voltage input.

1.3.2. Relay Circuit

This module is straightforward. As soon as the control unit decides that the current is high enough and sends trip signal to the tripping module, this module needs to cut the power supply.

1.3.3. Induction Motor

The AC induction motor used for fabrication is a current selection 1/4 HP motor, Grainger category number #3N843 (commercially discontinued).

1.3.4. Dyno Bench

- DC Power: the ± 120 V DC supply provides power up to 24 kW. This DC Power provides energy to the Dyno Bench.
- Dyno LabView: This is a LabView program to control the Dynamometer. This program is available to us through the ECE 431 course package. It inputs control signals (speed/ torque) to the dyno, which provides a specific speed/torque value for us to take reference.
- Dynamometer: this device is used for measuring force, torque, or power. Our motor as a rotating prime mover can be calculated by simultaneously measuring torque and rotational speed (RPM). In our experiment, the dynamometer is driven as an absorption or passive dynamometer, in another word, the load.

1.3.5. Control Circuit

- Current Sensing Module
This module needs to be able to measure the current and outputs some values that are accurate and can be used by the control unit. The relationship between the current being measured and the output should be consistent and reliable. It should also be sensible enough to distinguish small current changes.
- Control Unit
This module is the core of the circuit. The output of the current sensing module will be used as an input to the control unit. The control unit will then use that value to determine which warning to send out to the users. It also needs to continuously recheck the input value since the current value might change anytime.

1.3.6. Response Circuit

- Warning Module
This module has the responsibility to let users know when the current is in unfavorably high ranges. Since the running motor will be producing a lot of noise and getting most of the attention, the most important thing is that the warnings are noticeable.

2 Design

2.1 General Design Alternatives

2.1.1 Current Sensor

There were several current sensors to choose from. The CSA-1VG-SO has a high sensitivity but cannot handle the high current values. FW BELL's current sensors are very accurate and can test the current in desired range, but they are also much more expensive. We eventually narrowed down to Allegro's Hall Effect - based ACS758 current sensor. It can handle very high current values. Furthermore, it has an acceptable sensitivity (40 mV/A) with a reasonable price. The only problem is that the two pins that the measured current goes through are very large physically and do not fit into normal circuit boards. However, with all the benefits mentioned, we chose ACS758 over others and decided to use alligator clips to connect between the two large pins and the circuit board.

2.1.2 Microcontroller

The microcontroller picking process was a lot easier. The functions needed in this project are quite basic. The most important function is analog to digital conversion with high accuracy. The PIC16F887 microcontroller is a very popular one and we considered it first. Since it has a 10-bit analog to digital conversion function while many others only support 8-bit, we decided to go ahead and use PIC16F887.

2.1.3 Tripping Module

It was a struggle trying to find a chip that would take signals from the microcontroller to trip the circuit. At first we considered circuit breakers. While they certainly have the ability to trip the circuit, their rated current for tripping is predetermined. This defeats the purpose of having the microcontroller. Then we moved on to contactors. Contactors use a control signal to decide whether to trip. However, because contactors are mostly used for very large systems with large current and voltage values, the coil voltage is usually 220 V or 230 V, which is obviously too high for the microcontroller. After further research, we found relays that are suited for lower rated purposes. The requirements for the relays are 5VDC coil voltage and at most 20 mA coil current due to the limitations of PIC16F887. We eventually decided to go with ATX269TH.

2.1.4 Rotor Fabrication

The selection of conducting material is one of the major concerns in rotor casting. Aluminum rotors are widely used in the industry field due to its low cost and relatively high efficiency. To get a better design flexibility and more compact motor than the aluminum one, materials that have a higher conductivity are what we are looking for. Due to its high conductivity ($\sigma_{Cu} = 5.96 \times 10^7 \text{ S/m}$ at 20 °C) compared to aluminum ($\sigma_{Al} = 3.5 \times 10^7 \text{ S/m}$ at 20 °C), copper has the potential for replacing the commonly used conducting materials.

The two choices for copper rotor fabrication are copper casting and copper bars insertion. Since copper has a high melting point, 1085 °C, copper casting is only viable in foundries, in which case we cannot manage due to the time frame of the senior design course. Therefore we chose the second option: copper bars insertion and welding the ending rings, both of which could be done in the ECE machine shop.

2.2 Equations and Simulations

2.2.1 Motor Parameters Calculation and test circuit

In order to calculate motor parameter, a set of tests needs to be performed on the machine. These tests were performed on all three rotors (Prime rotor 1, prime rotor 2, and fabricated copper rotor).

- **DC Test:** Obtaining *stator resistance* r_1 for each phase.
- **Open Circuit Test:** Obtaining *core loss (referred to stator)* r_c and *magnetizing reactance (referred to stator)* x_m .
- **Short Circuit Test:** Obtaining R_r' (rotor single-phase winding and external resistance), x_1 - stator single phase leakage reactance, x_2 - rotor single phase leakage reactance.
- **Load Test:** Obtaining the experimental torque speed curve.

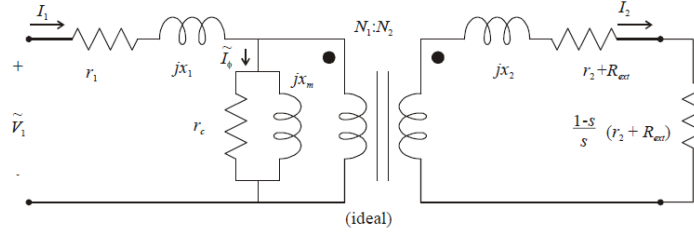


Figure 2. Induction Motor Equivalent Circuit ^[1]

Calculation Procedure

i. Preliminary Calculation

From DC Test:

$$R_s = \frac{V_{DC}}{I_{DC}} \quad (1)$$

$$r_1 = R_s / 2 = \frac{1}{2} R_s \quad (2)$$

From No Load Test (Assume $r_1 = 0, X_1 = 0$):

$$r_c = \frac{V_{NL}^2}{P_{NL}} \quad (3)$$

$$Q_{NL} = \sqrt{(\sqrt{3} V_{NL} I_{NL})^2 - P^2} \quad (4)$$

$$X_m = \frac{\left(\frac{V_{NL}}{\sqrt{3}}\right)^2}{\frac{1}{3} Q_{NL}} = \frac{V_{NL}^2}{Q_{NL}} \quad (5)$$

Blocked Rotor Test (Assume $X_m \rightarrow \infty, r_c \rightarrow \infty$)

$$R'_r = \frac{P_{BR}}{3I_{BR}^2} - r_1 \quad (6)$$

$$Q_{BR} = \sqrt{(\sqrt{3}V_{BR}I_{BR})^2 - P^2} \quad (7)$$

$$X_1 + X'_2 = \frac{Q_{BR}}{3I_{BR}^2} \quad (8)$$

Assume NEMA A connection, then $X_1 = X_2$.

ii. Iteration Calculation

No Load Test (Use r_1 and X_1 as calculated in procedure i):

Let X_m/r_c be Z_{eq} , then

$$P_{NL} = 3I_{NL}^2(r_1 + R_{eq}) \quad (9)$$

$$R_{eq} = \frac{P_{NL}}{3I_{NL}^2} - r_1 \quad (10)$$

$$Q_{NL} = 3I_{NL}^2(X_1 + X_{eq}) \quad (11)$$

$$X_{eq} = \frac{Q}{3I_{NL}^2} - X_1 = r_c + jX_m \quad (12)$$

Blocked Rotor Test (Use X_m and r_c as obtained in current iteration):

$$I_{BR} = I_{BR} \angle I_{BR} \quad (13)$$

Let V_1 be the voltage across r_1 and X_1 , V_2 be the voltage across R'_r and X'_2 .

$$V_1 = I_{BR} \angle I_{BR} (r_1 + jX_1) \quad (14)$$

$$Q_{NL} = 3I_{NL}^2(X_1 + X_{eq}) \quad (15)$$

$$V_2 = \frac{V_{BR}}{\sqrt{3}} - V_1 \quad (16)$$

$$\frac{V_2}{I_{BR}} = R_r' + jX_2' \quad (17)$$

* **Note:** repeat the iteration steps until the result for each parameter falls within $\pm 5\%$ range.

2.2.2 Motor Torque Calculation

According to [3], the theoretical torque is:

$$T_{th} = \frac{s|V_1|^2 R_r'}{\omega_e [(r_1 s + R_r')^2 + (X_1 + X_2')^2 s^2]} \times \frac{3P}{2} \quad (18)$$

ω_r is the mechanical rotor speed:

$$\omega_r = 60\pi(1 - s) = \frac{\omega_e}{\frac{P}{2}}(1 - s) \quad (19)$$

ω_e is the speed of revolving magnetic field (synchronous speed):

$$\omega_e = 60 * 2\pi \frac{rad}{s} = 3600RPM \quad (20)$$

2.2.3 Motor Performance Simulation

A finite element analysis software JMAG is used to simulate the performance of induction motor. Two sets of simulation are performed: original lamination with different cage materials, and different lamination with aluminum cage only.

i. Al & Cu Torque vs. Speed in Original Lamination

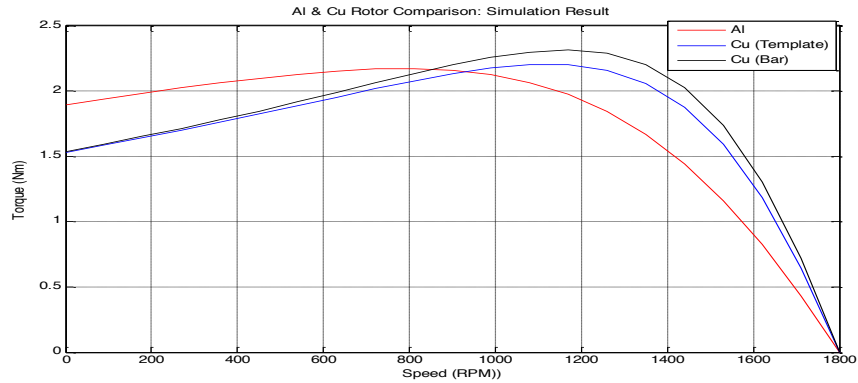


Figure 3. Al vs. Cu rotor comparison: Al (Red); Cu (Blue, Template): the simulation that uses the rotor's original parameters; Cu (Black, Bar): the simulation that uses the copper bar parameters, which is the case when using casting method.

ii. Lamination Comparison with Aluminum Cage

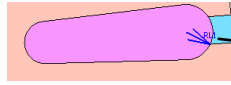


Figure 4. Bar outer radius (RL1)

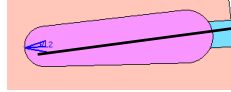


Figure 5. Bar inner radius (RL2)

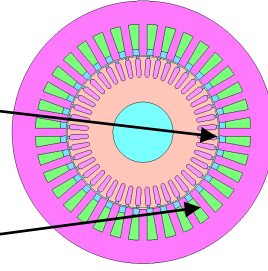


Figure 6. Induction motor cross-section view

The only two variables in rotor lamination that affect motor performance are bar outer radius (RL1) and bar inner radius (RL2). In simulation, both variables are varied individually with a step difference of $\Delta_{RL1} = 0.03 \text{ mm}$ and $\Delta_{RL2} = 0.1 \text{ mm}$. The comparison graphs are listed below:

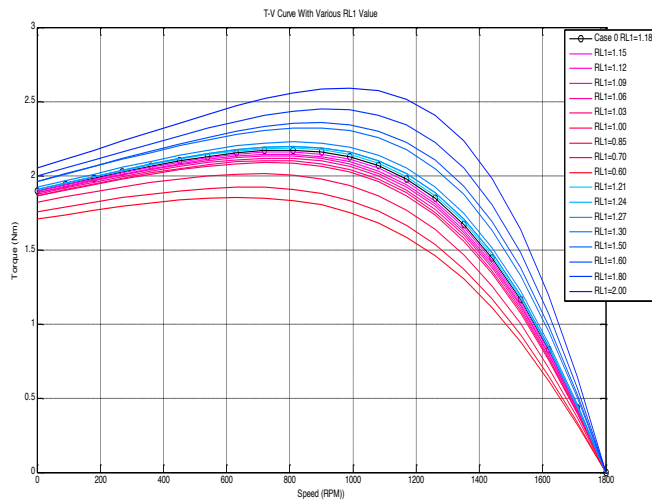


Figure 7. Torque vs. Speed curve when using RL1 as the only Variable

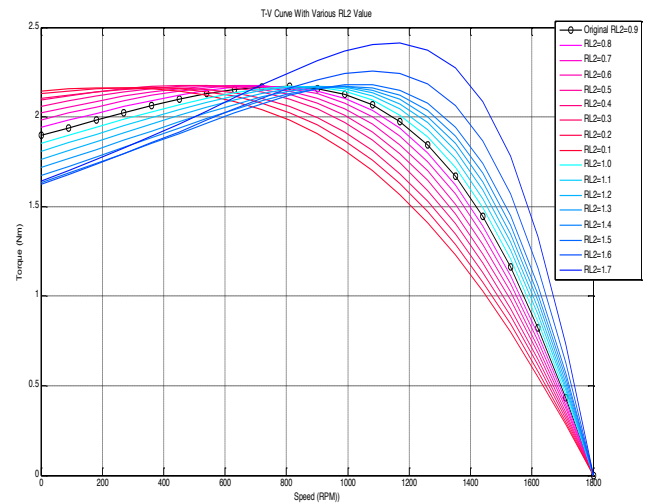


Figure 8. Torque vs. speed curve when using RL2 as the only Variable

From Figure 7, as RL1 increases, the maximum torque increases as well as the speed at which maximum torque is reached, but the starting torque increases as well. From Figure 8, as RL2 increases, the maximum torque increase as well as the speed at which maximum torque is reached, and the starting torque decreases. Therefore, the optimized case is reached when selecting RL1 and RL2 at their maximum value: $RL1 = 2 \text{ mm}$, and $RL2 = 1.7 \text{ mm}$; the worst case is reached when selecting RL1 and RL2 at their minimum value: $RL1 = 0.6 \text{ mm}$, and $RL2 = 0.1 \text{ mm}$. The lamination schematics for these three cases are shown in Figure 9, 10, and 11. Their simulated torque vs. speed curve is shown in Figure 12.

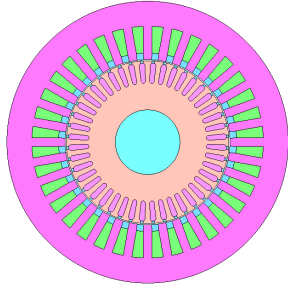


Figure 9. Original Motor Cross-section View

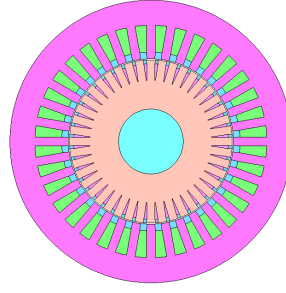


Figure 10. Worst Case Cross Section View

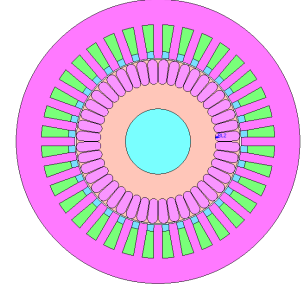


Figure 11. Optimized Case Cross Section View

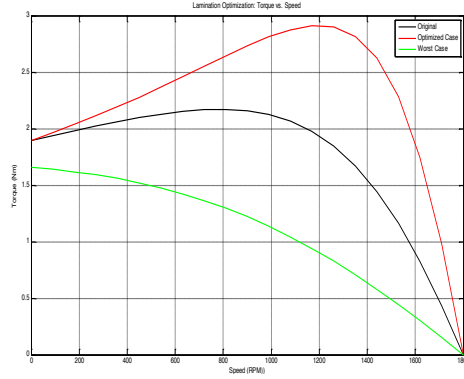


Figure 12. Torque vs. Speed: Lamination Comparison

*Original (Reference) Case:

RL1= 1.18 mm, RL2 = 0.9mm

*Extreme Cases:

Optimized Case: RL1 = 2mm,
RL2 = 1.7 mm

Worst Case: RL1= 0.6mm,
RL2 = 0.1mm

2.3 Detailed Description of Design

2.3.1 Current Sensing Module

The design for the current sensing module is straightforward. Assuming that all three currents in the 3 phase system are balanced, only one of the three currents needs to be measured. Therefore, we only need one current sensor. When no current is detected, the current sensor will output $V_d/2 = 2.5$ V. Given the sensitivity 40 mV/A, we can derive the relation between the measured current and the output analog voltage:

$$V_{out} = 2.5 + 0.04 \times I_{measured} \quad (21)$$

This formula will be used several times later in this paper.

Wiring details are discussed here. Pin 1 (VCC) is connected to a 5 V power source. Pin 2 (GND) is connected to ground. The output analog voltage at pin 3 (Vout) is connected to analog input pin 2 (AN0) of the microcontroller. The current to be tested flows in at pin 4 (IP+) and flows out at pin 5 (IP-). The direction of the current is important because the chosen current sensor is bidirectional. If the direction

of the current is the opposite, the output analog voltage would be decreasing as current increases. Pin 5 is then connected to pin 5 of one of the relays.

2.3.2 Warning Module

After some discussions, we decided to have two levels of warning: a LED light and a buzzer. When the current is just a little over the rated current, the LED light would be turned on. When the current is in a larger range, the buzzer would sound to warn users. The important thing here is that the buzzer's sound need to be loud enough to overcome motor's operating noise to get users' attention. After testing with different resistors with the buzzer, I decided to use a 100 Ω resistor since the sound is loud enough to command attention but not annoying. The specific current ranges the LED and the buzzer operate in and wiring are discussed in the control unit section below.

2.3.3 Tripping Module

Since we need to trip currents in all three phases in order to cut power source to motor, three relays are needed. The relays are all 2-coil latch relays. Pins 4 and 9 are COMM. Pins 3 and 10 are normally closed (NC). Pins 5 and 8 are normally open (NO). When relays are in the state where COMM and NC pins are connected, if voltage is applied cross pins 1 and 12, COMM and NC would be disconnect and COMM and NO would be connected. When COMM and NO are originally connected, if voltage is applied cross pins 6 and 7, COMM and NO would be disconnected and COMM and NC would be connected.

To distinguish the two different modes, we decided to let currents flow through pins 3 and 4 and LED circuits go through pins 10 and 9. The key is that pins 3 and 4 and pins 9 and 10 are either both connected or both disconnected. Therefore, when currents are flowing through relays, the LED lights should be on. When relays switch modes to trip the circuit, the LED lights should be off. This way it is easier for people to see when tripping happens. Last but not least, voltage is applied across pins 6 and 7 to reset the relays when the microcontroller is reset.

Now we can discuss how to wire the tripping module after all the designs are finalized. Since all three relays are wired identically, only one is discussed in detail. The phase current goes in pin 4 and leaves from pin 3. Pin 10 is connected to a LED light, then a 100 Ω resistor, and then a 5 VDC voltage supply. Pins 7, 9 and 12 are connected to ground. Pin 1 takes the trip signal from the control unit. Pin 6 takes the reset signal from the control unit.

2.3.4 Control Unit

The very first design problem was how to divide up the current ranges for different outputs. Our original plan from the design review was 1.25/1.5/2 A for LED/buzzer/tripping. However, these cutoffs were rejected for several reasons. First of all, the absolute maximum current rating for the relays is 2 A. We were afraid that relays might be damaged if we accidentally raised current to a value greater than 2A during testing, so we lowered the third cutoff from 2 A to 1.9 A. Furthermore, it was really difficult for the microcontroller to distinguish 1.25 A and 1.5 A. When $I = 1.25\text{A}$, $V_{out} = 2.5 + 0.04 \times 1.25 = 2.55\text{ V}$. When $I = 1.5\text{A}$, $V_{out} = 2.5 + 0.04 \times 1.5 = 2.56\text{ V}$. Since ADC is in 10 bit, there are ($2^{10} - 1 = 1023$) different binary numbers to represent 0 to 5 V. Thus, the corresponding numbers are $\frac{2.55}{5} \times 1023 = 522$, and $\frac{2.56}{5} \times 1023 = 524$ for currents 1.25 A and 1.5 A, respectively. Because these two values are only 2 bits apart, along with some other minor errors from the current sensor as well as the

microcontroller, it was impossible to distinguish these two cutoffs. Therefore, we widened the gap by changing the first two cutoffs to 1 A and 1.5 A.

The program in the microcontroller is written in C. The actual functionalities are straightforward and easy to implement. The software flowchart is shown as Figure 14. The actual code is attached in Appendix E. The very first thing for the microcontroller is sending reset signal to relays to ensure that they are in NC mode. Then it takes in the analog voltage value and stores it in a variable. After that it calculates the corresponding voltage values for all three cutoffs 1/1.5/1.9 A. Then it checks if the stored voltage value is smaller than the voltage value for 1 A. If yes, do nothing. If not, it checks if the stored voltage value is smaller than the voltage value for 1.5 A. If yes, send power to light up the LED. If not, it checks if the stored voltage value is smaller than the voltage value for 1.9 A. If not, send power to turn on the buzzer. If not, send trip signal to the relays.

Lastly, the microcontroller wiring is described. A 1 k Ω resistor is put between the 5 VDC power supply and pin 1 (VPP) to reduce voltage. Pins 12 and 31 (VSS) is connected to ground. Pins 11 and 32 (VDD) is set to 5V. The microcontroller takes the analog voltage input at pin 2 (AN0). Pins 23-25 (RC4-6) are connected to pin 6 of the relays. Pins 35-37 (RB2-4) are connected to pin 1 of the relays. Pin 33 (RB0) is connected to the LED, followed by a 100 Ω resistor and ground. Pin 34 (RB1) is connected to the buzzer, also followed by a 100 Ω resistor and ground. The detailed schematics are shown in the next section as Figure 13.

2.4 Schematics and Flow Diagram of Protection Circuit

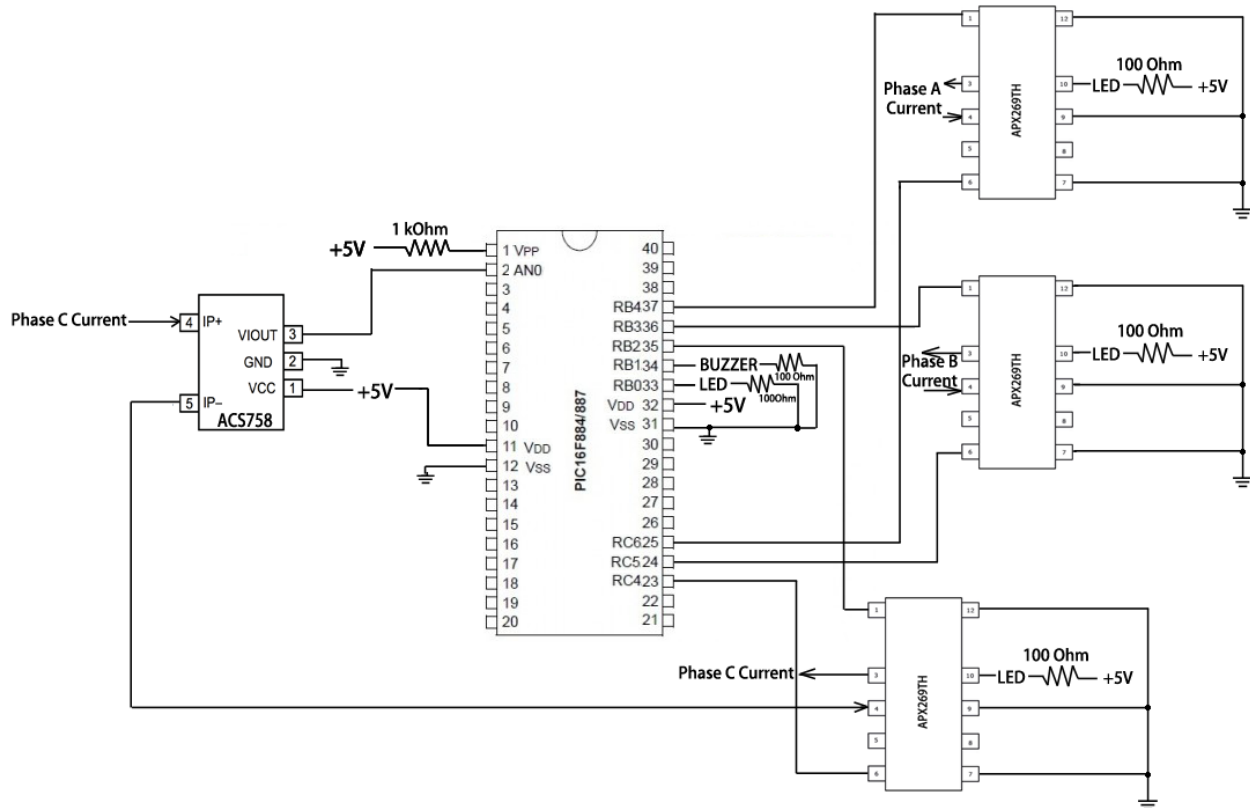


Figure 13. Schematics for Protection Circuit^{[2][3]}

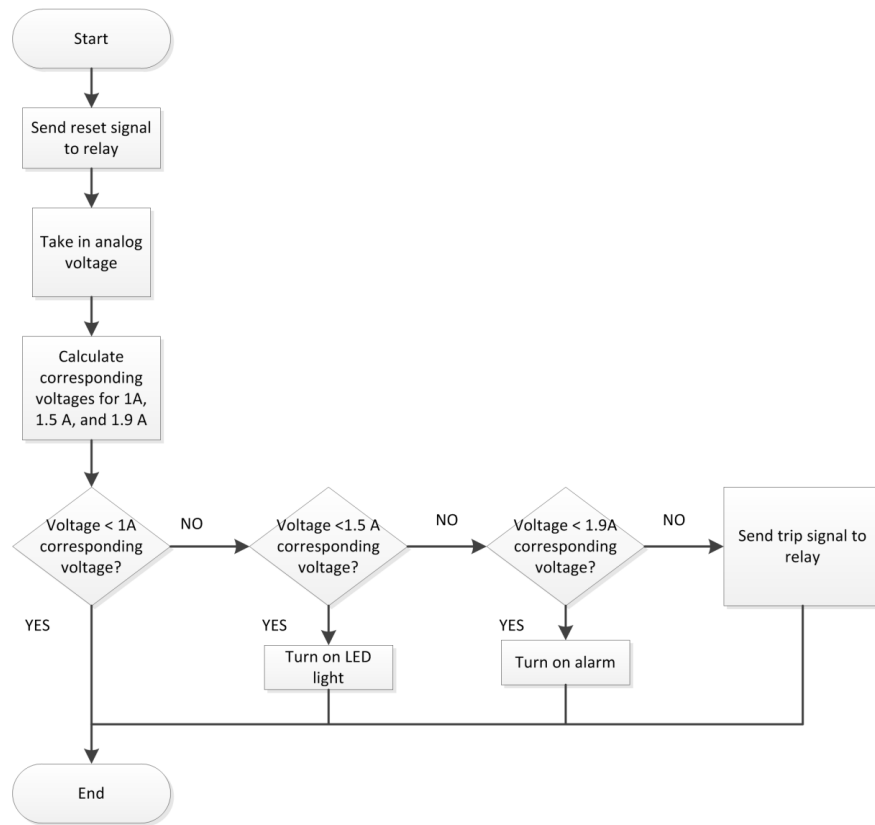


Figure 14. Flow Chart for Protection Circuit

3. Design Verification

This project's requirements and verifications are listed in Table 5 in Appendix A. All testing procedures and results are described in this section.

3.1 Current Sensor Functionality

Some testing was done to see how accurately the current sensor measured currents. We used bench current source to provide lin 0 A to 2 A in 0.1 A steps verified to within ± 0.001 A. Then we measured V_{out} in voltmeter mode to within ± 0.001 V. Recorded data points taken are in Table 6 in Appendix C. I is the input current and V is the output analog voltage. $V_{theoretical}$ is there to be compared with V . From the datasheet for the current sensor, when no current is supplied to the current sensor, the output voltage is $\frac{V_{dd}}{2} = 2.5$ V. The sensitivity of the current sensor is 40 mV/A. Therefore, Equation (21) is used to calculate the theoretical values of the output voltage. Figure 15 is the plot comparing actual and theoretical values.

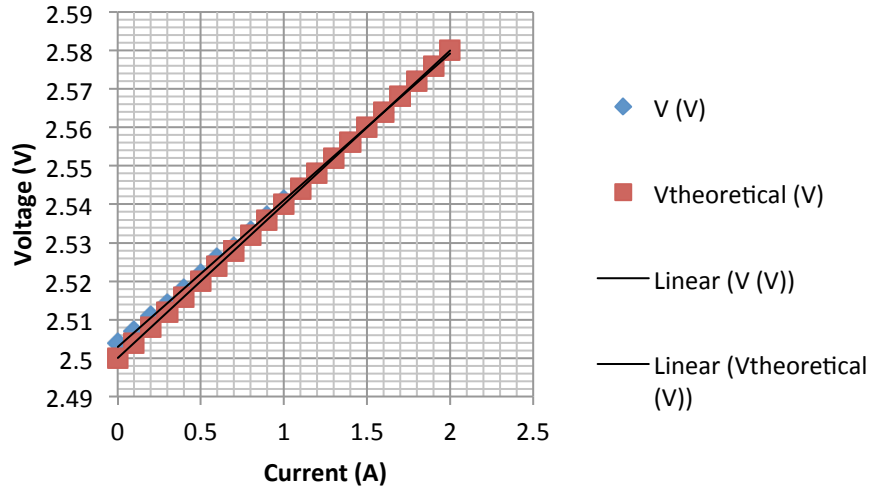


Figure 15. V_{out} vs. I Curve for Current Sensor

We then performed linear regression and the results are in Table 7, 8, 9 in Appendix C. Since R square (0.99955) is very close to 1 and standard error (0.000515) is basically 0, the regression is statistically significant. Therefore, V_{out} is indeed linear with I_{in} . This verifies requirement 1.

Now let us compare the intercept and slope values.

$$\text{Intercept error: } \frac{2.503 - 2.5}{2.5} = 0.12\%;$$

$$\text{Slope error: } \frac{0.04 - 0.038}{0.04} = 5\%$$

Since both the intercept and the slope are within 5% error, this satisfies requirement 2.

3.2 Final Circuit

We provided power to the circuit. All 3 LED lights connected to relays were all on. We were controlling the current that was going through the current sensor. We increased the current from 0 to 2 A in 0.1 A steps. Nothing was happening when the current was below 1A. As soon as the current hit 1 A, the red LED light connected to pin 33 of the microcontroller was turned on. Then when the current got to 1.5 A, the LED light was turned off and the buzzer was turned on. Finally when the current got to 2.0 A, we heard the tripping sound of the relays and those three LED lights were turned off. After a while, the motor stopped completely. This confirmed that the relays tripped the circuit correctly, which confirmed requirement 5.

Then we cut the power to the circuit. We waited a moment before providing power again to the circuit. All 3 LED lights connected to the relays were originally off. After about one second, they were turned on. This confirmed that the reset signals were sent when microcontroller was reset, which confirmed requirement 3.

We ran the same tests with 0.01A steps numerous times to get a better sense of exactly what current values triggered different levels of responses. The ranges of current values that triggered next level of responses were 1.00-1.05A for 1A, 1.4-1.55A for 1.5A, and 1.9-2.0A for 1.9A. Since all these ranges were in the range +/- 0.1A of the intended cutoffs, requirement 4 was verified as well.

3.3 Rotor Testing

After running all DC test, no load test, and blocked rotor test on the two reference motors, we calculated the performance parameters and listed them in Table 1.

Table 1. Reference Motors Parameters

	Motor 1	Motor 2	%diff
$R_1(\Omega)$	12.97	12.638	-2.56%
$R_c(\Omega)$	2296.49	2983.09	29.90%
$X_m(\Omega)$	197.733	195.535	-1.11%
$R_r'(\Omega)$	8.94	9.54	6.71%
$X_1/X_2'(\Omega)$	12.26	11.5	-6.2%

The load test gives experimental data points for the torque-speed curve. Figure 16 was obtained comparing experimental and theoretical curves for both motors.

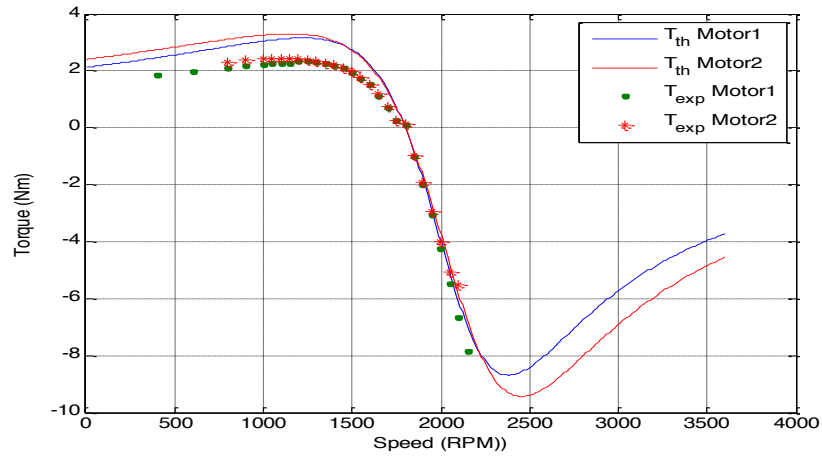


Figure 16. Reference Motors Torque-Speed Curve

Following the preliminary tests, we did a same set of performance tests on the motor with copper rotor inserted. Table 2 shows the comparison between the reference motor and the revised motor.

Table 2. Al vs. Cu Motor Parameters Comparison

	Al Rotor	Cu Rotor	%diff
$R_1(\Omega)$	12.970	12.567	-3.10%
$R_c(\Omega)$	2296.490	2243.570	-2.33%
$X_m(\Omega)$	197.733	202.119	2.21%
$R_r'(\Omega)$	8.940	9.262	3.60%
$X_1/X_2'(\Omega)$	12.260	16.874	37.63%

With the load tests, we obtained a set of data points for the torque-speed curve. Figure 17 was obtained comparing the experimental curve with the theoretical and simulation ones.

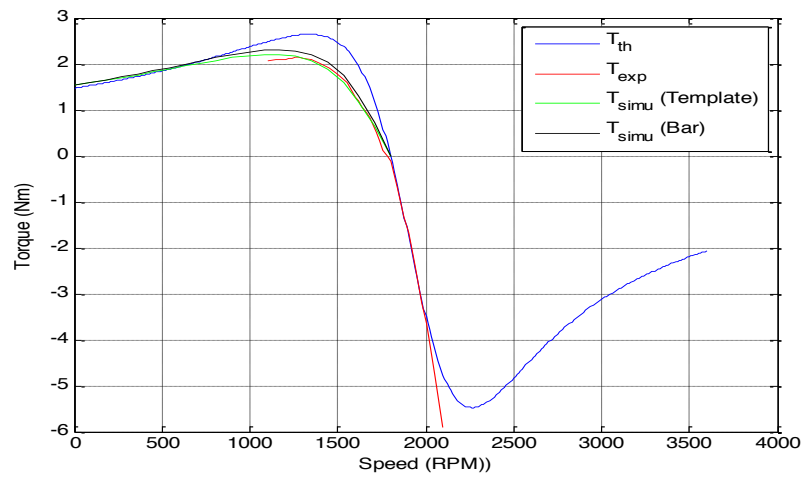


Figure 17. Copper Rotor Torque Speed Curve

The comparison between the aluminum and copper rotors is shown in Figure 18.

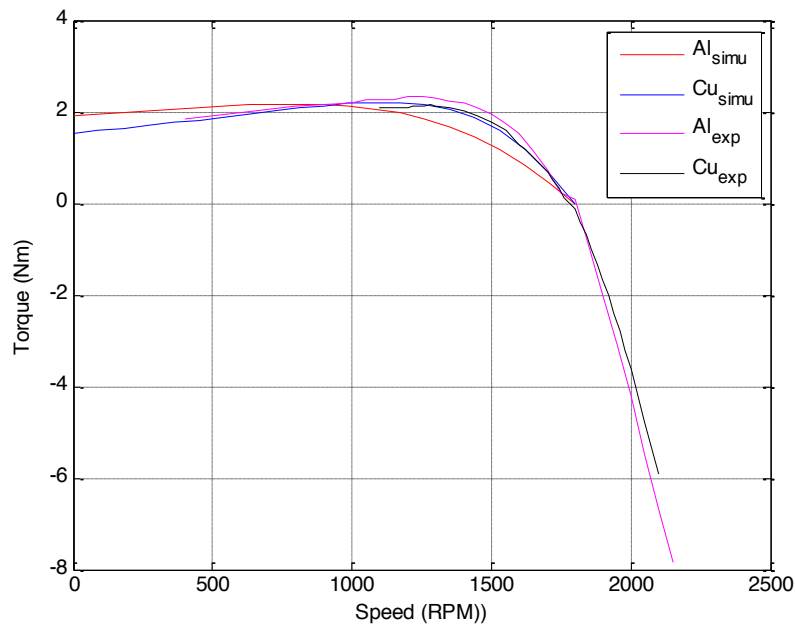


Figure 18. Al vs. Cu Rotor Comparison

From the above plots, we did not see a notable improvement of the copper rotor. Possible reasons are listed below:

- Copper bars were used instead of copper casting. The air gap in the rotor slots cancels out the high conductivity of copper;
- Welding for copper rotors increases the rotor resistance which cancels out the low resistivity of copper;
- The motor we chose is a small one, the rated output power of which is only ¼ HP. This makes it difficult for us to detect a prominent improvement.

4. Costs

Table 3. Equipment and Material Cost

Equipment & Material Cost			
Item Description	Item Price	Quantity	Total
1/4 HP Commercial Motor *	\$185.5/unit	2 units	\$371.00
Copper	\$3.87/Lb	1 Lb	\$3.87
Current Sensor	\$7/unit	1 unit	\$7.00
MicroController	\$3.71/unit	1 unit	\$3.71
1K Ohm Resister	\$0.68/unit	1 unit	\$0.68
LED	\$0.42/unit	4 unit	\$1.68
100 Ohm Resister	\$0.75/unit	5 unit	\$3.75
Single Phase Relay	\$5.12/ unit	3 unit	\$15.36
Buzzer	\$1.99/unit	1 unit	\$0.99
Sodium Hyoxide (NaOH)	\$27.45/bottle	1 bottle	\$27.45
Estimate Total Equipment & Material Cost			\$435.49

Table 4. Labor Cost

Labor Cost				
Item Description	Item Price	Quantity	Total	Total * 2.5
Student 1	\$20/hour	80 hours	\$1,600.00	\$4,000.00
Student 2	\$20/hour	80 hours	\$1,600.00	\$4,000.00
Student 3	\$20/hour	80 hours	\$1,600.00	\$4,000.00
Research Engineer	\$30/hour	20 hours	\$600.00	\$1,500.00
Research Lab Shop Supervisor	\$30/hour	15 hours	\$450.00	\$1,125.00
Estimate Total Labor Cost			\$4,800.00	\$12,000.00

The total cost of the entire project is:

$$Cost_{total} = Labor\ Cost + Equipment\ Cost = 435.49 + \$12000 = \$12435.49 \quad (22)$$

5. Conclusion

5.1 Accomplishments

We originally used 8-bit analog to digital conversion, and that made it almost impossible for the microcontroller to distinguish current values that were with 0.5 A. After consulting with some TAs, we decided to switch to 10-bit, and that greatly increased the sensitivity of the microcontroller.

Another problem we had was that when current values were close to a cutoff value, the microcontroller output was constantly switching between modes. That was when we learned the importance of adding delays in the code. Every time a decision was made by the microcontroller, we added a delay of 100 ms before it took in an input value again. This decision vastly improved the stability and reliability of the circuit.

For this project, although we were not able to cast a copper rotor, yet we managed to find an alternative, inserting copper bars into the rotor slots with ending rings at each end, within the time constrain. We succeeded in running all the DC tests, Open Circuit Tests, Short Circuit Test, and Load Tests to get parameters and curves we needed without failing the circuit. In addition, all the experimental curves matched the theoretical curve very closely. We were also able to use JMAG to get simulation results for various laminations because we did not have time to change the actual steel core shape.

5.2 Uncertainties

One uncertainty of the circuit is the potential current spikes caused by rapid current changes. During testing, we realized that when we suddenly changed the current values by a relatively large amount, the circuit was not reading the input very accurately. This could be due to the fact that the current needed 4 to 5 power cycles to stabilize. Even though this was certainly not desirable, our circuit eventually got back to normal after a few seconds.

For JMAG simulation, we assumed the reference rotors were made of pure aluminum; however, they turned out to be made of aluminum alloy. If the conductivity and permeability of the aluminum alloy were available, we would be able to get more accurate simulation results. Due to the restriction of casting equipment, we used copper bars instead. This caused air gap in the rotor slots, and welding at the rotor ends increased resistance.

5.3 Ethical considerations

We agree to uphold the IEEE code of Ethics. The following ethical concerns will be applied to our project:

- to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;
- to be honest and realistic in stating claims or estimates based on available data;
- to improve the understanding of technology; its appropriate application, and potential consequences;
- to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others;
- to avoid injuring others, their property, reputation, or employment by false or malicious action;

5.4 Future work

5.4.1 Protection Circuit Suggestions

Due to limited budget of this project, we were forced to pick our current sensor with 40 mV/A. However, there are current sensors out there with higher sensitivity that are more expensive. If high sensitivity is what you want, you might want to spend more money to get a better and more accurate current sensor.

We were not able to find a 3 phase relay chip that would trip all 3 phase currents at the same time. While 3 individual relays work fine in the project, there are still inevitable delays that result in a longer tripping process. We highly recommend a 3 phase relay/contactors for any future work. This would not only shorten the tripping process, but also reduce the number of separate components to fit on the board.

5.4.2 Rotor Design Suggestions

Since the rotor we chose was very small (only ¼ HP), the improvements might not be significant. We recommend using larger motors in order to get more obvious improvements.

We used copper bars instead of copper casting for the rotor fabrication. To get more prominent improvements and minimize rotor resistance, it would be ideal to find a local foundry to cast the rotor.

We assumed the original rotors were made of aluminum. To get better simulation results, we suggest sending the rotor to a local factory to measure the accurate electrical conductivity (σ) and magnetic permeability (μ).

References

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- [2] "PIC16F87XA Data Sheet", <http://ww1.microchip.com/downloads/en/DeviceDoc/39582b.pdf>
- [3] "ACS754LCB-050-PFF - Current Sensor - Allegro Micro Systems",
<http://www.alldatasheet.com/datasheet-pdf/pdf/120875/ALLEGRO/ACS754LCB-050-PFF.html>

Appendix A Requirement and Verification Table

Table 5. Requirements and Verification Table

Requirements	Verification	Verification status (Y or N)
1. Current sensor's Vout must be linear with lin.	1. Use bench current source to provide lin 0A to 2A in .1A steps. Measure with DMM in ammeter mode. Verify to within +/- .001A. Measure Vout in voltmeter mode to within +/- .001V. Record values. Plot V vs. I. Perform linear regression analysis. The regression results must be statistically significant (R square close to 1 and standard error close to 0).	Y
2. Current sensor conversion error must be in acceptable range	2. Compare the slope and intercept obtained from linear regression with current sensor's sensitivity and offset. The difference must be within 5%	Y
3. All three relays should be reset to Normally Closed states when the circuit is provided with power.	3. Cut the power and then provide the power to reset. All three LEDs using Normally Closed pins of the relays should be on.	Y
4. Microcontroller needs to make accurate comparisons with three levels of over current values	4. Control the current that goes through the current sensor. Increase the current from .8 to 2 A in 0.1A steps. The LED should light up at 1A +/- 0.1A. The buzzer should sound at 1.5A +/- 0.1A. The relays should trip at 1.9A +/- 0.1A.	Y
5. The relays should trip the circuit correctly	5. All three relays should get the tripping signal one by one with a 100 ms delay in between. When a relay trips, a switching sound should be heard and the LED should be off.	Y
6. Compare the parameters of the two original motors; make sure the two motor properties are identical. a. Perform prime calculation to obtain the parameter values b. Iteration must be made to refine the parameters calculated from 1a. c. Parameters for both motors need to be compared and fall within 10% difference. d. The two motors testing result must matches each other	6. Follow ECE 431 testing procedures on both motors to obtain the needed motor parameter values. a. Use standard calculation method to calculate parameters b. Three iterations were made, each parameters converges to a constant value c. Use MATLAB to sketch the testing data and compare the testing results.	Y
7. Two original motors' geometries must be identical, the percent difference needs to fall within $\pm 5\%$	7. Use digital caliper to measure both motors' geometries and compare the result.	Y
8. Based on the parameters obtained in 2, run simulation for both original motor and designed copper motor to obtain a set of comparison file, i.e.	8. Use Finite element analysis software (JMag) to obtain the required curves and files.	Y

torque vs. speed curve, etc.		
9. Etches all aluminum away from one of the original rotors. <ul style="list-style-type: none"> a. Obtain the steel core b. Obtain the cage volume (aluminum volume) 	9. Use base solution (NaOH) to etch away the aluminum. <ul style="list-style-type: none"> e. Weigh the steel core after etching to obtain the mass of the steel. f. Compare mass difference before and after etching, and then calculate the aluminum volume. 	Y
10. Make the copper rotor based on the steel core obtained from 4. <ul style="list-style-type: none"> a. Obtain the needed copper mass b. The copper rotor geometry must fall within $\pm 5\%$ of the aluminum one. c. The copper rotor must be able to run without mechanical fault. 	11. Insert Cu bars into motor slots then cast the rotor with pure copper. <ul style="list-style-type: none"> a. Based on the aluminum volume obtained from 4b to calculate the estimated weight of copper needed for rotor cage. b. Use digital caliper to measure the copper rotor geometry c. Check the rotor balance with the help from power lab and machine shop 	Y
12. Obtain the parameter for the copper rotor.	12. Run the same set of tests for the copper rotor; compare the testing performance result with the JMAG simulation.	Y
13. Analyze Cu rotor performance	13. Using the calculated result from 6 to plot the Torque vs. Speed curve for the copper rotor.	Y
14. Compare the Al and Cu rotor performance	14. Compare the experimental Torque vs. Speed curve for both Cu and Al rotors, and then compare the points where maximum torque is obtained.	Y

Appendix B Sample Motor Parameter Calculation (Motor 1)

Prime Calculation

i. DC Test

$$R_s = \frac{V_{DC}}{I_{DC}} = \frac{25.1 V}{0.99 A} = 25.94 \Omega \quad (1)$$

$$r_1 = R_s // R_s = \frac{1}{2} R_s = 12.97 \Omega \quad (2)$$

ii. No Load Test (Assume $r_1 = 0, x_1 = 0$)

$$r_c = \frac{\left(\frac{V_{NL}}{\sqrt{3}}\right)^2}{\frac{1}{3} P_{NL}} = \frac{V_{NL}^2}{P_{NL}} = \frac{220.4^2}{32.7} = 1485.509 \Omega \quad (3)$$

$$Q_{NL} = \sqrt{(\sqrt{3} V_{NL} I_{NL})^2 - P^2} = 228.243 \text{ VAR} \quad (4)$$

$$X_m = \frac{\left(\frac{V_{NL}}{\sqrt{3}}\right)^2}{\frac{1}{3} Q_{NL}} = \frac{V_{NL}^2}{Q_{NL}} = \frac{220.4^2}{228.243} = 212.827 \Omega \quad (5)$$

iii. Blocked Rotor Test (Assume $X_m \rightarrow \infty, r_c \rightarrow \infty, r_1 = 12.97 \Omega$)

$$P_{BR} = 3 I_{BR}^2 (r_1 + R_r') \quad (6)$$

$$R_r' = \frac{P_{BR}}{3 I_{BR}^2} - r_1 \quad (7)$$

$$R_r' = 8.934 \Omega \quad (8)$$

$$Q_{BR} = \sqrt{(\sqrt{3} V_{BR} I_{BR})^2 - P^2} = 76.236 \text{ VAR} \quad (9)$$

$$X_1 + X_2' = \frac{Q_{BR}}{3 I_{BR}^2} = 24.521 \Omega \quad (10)$$

Assume NEMA A connection ($X_1 = X_2'$):

$$X_1 = X_2' = 12.26 \Omega \quad (11)$$

Iteration 1

i. No Load Test (Use $r_1 = 12.97 \Omega, X_1 = 12.26 \Omega$)

Let $X_m // r_c$ be Z_{eq} , then

$$P_{NL} = 3 I_{NL}^2 (r_1 + R_{eq}) \quad (12)$$

$$R_{eq} = \frac{P_{NL}}{3 I_{NL}^2} - r_1 = 29.878 - 12.97 = 16.9 \Omega \quad (13)$$

$$Q_{NL} = 3 I_{NL}^2 (X_1 + X_{eq}) = 228.243 \text{ VAR} \quad (14)$$

$$X_{eq} = \frac{Q}{3 I_{NL}^2} - X_1 = 196.286 \Omega \quad (15)$$

$$Z_{eq} = 16.9 + j196.286 \Omega \quad (16)$$

Then

$$X_m = 197.741 \Omega \text{ and } r_c = 2296.67 \Omega$$

ii. Blocked Rotor Test (Assume $X_m = 197.741 \Omega, r_c = 2296.67 \Omega$)

$$I_{BR} = I_{BR} \angle I_{BR} = 1.018 \angle I_{BR} = 0.678 - j0.76 A \quad (17)$$

$$\angle I_{BR} = -\cos^{-1} \frac{68.1}{\sqrt{68.1^2 + 76.236^2}} = -48.226^\circ \quad (18)$$

Let V_1 be the voltage across r_1 and X_1 , V_2 be the voltage across R_r' and X_2' .

$$V_1 = I_{BR} \angle I_{BR} (r_1 + jX_1) = 18.1039 - j1.532 V \quad (19)$$

$$V_2 = \frac{V_{BR}}{\sqrt{3}} - V_1 = 15.368 + j1.532 V \quad (20)$$

$$R_r + jX_2' = \frac{V_2}{I_{BR}} = 8.9 + j12.26 \Omega \quad (21)$$

$$\boxed{R_r' = 8.9\Omega} \text{ and } \boxed{X_2' = 12.26\Omega}$$

Iteration 2

- i. No Load Test (Use $r_1 = 12.97\Omega$, $X_1 = 12.26\Omega$)
Let X_m/r_c be Z_{eq} , then

$$P_{NL} = 3I_{NL}^2(r_1 + R_{eq}) \quad (22)$$

$$R_{eq} = \frac{P_{NL}}{3I_{NL}^2} - r_1 = 29.878 - 12.97 = 16.9 \Omega \quad (23)$$

$$Q_{NL} = 3I_{NL}^2(X_1 + X_{eq}) = 228.243 \text{ VAR} \quad (24)$$

$$X_{eq} = \frac{Q}{3I_{NL}^2} - X_1 = 196.286 \Omega \quad (25)$$

$$Z_{eq} = 16.9 + j196.286\Omega \quad (26)$$

Then

$$\boxed{X_m = 197.741\Omega}, \text{ and } \boxed{r_c = 2296.67\Omega}$$

- ii. Blocked Rotor Test (Assume $X_m = 197.741\Omega$, $r_c = 2296.67\Omega$)

$$I_{BR} = I_{BR} \angle I_{BR} = 1.018 \angle I_{BR} = 0.678 - j0.76 \text{ A} \quad (27)$$

$$\angle I_{BR} = -\cos^{-1} \frac{68.1}{\sqrt{68.1^2 + 76.236^2}} = -48.226^\circ \quad (28)$$

Let V_1 be the voltage across r_1 and X_1 , V_2 be the voltage across R_r' and X_2' .

$$V_1 = I_{BR} \angle I_{BR} (r_1 + jX_1) = 18.1 - j1.53 \text{ V} \quad (29)$$

$$V_2 = \frac{V_{BR}}{\sqrt{3}} - V_1 = 15.37 + j1.53 \text{ V} \quad (30)$$

$$R_r + jX_2' = \frac{V_2}{I_{BR}} = 8.94 + j12.268 \Omega \quad (31)$$

$$\boxed{R_r' = 8.94\Omega} \text{ and } \boxed{X_2' = 12.268\Omega}$$

Iteration 3

- i. No Load Test (Use $r_1 = 12.97\Omega$, $X_1 = 12.268\Omega$)
Let X_m/r_c be Z_{eq} , then

$$P_{NL} = 3I_{NL}^2(r_1 + R_{eq}) \quad (32)$$

$$R_{eq} = \frac{P_{NL}}{3I_{NL}^2} - r_1 = 29.878 - 12.97 = 16.9 \Omega \quad (33)$$

$$Q_{NL} = 3I_{NL}^2(X_1 + X_{eq}) = 228.243 \text{ VAR} \quad (34)$$

$$X_{eq} = \frac{Q}{3I_{NL}^2} - X_1 = 196.278 \Omega \quad (35)$$

$$Z_{eq} = 16.9 + j196.278\Omega \quad (36)$$

Then

$$\boxed{X_m = 197.733\Omega}, \text{ and } \boxed{r_c = 2296.49\Omega}$$

- ii. Blocked Rotor Test (Assume $X_m = 197.733\Omega$, $r_c = 2296.49\Omega$)

$$I_{BR} = I_{BR} \angle I_{BR} = 1.018 \angle I_{BR} = 0.678 - j0.76 \text{ A} \quad (37)$$

$$\angle I_{BR} = -\cos^{-1} \frac{68.1}{\sqrt{68.1^2 + 76.236^2}} = -48.226^\circ \quad (38)$$

Let V_1 be the voltage across r_1 and X_1 , V_2 be the voltage across R_r' and X_2' .

$$V_1 = I_{BR} \angle I_{BR} (r_1 + jX_1) = 18.1 - j1.53 \text{ V} \quad (39)$$

$$V_2 = \frac{V_{BR}}{\sqrt{3}} - V_1 = 15.3668 + j1.5V \quad (40)$$

$$R_r + jX_2' = \frac{V_2}{I_{BR}} = 8.94 + j12.26 \Omega \quad (41)$$

$$\boxed{R_r' = 8.94\Omega} \text{ and } \boxed{X_2' = 12.26\Omega}$$

In the calculations shown above, after three iterations, all motor parameters converge.

Appendix C Current Sensor Data Analysis

Table 6. Current Sensor Testing Data

I (A)	V (V)	$V_{theoretical}$ (V)
0.00		
1	2.504	2.50004
0.1	2.507	2.504
0.2	2.511	2.508
0.3	2.514	2.512
0.4	2.518	2.516
0.5	2.522	2.52
0.6	2.526	2.524
0.7	2.529	2.528
0.8	2.533	2.532
0.9	2.537	2.536
1	2.541	2.54
1.1	2.544	2.544
1.2	2.548	2.548
1.3	2.552	2.552
1.4	2.556	2.556
1.5	2.56	2.56
1.6	2.564	2.564
1.7	2.568	2.568
1.8	2.572	2.572
1.9	2.576	2.576
2	2.58	2.58

Table 7 Summary Output 1

Regression Statistics	
Multiple R	0.999775056
R Square	0.999550163
Adjusted R Square	0.999526488
Standard Error	0.000515471
Observations	21

Table 8. Summary Output 2 (ANOVA)

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	0.011218	0.011218	42218.54	2.89E-33
Residual	19	5.05E-06	2.66E-07		
Total	20	0.011223			

Table 9. Summary Output 3

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>
Intercept	2.502871871	0.000217	11523.7	1.72E-66
X Variable 1	0.03817393	0.000186	205.4715	2.89E-33

Appendix D Motor Load Test Data

Table 10. Motor 1 Load Test Data

Speed [RPM]	T [Nm]
1000	2.095
1050	2.12
1100	2.17
1150	2.2
1200	2.215
1250	2.215
1300	2.17
1350	2.125
1400	2.065
1450	1.975
1500	1.87
1550	1.69
1600	1.455
1650	1.125
1700	0.725
1750	0.24
1800	0.105
1850	-1.005
1900	-1.995
1950	-3.055
2000	-4.23
2050	-5.465
2100	-6.68
2150	-7.835

Table 11. Motor 2 Load Test Data

Speed[RPM]	T [Nm]
800	2.32
900	2.38
1000	2.415
1050	2.42
1098	2.43
1148	2.43
1198	2.405
1248	2.38
1298	2.325
1348	2.265
1398	2.21
1448	2.115
1498	1.98
1548	1.785
1598	1.53
1648	1.185
1698	0.765
1748	0.245
1798	0.125
1848	-0.99
1898	-1.93
1948	-2.945
1998	-4.015
2048	-5.055
2098	-5.5

Table 12. Copper Rotor Load Test

Speed[RPM]	T [Nm]
1100	2.075
1150	2.08
1180	2.09
1200	2.1
1220	2.115
1240	1.125
1260	2.135
1280	2.15
1300	2.13
1350	2.08
1400	2.01
1450	1.905
1500	1.765
1550	1.6
1600	1.285
1620	1.185
1640	1.07
1660	0.945
1680	0.82
1700	0.67
1720	0.505
1740	0.33
1760	0.13
1780	0
1800	-0.11
1820	-0.4
1840	-0.7
1860	-1.005
1880	-1.34
1900	-1.665
1920	-2.03
1940	-2.405
1960	-2.79
1980	-3.205
2000	-3.64
2050	-4.745
2100	-5.895

Appendix E Microcontroller Code

```
#include <16F887.h>
#DEVICE ADC = 10
#use delay(clock=20000000)
#define MY_TRISA 0b11111111
#define MY_TRISB 0b00000000
#define MY_TRISC 0b00000000

void main(void)
{
    int16 input = 0;
    int16 val1 = 520;
    int16 val2 = 523;
    int16 val3 = 527;
    setup_port_a(ALL_ANALOG);
    setup_adc(ADC_CLOCK_INTERNAL);
    set_adc_channel(0); //read from AN0
    output_low(PIN_B0);
    delay_ms(100);
    output_low(PIN_B1);
    delay_ms(100);
    output_low(PIN_B2);
    delay_ms(100);
    output_low(PIN_B3);
    delay_ms(100);
    output_low(PIN_B4);
    delay_ms(100);
    output_high(PIN_C4);
    delay_ms(100);
    output_low(PIN_C4);
    output_high(PIN_C5);
    delay_ms(100);
    output_low(PIN_C5);
    output_high(PIN_C6);
```

```
    delay_ms(100);
    output_low(PIN_C6);
    while(true)
    {
        input = read_adc();
        if(input<val1)
        {
            delay_ms(1000);
        }
        else if(input<val2)
        {
            output_high(PIN_B0);
            delay_ms(1000);
        }
        else if(input<val3)
        {
            output_high(PIN_B1);
            delay_ms(1000);
        }
        else
        {
            output_high(PIN_B4);
            delay_ms(100);
            output_low(PIN_B4);
            output_high(PIN_B3);
            delay_ms(100);
            output_low(PIN_B3);
            output_high(PIN_B2);
            delay_ms(100);
            output_low(PIN_B2);
        }
    }
}
```