Comparative Motor Design

Design Review

Spring 2012

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Team number: 6

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1. Introduction

1.01. Statement of Interest

Today many induction motors are serving critical processes that do not have a back up. Since any failure is very costly, it is tempting to choose costly components not required for the specific situation while pursuing maximum reliability. The challenge is to maximize reliability without over spending. Therefore, it is necessary to come up with new rotor constructions with better efficiency.

1.02. Objectives

Our group will begin with a small commercial AC induction motor and design two improved rotor configurations that support comparative analysis in the lab. One rotor would be based on the commercial product, but would increase the amount of aluminum in the conductor bars to improve efficiency. The second would use copper in place of aluminum. Our team will develop and analyze the two rotor designs, arrange for rotor fabrication, and then test all three rotors for dynamic and steady-state performance. Finite element analysis software (JMAG) will be used to do the computer simulation comparisons for the designed rotors. If time permits, we will consider and test other factors, such as different material and geometric shapes of the rotor, to further improve efficiency.

To insure a safe testing environment, we will also design and implement an over current protection circuit to complement our motor. The circuit has three levels of alarm. When the detected current is 25% over the rated current of the motor, the LED would light up. When it is 50% over, the alarm would sound. When it is 100% over, the contactor would trip the circuit.

Benefits	Features
• High efficiency • Notify users unwanted conditions • Protect users from danger • Provide a reference for future motor material selection and design	• Detailed comparison data set for different motor designs • Best efficiency-cost ratio • Detect over current • Trips circuit in high over current conditions

2. Design

2.01. Block Diagram

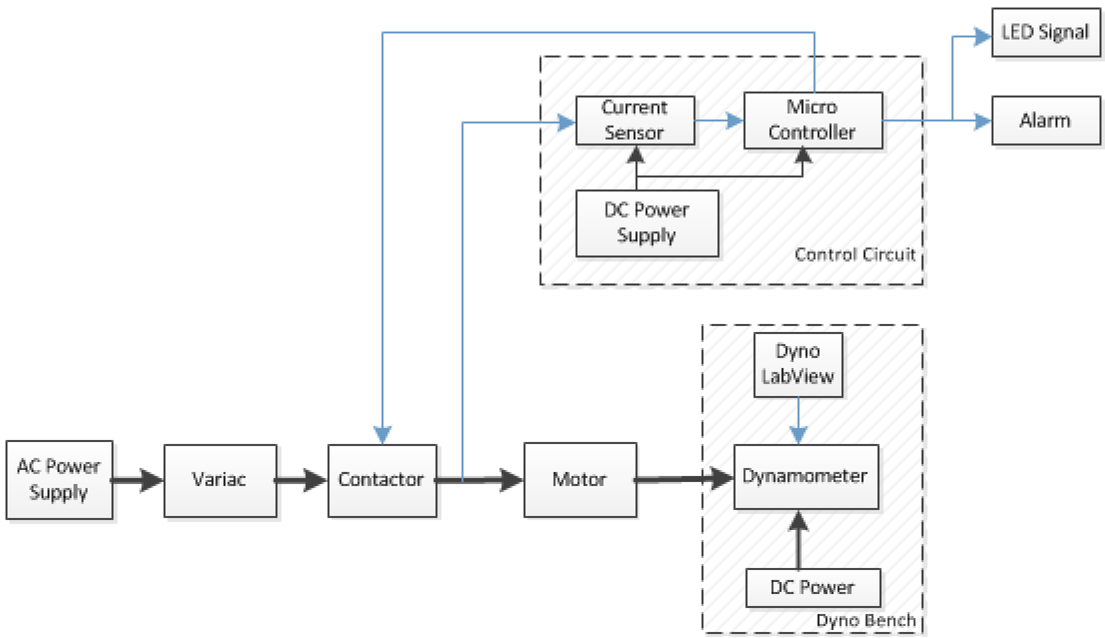


Figure 1 Block Diagram

2.02. Block Descriptions

2.02.1. Control Circuit

- DC Power Supply: This DC Power provides Vdd (0-5V) for the current sensor and Micro Controller.
- Current Sensor (ACS758LCB-050-PFF): The current sensor will take in the operating current and then induce the current to a corresponding analog voltage value to input to PIC microcontroller.
- Micro Controller (PIC16F877A): The microcontroller is used to take in the analog voltage value from the sensor and compare with 25% ,50% and 100% over current values. When a condition is met, it sends ON signal to LED, alarm and contactor.

2.02.2. Signal Response Performance

- LED Signal: This is an LED Signal light that would turn on when a turn on signal is sent by the microcontroller (125% of the rated current flow in the power circuit).
- Alarm: When the current passing through the power circuit is about 150% of rated current, the microcontroller will send turn on the alarm.
- Contactor: The monitor will take signal from the microcontroller and trip the circuit when the current gets above 200% of rated current.

2.02.3. Power Circuit

- AC Power Supply: the 60 Hz AC supply provides power up to 225 kVA, 230 V AC power to the entire power circuit.

- Variac ™: an autotransformer that varies the output voltage for a steady AC input voltage. It provides us various levels of motor input voltage that can be used for motor performance testing.
- Motor: Current Selection 1/4 HP motor, Grainger category number #3N843 (commercially discontinued). This is a small induction motor we selected for lab testing and rotor fabrication.
- 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.

2.03. Schematics

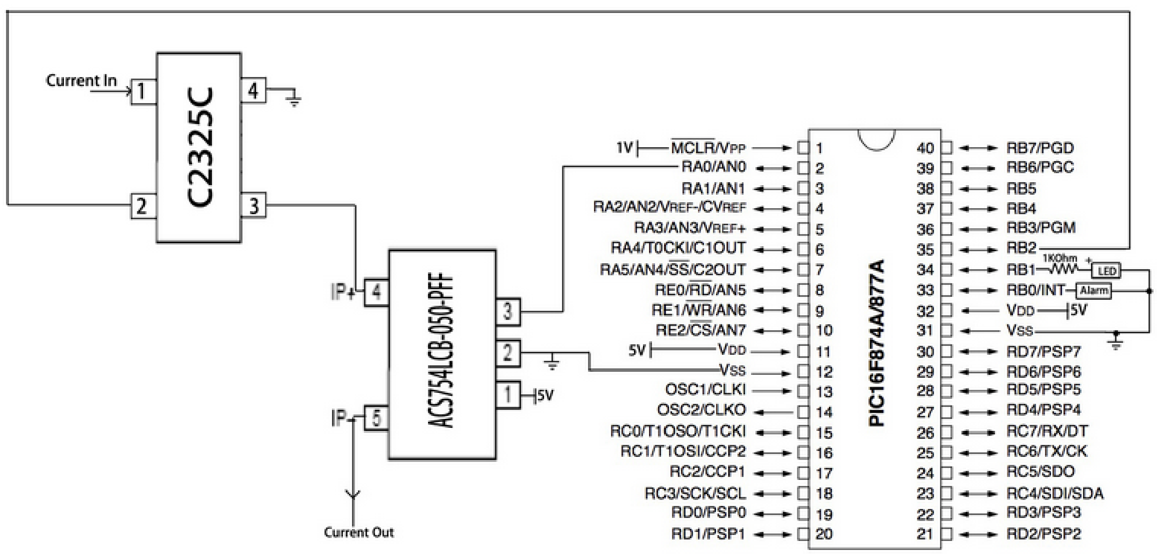


Figure 2. Relay Circuit Schematic [2] [3]

Current Sensor: The current to be tested flows in at pin 4 (IP+) and flows out at pin 5 (IP-). 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 (RA0/AN0) of the microcontroller.

Microcontroller: The programming voltage input at pin 1 (VPP) is set to 1V. Pin 12 and 31 (VSS) is connected to ground. Pin 11 and 32 (VDD) is set to 5V. The microcontroller takes the analog voltage input at pin 2 (RA0/AN0) and sends digital output at pin 33 (RB0), 34(RB1) and 35(RB2), which are connected to LED, alarm and contactor. Before pin 34 reaches the LED, a 1k Ohm resistor is placed to reduce current.

Contactor: The current goes through the contactor. The power supply nodes of the contactor is connected to ground and pin 35 (RB2) of the microcontroller. When the condition is met, microcontroller will provide power to the contactor to trip the circuit.

2.04. Flow Chart

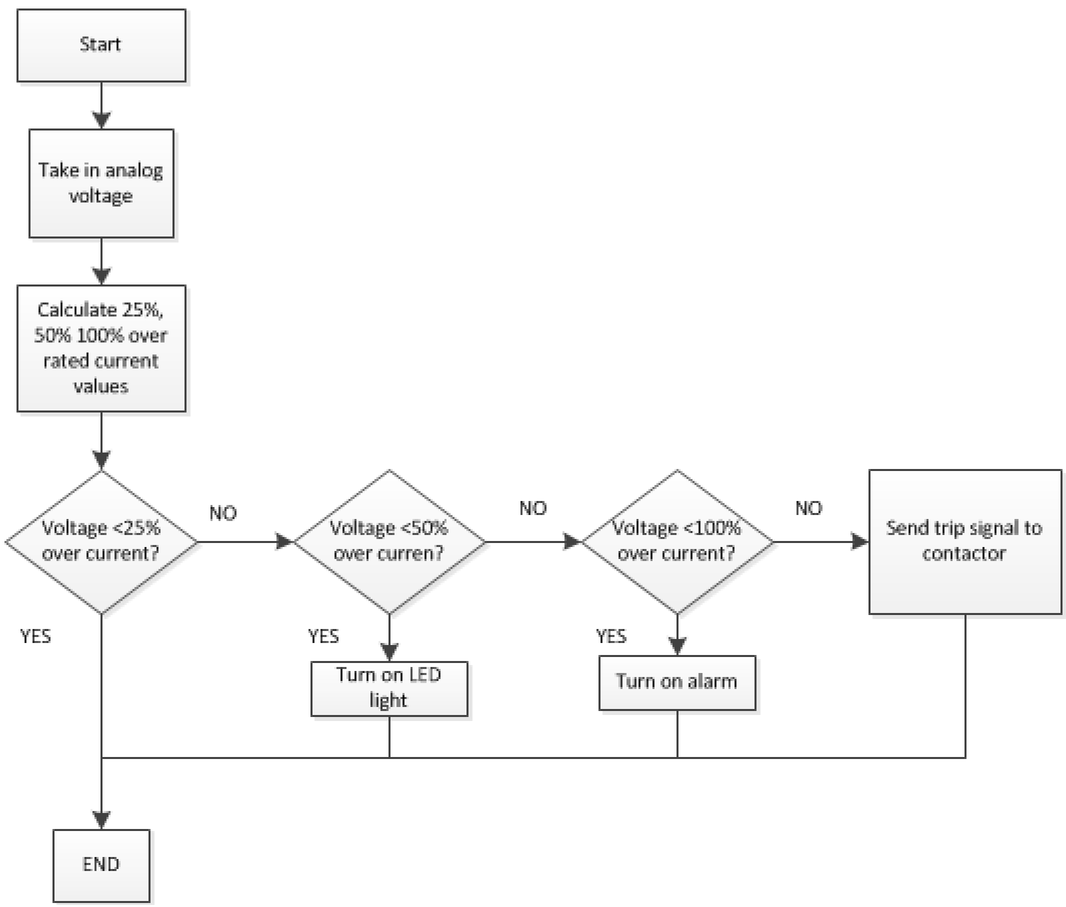


Figure 3. Flow Chart

2.05. Performance Requirements

In case to have a steady performance environment for the designed motors, the requirement for testing operation is 208-220/440 V, 60/50 Hz, maximum ambient temperature 40^{o}C. The designed rotors will be made of electrolytic aluminum and electrolytic copper. Other reasonable metal material will also be considered. The current sensor should convert the current input into analog voltage output. Since the input/output relationship is linear, the current and voltage values should form a straight line. The microcontroller should take in the analog voltage value from the current sensor accurately. The program in microcontroller should make accurate comparisons with the actual current value with the three different levels of over current values. The program then should send the right signal to LED and alarm. When LED and alarm receives signal from microcontroller, they should operate accordingly. Last but not least, monitor should display current value accurately.

3. Verification

Requirements	Verification
1. Current sensor's Vout must be linear with Iin.	Use bench current source to provide Iin .1A to 3A in .1A steps. Measure with DMM in ammeter mode. Verify to within +/- .001A. Measure Vout in voltmeter mode to within +/- .01V. Record values. Plot V vs. I. Perform linear regression analysis. Measured standard error must be less than 5%
2. Current sensor conversion error must be in acceptable range	Compare the slope obtained from linear regression with current sensor's convert ratio. The difference must be within 1%
3. Microcontroller needs to take the analog voltage input accurately	Use bench current source to provide ten random current values. For each current input, measure the voltage output with a DMM in voltmeter mode. Put a breakpoint right after microcontroller takes in the voltage values. Check the value of the register that stores the voltage values. Convert the binary number to decimals. Compare the measured and stored voltage numbers. These voltage numbers should be within 1% to three decimal places.
4. LED, alarm, and contactor should operate when the corresponding microcontroller output is high	Make pin 34 output to be high, check if the LED lights up. Then make pin 33 output to be high, check if the alarm makes sound. Last make pin 35 output to be high, check if the contactor trips the circuit.
5. Microcontroller needs to make accurate comparisons with three levels of over	Calculate 25, 50, and 100% over current values. Make the input a value less than 125% of the rated current. Check that none is operating. Then make

current values	the input value greater than or equal to 125% but less than 150% of the rated current. Check that only LED is on. Make the input value greater than or equal to 150% but less than 200% of the rated current, check that only alarm is on. Last make the input value greater than or equal to 200%, check that the contactor trips the circuit.

3.01. Testing Procedures

3.01.1. Preliminary Motor Testing

To ensure the only difference that affects our motor performance is the rotor property, we need to test the two original motors and make sure that they have identical parameters and electrical property. The preliminary testing includes the tests listed below:

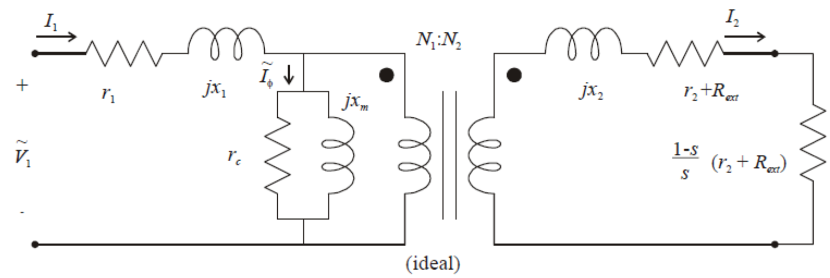


Figure 4. Equivalent Circuit of One Phase of A Three-Phase Induction Machine [4]

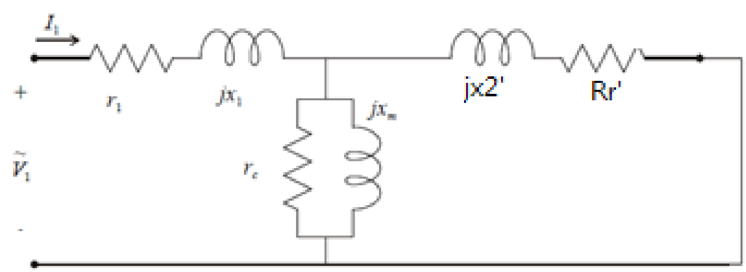


Figure 5. Simplified Equivalent Circuit [4]

- **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 $r_2 + R_{ext}$, (where r_2 is rotor single-phase winding resistance, and R_{ext} is External resistance), x_1 - stator single phase leakage reactance, x_2 - rotor single phase leakage reactance.
- **Load Test:** Obtaining the experimental torque speed curve.

(From the tests listed above, we will obtain the data that are needed to analyze the motor performance, i.e. torque vs. speed curve. These analyses will be applied on all three rotors that we have: reference rotor, aluminum rotor, and copper rotor.)

(For motors' parameters, calculations, graphs, please see Appendix I)

3.01.2. Rotor Geometry Measurement

The original rotor geometry is necessary for 4.01.3 Simulation and for future rotor fabrication. We will use digital caliper to measure the needed information.

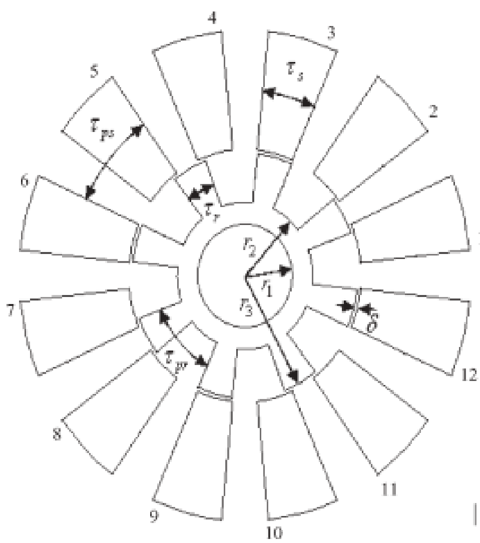


Figure 6. Rotor Cross-Section [1]

Parameter	Symbol
Inner Rotor Radius	r_1
Slot Radius	r_2
Rotor Radius	r_3
Rotor Tooth Width	τ_r
Rotor Pole Pitch	τ_{pr}
Axial Thickness	h

In our rotor design, we have several options:

- Keep the original rotor shape, use different materials: electrolytic aluminum and copper.
- Change rotor slot shape: tooth width, tooth area, number, etc.

(Note: The figure 5 is a sample graph that demonstrates the motor cross-section. The actual cross-section of the rotor will be measured and updated.)

3.01.3. Simulation

Finite electromagnetic analysis software will be used to test the designed two rotors. Once the rotor geometry is determined, we will use JMAG to analyze the magnetic filed in different rotors (rotor shape, material, etc). The simulation result would be our reference data. After the designed rotors are fabricated, we will compare the simulation result with the testing result.

3.02. Tolerance Analysis

In our project, the variation of casting material amount would affect greatly on motors' operation. The amount of aluminum and copper used in simulation may not actually matches the amount of casting material used in the real fabrication process. Therefore, in our tolerance analysis, we will examine how ideal simulation efficiency varies with the actual efficiency while $\pm$5% material amount difference may occur.

4. Cost

4.01. Equipment & 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	20 Lb	$77.40
Aluminum	$1.15/Lb	6 Lb	$6.90
Current Sensor	$7/unit	3 unit	$21.00
MicroController	$3.71/unit	1 unit	$3.71
1K Resister	$0.68/unit	1 unit	$0.68
LED	$0.42/unit	1 unit	$0.42
Contactor	$10.95/ unit	1 unit	$10.95
Buzzer	$1.99/unit	1 unit	$1.99
Estimate Total Equipment & Material Cost			$494.05

** The motor type we choose for this project is Grainger #3N843, which is discontinued. Therefore for the price estimation, we choose the price for ¼ HP commercial Motor Grainger Item # 2K505.*

<u>Material Quantity Calculation</u>

We estimated the volume for casting material is 1 liter. For Copper, whose density ρ=8.94kg/L, the mass for copper is $m_{Cu} = 8.94kg$, approximately 20Lb. Similarly, the density of Aluminum is $\rho = 2.7kg/L$, the mass for aluminum is $m_{Al} = 2.7kg$, approximately 6Lb.

4.02. Labor Cost

Labor Cost				
Item Description	Item Price	Quantity	Total	Total * 2.5
Foundary Labor	$200/unit	2 units	$400.00	$1,000.00
Xiaowen Bai	$20/hour	8 weeks	$1,600.00	$4,000.00
Li Cai	$20/hour	8 weeks	$1,600.00	$4,000.00
Cheng Xu	$20/hour	8 weeks	$1,600.00	$4,000.00
Estimate Total Labor Cost			$5,200.00	$13,000.00

4.03. Total Cost

Equipment and Material Cost	$483.10
Labor Cost	$13,000.00
Total Cost	$13,483.10

5. Schedule

Week	Tasks	Member
2/6	Proposal Research Background Paper Analyzing cost	Xiaowen
	Proposal IEEE Code of Ethics	Li
	Proposal Arrange appointments	Cheng
2/13	Sign-up for design review Preliminary Testing for Original Rotor	Xiaowen
	Contact local foundry Contact ECE stores and partshop	Li
	Preliminary Testing for Original Rotor Research IEEE Standard for Motor Testing	Cheng
2/20	Preliminary Data Analysis Prepare for design review	Xiaowen
	Prepare for design review	Li
	Preliminary Data Analysis Prepare for design review	Cheng
2/27	Original Motors Testing Original Motors Comparison Design Review Paper	Xiaowen

	Data Record Circuit Design Geometry Measurement	Li
	Original Motors Testing Original Motors Parameter Calculation Geometry Measurement	Cheng
3/5	JMAG Simulation	Xiaowen
	Contact local foundry	Li
	Motor Geometry Acquisition	Cheng
3/12	Test Aluminum Motor JMAG Simulation	Xiaowen
	Circuit Design	Li
	Test Aluminum Motor Motor Parameter Calculation	Cheng
3/19	Spring Break	
3/26	Sign-up for Mock-up Presentation Aluminum Rotor Analysis JMAG Simulation Result Compare (Al)	Xiaowen
	Circuit Design Data Compilation	Li
	Aluminum Rotor Analysis Compare data with preliminary data	Cheng
4/2	Test Copper Motor Motor Analysis JMAG Simulation Result Compare (Cu)	Xiaowen
	Circuit Design Data Compilation	Li
	Test Copper Motor Motor Parameter Calculation	Cheng
4/9	Test Copper Motor Motor Analysis JMAG Simulation Result Compare (Cu)	Xiaowen
	Circuit Design Data Compilation	Li
	Aluminum Rotor Analysis Compare data with preliminary data	Cheng
4/16	Sign-up for Demo and Presentation Cost Efficiency Comparison	Xiaowen
	Cost Efficiency Comparison	Li
	Analyze differences among three rotors	Cheng
4/23	Prepare for Demo and Presentation Work on Final Paper	Xiaowen
	Prepare for Demo and Presentation Work on Final Paper	Li
	Prepare for Demo and Presentation Work on Final Paper	Cheng
4/30	Work on Final Paper	Xiaowen
	Work on Final Paper	Li
	Work on Final Paper	Cheng

6. Ethical Considerations

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

I. 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;

3. to be honest and realistic in stating claims or estimates based on available data;

5. to improve the understanding of technology; its appropriate application, and potential consequences;

7. to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others;

9. to avoid injuring others, their property, reputation, or employment by false or malicious action;

Citation

[1] V. Behjat, A. Vahed "Study the Influence of Geometric Parameters On the Torque of Electrostatic Micro-motors" Elecrical Engineering (2006) 89: 61–65, DOI 10.1007/s00202-005-0314-2

[2] "PIC16F87XA Data Sheet", http://ww1.microchip.com/downloads/en/DeviceDoc/39582b.pdf

[3] "ACS754LCB-050-PFF - Current Sensor - Allegro MicroSystems", http://www.alldatasheet.com/datasheet-pdf/pdf/120875/ALLEGRO/ACS754LCB-050-PFF.html

[4] P. W. Sauer, P. T. Krein, P. L. Chapman, "ECE 431 Electric Machinery Course Guide and Laboratory Information" Ver.4.5, January 2011.

Appendix 1: Motor Parameters Testing Result and Calculation

I. Motor 1

Prime Calculation

The equivalent circuit is as shown in **Figure 5.**

i. DC Test

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

$$\boxed{r_1 = R_s // R_s = \frac{1}{2} R_s = 12.97\ \Omega}$$

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

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

(3) $$Q_{NL} = \sqrt{\left(\sqrt{3}V_{NL}I_{NL}\right)^2 - P^2} = 228.243\ VAR$$

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

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

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

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

(7) $$\boxed{R_r' = 8.934\Omega}$$

(8) $$Q_{BR} = \sqrt{\left(\sqrt{3}V_{BR}I_{BR}\right)^2 - P^2} = 76.236\ VAR$$

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

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

(10) $$\boxed{X_1 = X_2' = 12.26\ \Omega}$$

Result for Prime Calculation

$r_1(\Omega)$	$r_c\ (\Omega)$	$X_m\ (\Omega)$	$R_r'\ (\Omega)$	$X_1\ (X_2')(\Omega)$
12.97	1485.509	212.827	8.934	12.26

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

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

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

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

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

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

Then

(16) $\boxed{X_m = 197.741\Omega}$, and $\boxed{r_c = 2296.67\Omega}$

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

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

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

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

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

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

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

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

Result for First Iteration				
$r_1(\Omega)$	$r_c\ (\Omega)$	$X_m\ (\Omega)$	$R_r{}'\ (\Omega)$	$X_1\ (X_2{}')(\Omega)$
12.97	2296.67	197.741	8.9	12.26

<u>Iteration 2</u>

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

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

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

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

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

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

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

Then

$$(27) \quad \boxed{X_m = 197.741\Omega}, \text{ and } \boxed{r_c = 2296.67\Omega}$$

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

$$(28) \quad I_{BR} = I_{BR}\angle I_{BR} = 1.018\angle I_{BR} = 0.678 - j0.76\ A$$

$$(29) \quad \angle I_{BR} = -\cos^{-1}\frac{68.1}{\sqrt{68.1^2+76.236^2}} = -48.226^o$$

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

$$(30) \quad V_1 = I_{BR}\angle I_{BR}(r_1 + jX_1) = 18.1 - j1.53\ V$$

$$(31) \quad V_2 = \frac{V_{BR}}{\sqrt{3}} - V_1 = 15.37 + j1.53V$$

$$(32) \quad R_r + jX_2' = \frac{V_2}{I_{BR}} = 8.94 + j12.268\ \Omega$$

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

Result for Second Iteration				
$r_1(\Omega)$	$r_c\ (\Omega)$	$X_m\ (\Omega)$	$R_r{}'\ (\Omega)$	$X_1\ (X_2{}')(\Omega)$
12.97	2296.67	197.741	8.94	12.268

<u>Iteration 3</u>

i. No Load Test (Use $r_1 = 12.97\Omega, X_1 = 12.268\Omega$)

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

$$(33) \quad P_{NL} = 3I_{NL}^2(r_1 + R_{eq})$$

$$(34) \quad R_{eq} = \frac{P_{NL}}{3I_{NL}^2} - r_1 = 29.878 - 12.97 = 16.9\ \Omega$$

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

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

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

Then

(38) $\boxed{X_m = 197.733\Omega}$, and $\boxed{r_c = 2296.49\Omega}$

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

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

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

Let V_1 be the voltage across r_1 *and* X_1, V_2 be the voltage across R_r' *and* $X_2{}'$.

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

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

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

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

Result for Third Iteration				
$r_1(\Omega)$	$r_c\ (\Omega)$	$X_m\ (\Omega)$	$R_r{}'\ (\Omega)$	$X_1\ (X_2{}')(\Omega)$
12.97	2296.49	197.733	8.94	12.26

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

Motor 1 Torque vs. Speed Curve Theoretical and Experimental Comparison

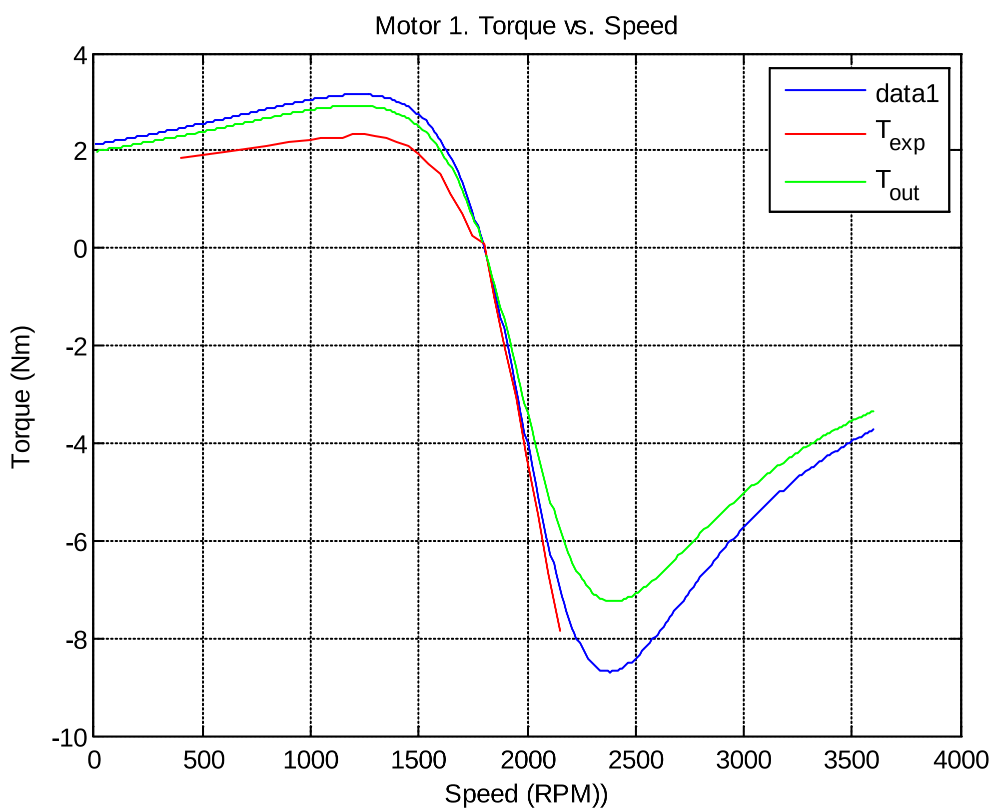


Figure 7. Motor 1 Torque Speed Curve Comparison

In Figure 1, we are using the refined formulas shown below:
The refined calculated torque T_{th} is:

$$(44) \quad T_{th} = \frac{s|V_1|^2 R_r'}{\omega_e[(r_1 s + R_r')^2 + (X_1 + X_2')^2 s^2]} \times \frac{3P}{2}$$

$$(45) \quad T_{out} = \frac{P_{out}}{\omega_r} = \frac{3I_2^2 R_r'(1-s)/s}{\omega_r}$$

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

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

$$(46) \quad \omega_e = 60 * 2\pi \frac{rad}{s} = 3600RPM$$

ω_{rm} is the mechanical rotor speed

II. Motor 2

<u>Prime Calculation</u>

The equivalent circuit is as shown in **Figure 5.**

iv. DC Test

$$(1) \quad R_s = \frac{V_{DC}}{I_{DC}} = \frac{25.1\,V}{0.99\,A} = 25.276\,\Omega$$

$$(2) \quad \boxed{\mathrm{r}_1 = \mathrm{R_s}//\mathrm{R_s} = \frac{1}{2}R_s = 12.638\,\Omega}$$

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

$$(3) \quad \boxed{r_c = \frac{\left(\frac{V_{NL}}{\sqrt{3}}\right)^2}{\frac{1}{3}P_{NL}} = \frac{V_{NL}^2}{P_{NL}} = \frac{220.4^2}{32.7} = 1699.58\Omega}$$

$$(4) \quad Q_{NL} = \sqrt{\left(\sqrt{3}V_{NL}I_{NL}\right)^2 - P^2} = 230.572\,VAR$$

$$(5) \quad \boxed{X_m = \frac{\left(\frac{V_{NL}}{\sqrt{3}}\right)^2}{\frac{1}{3}Q_{NL}} = \frac{V_{NL}^2}{Q_{NL}} = \frac{220.4^2}{228.243} = 209.341\Omega}$$

vi. Blocked Rotor Test (Assume $X_m \to \infty, r_c \to \infty, r_1 = 12.638\Omega$)

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

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

$$(8) \quad \boxed{R_r' = 9.541\Omega}$$

$$(9) \quad Q_{BR} = \sqrt{\left(\sqrt{3}V_{BR}I_{BR}\right)^2 - P^2} = 73.709\,VAR$$

$$(10) \quad X_1 + X_2' = \frac{Q_{BR}}{3I_{BR}^2} = 23.025\,\Omega$$

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

$$(11) \quad \boxed{X_1 = X_2' = 11.512\,\Omega}$$

Result for Prime Calculation

$r_1(\Omega)$	$r_c\ (\Omega)$	$X_m\ (\Omega)$	$R_r'\ (\Omega)$	$X_1\ (X_2')(\Omega)$

12.638	1699.58	209.341	9.541	11.512

Iteration 1

iii. No Load Test (Use $r_1 = 12.638\Omega, X_1 = 11.512\Omega$)

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

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

$$(13) \quad R_{eq} = \frac{P_{NL}}{3I_{NL}^2} - r_1 = 29.878 - 12.97 = 12.762\ \Omega$$

$$(14) \quad Q_{NL} = 3I_{NL}^2(X_1 + X_{eq}) = 230.572\ VAR$$

$$(15) \quad X_{eq} = \frac{Q}{3I_{NL}^2} - X_1 = 194.7\ \Omega$$

$$(16) \quad Z_{eq} = 12.762 + j194.7\Omega$$

Then

$$(17) \quad \boxed{X_m = 195.537\Omega}, \text{ and } \boxed{r_c = 2983.15\Omega}$$

iv. Blocked Rotor Test (Assume $X_m = 195.537\Omega, r_c = 2983.15\Omega$)

$$(18) \quad I_{BR} = I_{BR}\angle I_{BR} = 1.033\angle I_{BR} = 0.717 - j0.744\ A$$

$$(19) \quad \angle I_{BR} = -\cos^{-1}\frac{71}{\sqrt{71^2+73.709^2}} = -46.072^o$$

Let V_1 be the voltage across r_1 *and* X_1, V_2 be the voltage across R_r' *and* $X_2{}'$.

$$(20) \quad V_1 = I_{BR}\angle I_{BR}(r_1 + jX_1) = 17.63 - j1.15\ A$$

$$(21) \quad V_2 = \frac{V_{BR}}{\sqrt{3}} - V_1 = 15.398 + j1.14857V$$

$$(22) \quad R_r + jX_2' = \frac{V_2}{I_{BR}} = 9.54 + j11.5\ \Omega$$

$$\boxed{R_r' = 9.54\Omega} \text{ and } \boxed{X_2{}' = 11.5\Omega}$$

Result for First Iteration				
$r_1(\Omega)$	$r_c\ (\Omega)$	$X_m\ (\Omega)$	$R_r{}'\ (\Omega)$	$X_1\ (X_2{}')(\Omega)$
12.638	2983.15	195.537	9.54	11.5

Iteration 2

i. No Load Test (Use $r_1 = 12.638\Omega, X_1 = 11.5\Omega$)

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

$$(23) \quad P_{NL} = 3I_{NL}^2(r_1 + R_{eq})$$

$$(24) \quad R_{eq} = \frac{P_{NL}}{3I_{NL}^2} - r_1 = 29.878 - 12.97 = 12.762\ \Omega$$

$$(25) \quad Q_{NL} = 3I_{NL}^2(X_1 + X_{eq}) = 230.572\ VAR$$

$$(26) \quad X_{eq} = \frac{Q}{3I_{NL}^2} - X_1 = 194.712\ \Omega$$

$$(27) \quad Z_{eq} = 12.762 + j194.712\Omega$$

Then

$$(28) \quad \boxed{X_m = 195.548\Omega}, \text{ and } \boxed{r_c = 2983.52\Omega}$$

ii. Blocked Rotor Test (Assume $X_m = 195.548\Omega, r_c = 2983.52\Omega$)

$$(29) \quad I_{BR} = I_{BR}\angle I_{BR} = 1.033\angle I_{BR} = 0.717 - j0.744\ A$$

$$(30) \quad \angle I_{BR} = -\cos^{-1}\frac{71}{\sqrt{71^2+73.709^2}} = -46.072^o$$

Let V_1 be the voltage across r_1 *and* X_1, V_2 be the voltage across R_r' *and* $X_2{}'$.

$$(31) \quad V_1 = I_{BR}\angle I_{BR}(r_1 + jX_1) = 17.6174 - j1.157\ A$$

(32) $V_2 = \frac{V_{BR}}{\sqrt{3}} - V_1 = 15.4 + j1.157V$

(33) $R_r + jX_2' = \frac{V_2}{I_{BR}} = 9.54 + j11.514\ \Omega$

$\boxed{R_r' = 9.54\Omega}$ and $\boxed{X_2{}' = 11.514\Omega}$

Result for Second Iteration				
$r_1(\Omega)$	$r_c\ (\Omega)$	$X_m\ (\Omega)$	$R_r{}'\ (\Omega)$	$X_1\ (X_2{}')(\Omega)$
12.638	2983.52	195.548	9.54	11.514

Iteration 3

v. No Load Test (Use $r_1 = 12.638\Omega, X_1 = 11.5\Omega$)

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

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

(35) $R_{eq} = \frac{P_{NL}}{3I_{NL}^2} - r_1 = 29.878 - 12.97 = 12.762\ \Omega$

(36) $Q_{NL} = 3I_{NL}^2(X_1 + X_{eq}) = 230.572\ VAR$

(37) $X_{eq} = \frac{Q}{3I_{NL}^2} - X_1 = 194.698\ \Omega$

(38) $Z_{eq} = 12.762 + j194.698\Omega$

Then

(39) $\boxed{X_m = 195.535\Omega}$, and $\boxed{r_c = 2983.09\Omega}$

vi. Blocked Rotor Test (Assume $X_m = 195.548\Omega, r_c = 2983.52\Omega$)

(40) $I_{BR} = I_{BR}\angle I_{BR} = 1.033\angle I_{BR} = 0.717 - j0.744\ A$

(41) $\angle I_{BR} = -\cos^{-1}\frac{71}{\sqrt{71^2+73.709^2}} = -46.072^o$

Let V_1 be the voltage across $r_1\ and\ X_1$, V_2 be the voltage across $R_r'\ and\ X_2{}'$.

(42) $V_1 = I_{BR}\angle I_{BR}(r_1 + jX_1) = 17.6284 - j1.147\ A$

(43) $V_2 = \frac{V_{BR}}{\sqrt{3}} - V_1 = 15.4 + j1.147V$

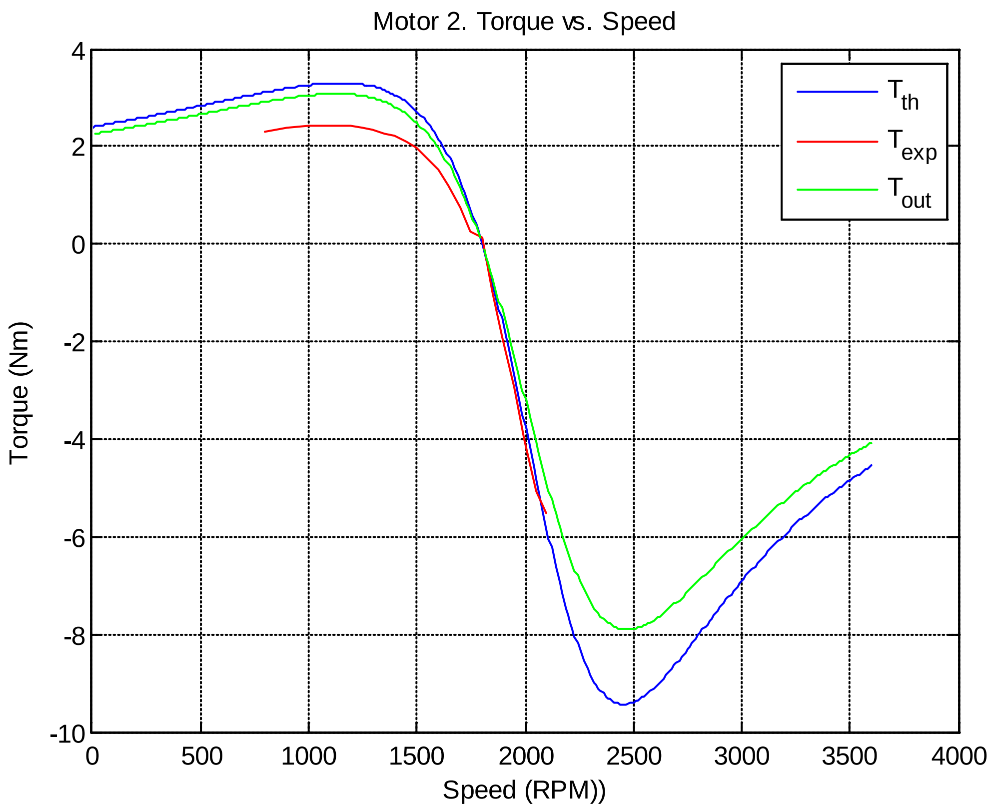
(44) $R_r + jX_2' = \frac{V_2}{I_{BR}} = 9.54 + j11.5\ \Omega$

$\boxed{R_r' = 9.54\Omega}$ and $\boxed{X_2{}' = 11.5\Omega}$

Result for Third Iteration				
$r_1(\Omega)$	$r_c\ (\Omega)$	$X_m\ (\Omega)$	$R_r{}'\ (\Omega)$	$X_1\ (X_2{}')(\Omega)$
12.638	2983.09	195.535	9.54	11.5

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

Motor 2 Torque vs. Speed Curve Theoretical and Experimental Comparison



(Note: the experimental torque-speed curve shown above is only the rated region, the complete experimental curve will be obtained on February 29th, 2012)

III. Motor 1 & Motor 2 Performance Comparison

Motor Parameters Comparison			
	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%

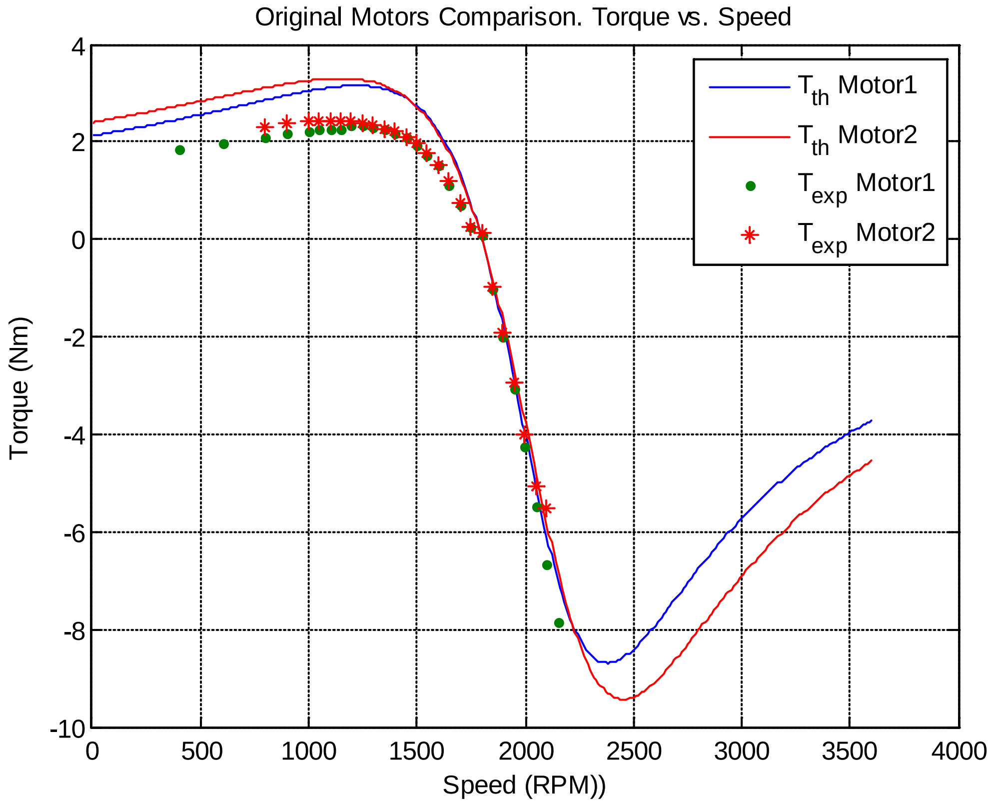


Figure 2. Motor 1 &2 Theoretical & Experimental Torque Speed Comparison