Utilization of High Efficient Single Phase Motor

Senior Project Report

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ABSTRACT

A Smith Motor is a three phase induction motor that has shunt capacitors parallel to its induction coils. The shunt capacitors provide balance and allow the motor to operate using a single phase power supply. Preliminary studies show that the Smith Motor is more efficient than a single phase induction motor powered by a single phase power supply, but less efficient than a three phase induction motor powered by a three phase power supply. The Smith Motor's advantage is its ability to operate from a single phase power source instead of having a three phase power source installed. Its limitation to operate properly for varying loads is its disadvantage. One way to solve this problem is to develop a control system that can change the capacitors to correspond with the different sets of loads. The three phase induction motor will be tested in order to calculate proper shunt capacitor values for the Smith Motor. Then the Smith Motor will be tested for its efficiency, power factor, winding current, and winding voltage at various loads. The data will be utilized in order to construct a control system (a switch) that changes the capacitor values. This will allow the Smith Motor to operate in a more balanced state for varying loads.

I. BACKGROUND

This project utilizes the Smith Motor created by Dr. Otto Smith. The Smith Motor is a three phase motor that has been modified to run using a single phase source. In figure 1, the capacitors are configured to balance the motor winding's voltages and currents. Using this configuration, Smith was essentially able to create a high efficient single phase motor using a three phase motor.

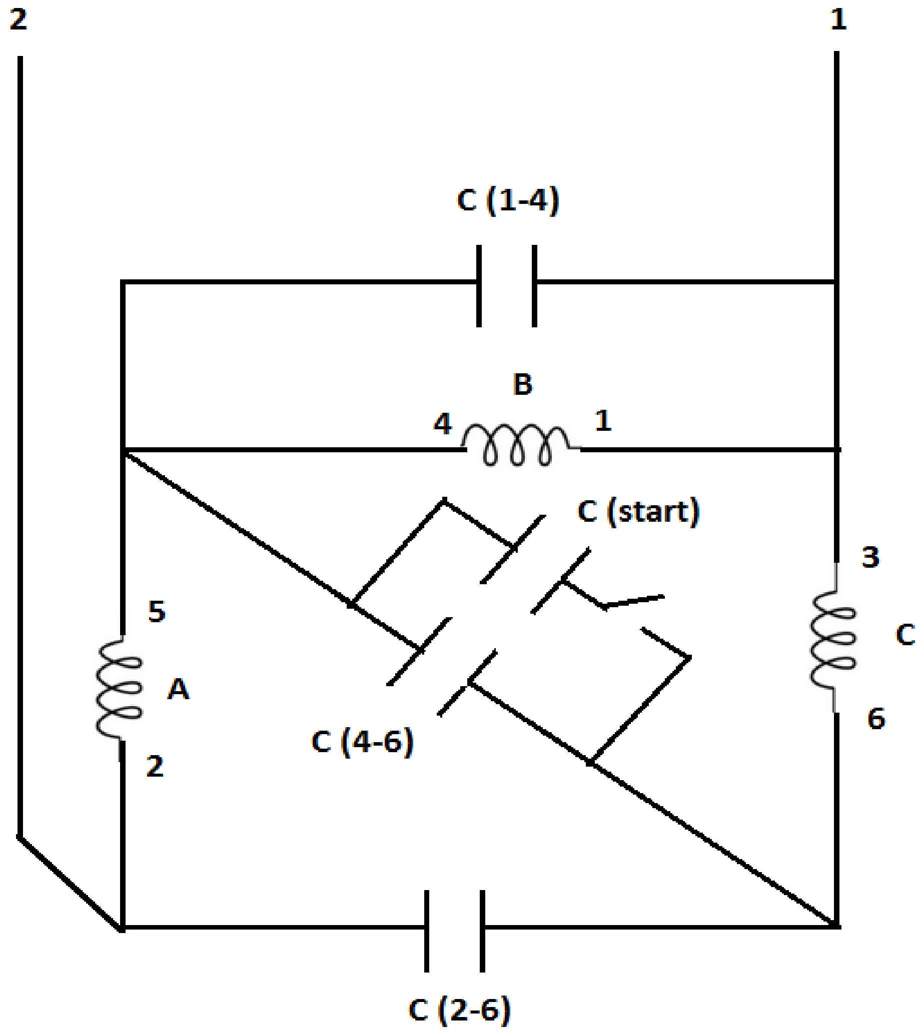


Figure 1: Smith Motor Design [9]

II. INTRODUCTION

The Smith Motor can operate using a single phase power source while still providing greater efficiency than a single phase induction motor and comparable efficiency to that of an ordinary three phase motor setup. According to previous studies, the efficiency increases of about an average of ten percent. The reason why the Smith Motor is not practical is due to its balancing characteristics. The Smith Motor design requires calculating capacitor values dependent on the operating load. If the motor is design to operate at full load, but the motor is operating at no load, the winding current will exceed the rated current of the motor. The purpose of this project is to overcome this condition by creating a control system that adds or subtracts capacitance to follow the change in the operating load. Solid state inverters, rotary phase converters, and digital phase converters currently exist as devices that allow a three phase motor to be powered by a single phase power source. The problems with these converters are their size, cost, or efficiency reduction. Thus, another problem to encounter is making the design small and inexpensive while maintaining high efficiency.

In 1995, Jon Morris' senior project (Figure 2) utilizes the Smith Motor by designing an automatic switch control that causes shunt capacitors to be added to the capacitor network. Doing so allows the Smith Motor design to switch from a 65.58 percent load design to a full load design. This method is valid because the 65 percent load characteristic did not cause the winding current to exceed the rated current conditions when operated at no load. His design utilizes an external power source and an AC/DC converter for the hysteresis comparator.

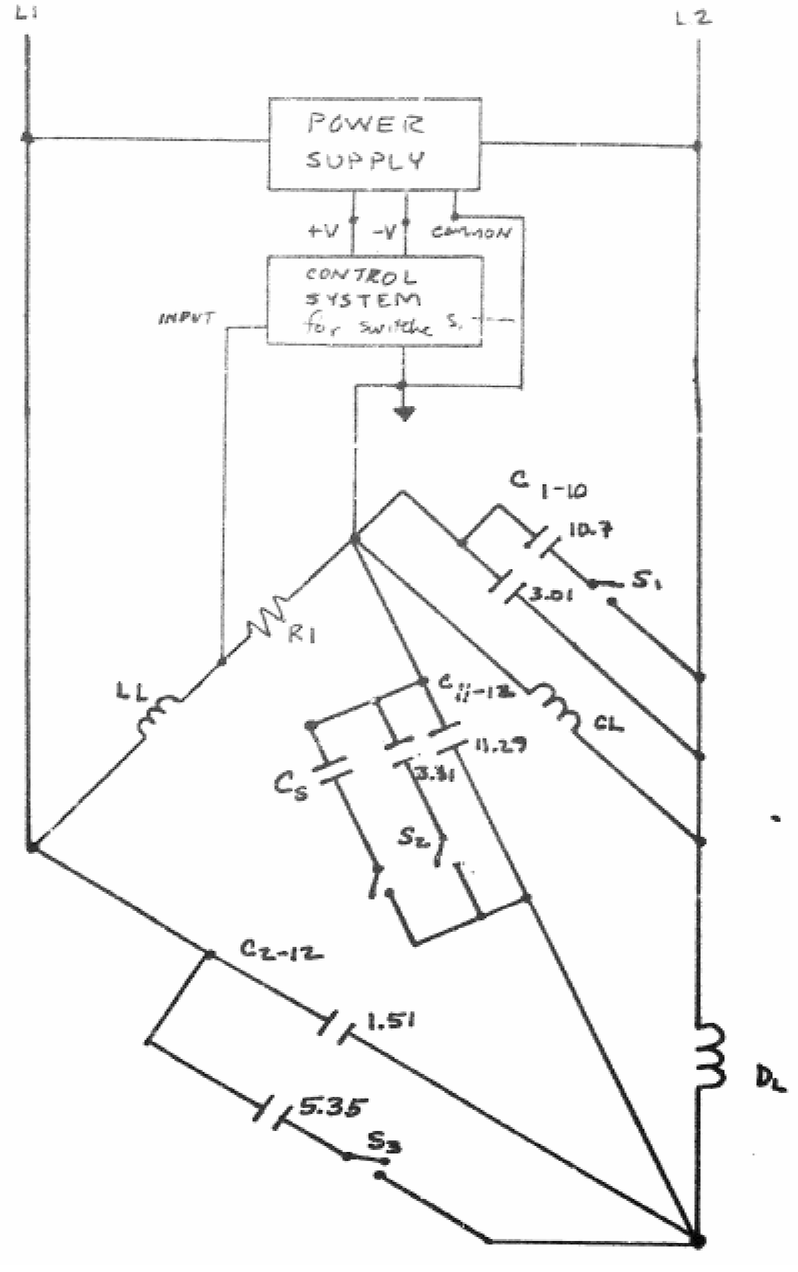
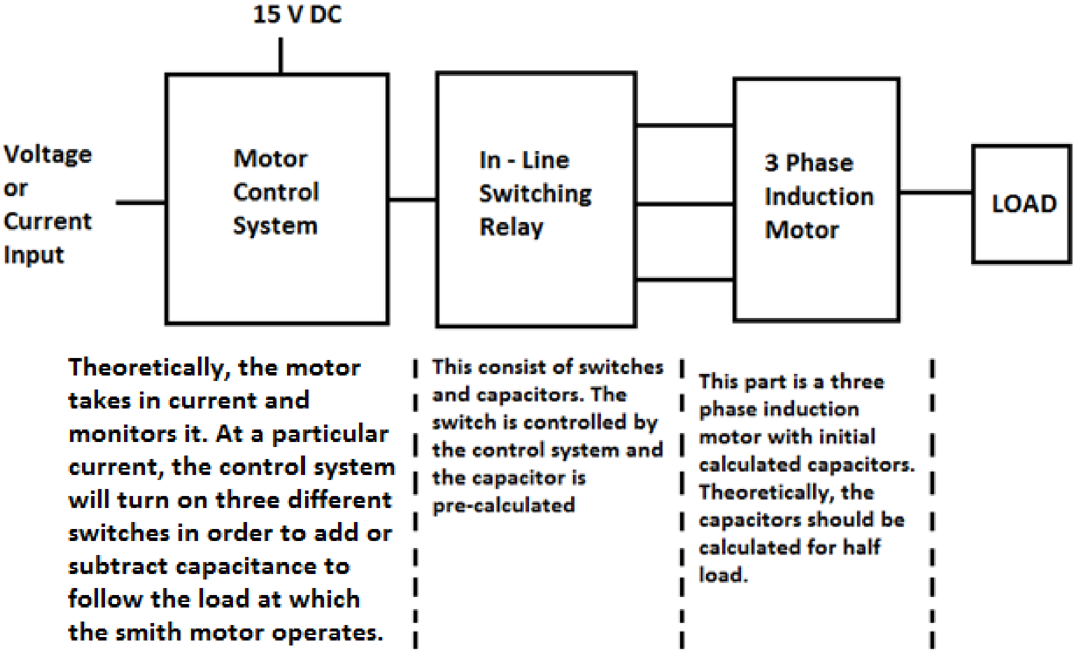


Figure 2: Jon Morris' Block Diagram [6]

The goal of the project is to create a control system that allows the Smith Motor to operate properly or smoothly from no load to full load while keeping the design cheap, efficient, and compact. This means choosing the better load design and choosing common ICs to create the control system.

III. PRELIMINARY DESIGN DISCUSSION

Figure 3 shows a high level block diagram of what the senior project must perform. There are many ways to design the control system. I must first choose between monitoring voltage or current as the input to my control system. The control system can be operated via microprocessor or analog components. The system will control the in-line switching relays that will add or subtract capacitance from the shunt capacitors. The capacitor load design will be chosen based on the voltage/current data of the three phase motor.



Theoretically, the motor takes in current and monitors it. At a particular current, the control system will turn on three different switches in order to add or subtract capacitance to follow the load at which the smith motor operates.

This consist of switches and capacitors. The switch is controlled by the control system and the capacitor is pre-calculated

This part is a three phase induction motor with initial calculated capacitors. Theoretically, the capacitors should be calculated for half load.

Figure 3: High Level Project Design Black Box Diagram Description

IV. PROJECTED REQUIREMENTS AND SPECIFICATIONS

Market Requirement	Engineering Specifications	Justifications
1	Design must perform an improvement of 5% or more in its efficiency	Study claims that the Smith Motor, if designed correctly, should have an increase in efficiency of at least 10%
2	Design shall use small analog components or microprocessor in order to reduce the size of the design	By designing a circuit instead of using a pre-built phase converter, the design can be easily added on
3	The design will be given a single-phase power source to operate on	The single phase to three phase interface will be one of its prime features so it may be useable via common households
4	The Bill of Materials must be less than $40	By using common analog components, the system can be repaired if broken and be easily available
Marketing Requirement 1. Higher Efficiency Compared to its Single-Phase Counterpart (> or = +5%) 2. Must fit Within a 5x5x5 inch Box 3. Must Operate from a Single-Phase Voltage Power Source 4. The Control System Must Be < $40		

Table 1: Project Design Requirements and Specifications

V. TESTING PART 1

The ultimate goal of this senior project is to compare the efficiency between a single phase motor, a three phase motor, and the Smith Motor. This section includes the data taken for the single phase induction motor, three phase squirrel cage induction motor, calculated capacitor value per load, and three different load design of the smith motor respectively.

As stated before, the Smith Motor is a unique design that utilizes shunt capacitors in order for it to operate from a single phase power supply. In order to calculate these capacitor values, I must first run the three phase motor using a three phase source for various loads and obtain the current and voltage characteristics of each winding/leg of the motor. The current and voltage values will be used to calculate the capacitance value for each winding per load design. The following tables and figures in this section includes the tested and calculated data.

Single Phase Induction Motor Measurements

Equipment:

WT130 Digital Power Wattmeter (EE 6230)
Dynamometer (EE 4519)
Multi-Function Machine Single Phase AC Motor

Nameplate Information – Single Phase Motor				
ID: 390532-7B	Type: CS	FR: L56	HP: 0.33	Hz: 60
RPM: 1725	Volts: 115	Amps: 5.8	PH: 1	Code: M

Table 2: Nameplate Information for the Single Phase Motor

Data – Single Phase Measurements							
Torque (in-lb)	Speed (RPM)	Voltage (V)	Current (A)	Power (W)	Power Factor	Output Power (W)	Efficiency (%)
0.03	1796	114.7	5.19	129	0.211	0.64	0.49
1	1794	114.7	5.16	146	0.249	21.24	14.55
2	1791	114.7	5.09	168	0.284	42.41	25.24
3	1788	114.5	5.13	190	0.321	63.51	33.43
4	1784	114.6	5.16	214	0.356	84.49	39.48
5	1780	114.4	5.19	237	0.394	105.38	44.46
6	1778	114.3	5.26	260	0.427	126.31	48.58
7	1774	114.2	5.42	283	0.463	147.03	51.95
8	1770	114.2	5.43	308	0.490	167.65	54.43
9	1767	114.1	5.50	334	0.526	188.29	56.37
10	1763	114.1	5.61	359	0.550	208.74	58.14
11	1760	114.1	5.75	384	0.575	229.22	59.69
12	1754	113.8	5.85	410	0.603	249.21	60.78

Table 3: Data for the Single Phase Motor

$\text{Power}_{\text{out}}$ (W) = 1.184×10^{-2} (W) * speed(RPM) * Torque(in-lb)

Three Phase Squirrel Cage Induction Motor Measurements

Equipment:

WT130 Digital Power Wattmeter (EE 6230)
Dynamometer (EE 4519)
Three-Phase Squirrel Cage Induction Motor: 4 - Voltage

Nameplate Information				
Type: TM-100-6	No: 884	Voltage: 208/240	Amps: 1.8/1.6	HP: 0.33
PH: 3	Cycle: 60	RPM: 1725	Code:	Duty: Cont.

Table 4: Nameplate Information for the Three Phase Squirrel Cage Motor

Data - Three Phase Measurements								
Torque (in-lb)	Speed (RPM)	Voltage (V)	Current (A)	Angle Θ (°)	Power (W)	$\text{Power}_{\text{out}}$ (W)	Efficiency (%)	Power Factor
0.46	1794	207.3	1.010	78.5	74	9.77	13.20	0.199
1	1791	207.2	1.016	76.4	88	21.21	24.10	0.235
2	1787	207.5	1.032	72.9	111	42.32	38.13	0.294
3	1783	207.2	1.048	69.5	132	63.33	47.98	0.350
4	1778	207.0	1.070	66.3	155	84.21	54.33	0.402
5	1773	207.1	1.108	63.1	180	104.96	58.31	0.452
6	1768	207.1	1.130	60.2	201	125.60	62.49	0.497
7	1764	206.9	1.167	57.4	225	146.20	64.98	0.539
8	1758	206.5	1.207	54.9	250	166.52	66.61	0.575
9	1753	206.8	1.254	52.4	275	186.80	67.93	0.610
10	1748	206.5	1.299	50.4	299	206.96	69.22	0.637
11	1743	206.7	1.347	48.3	323	227.01	70.28	0.665
12	1737	206.7	1.406	46.4	350	246.79	70.51	0.690
13	1732	206.6	1.462	44.6		266.59	71.28	0.712
14	1725	206.5	1.528	43.0	403	285.94	70.95	0.731

Table 5: Data for the Three Phase Squirrel Cage Motor

Capacitor Calculations

Governing Equation

$Z_C = V_C / I_C = -j / \omega C \quad \rightarrow \quad C = I_C / (2\,\pi\, f\, V_C)$

Equation for Each Capacitor

$C_{2\text{-}6} = I_{C\,2\text{-}6} / (2\,\pi\, f\, V_{C\,2\text{-}6})$, where $f = 60$ Hz , $V_{C\,2\text{-}6} = 240$, $I_{C\,2\text{-}6}$ calculated

$C_{1\text{-}4} = I_{C\,1\text{-}4} / (2\,\pi\, f\, V_{C\,1\text{-}4})$, where $f = 60$ Hz , $V_{C\,2\text{-}6} = 120$, $I_{C\,1\text{-}4}$ calculated

$C_{4\text{-}6} = I_{C\,4\text{-}6} / (2\,\pi\, f\, V_{C\,4\text{-}6})$, where $f = 60$ Hz , $V_{C\,2\text{-}6} = 208$, $I_{C\,4\text{-}6}$ calculated

Current of Needed Capacitor Calculation

$I_{C\,2\text{-}6} = 2I\sin(60^\circ - \Theta)$ $\qquad I_{C\,1\text{-}4} = I_{C\,2\text{-}6} = 2I\sin(60^\circ - \Theta)$ $\qquad I_{C\,4\text{-}6} = 2I\sin(\Theta^\circ - 30)$

Data - Three Phase Measurements (Full Load = 12 in-lb)							
Torque (in-lb)	Torque (% of FL)	$I_{C2\text{-}6}$	$I_{C1\text{-}4}$	$I_{C4\text{-}6}$	C2-6 (μF)	C1-4 (μF)	C4-6 (μF)
0.46	3.83	-0.641	-0.641	1.513	-7.084	-14.2	19.3
1	8.33	-0.574	-0.574	1.472	-6.341	-.2.7	18.8
2	16.66	-0.461	-0.461	1.405	-5.093	-10.2	17.9
3	25.00	-0.346	-0.346	1.333	-3.823	-7.65	17.0
4	33.33	-0.235	-0.235	1.267	-2.595	-5.19	16.2
5	41.66	-0.120	-0.120	1.210	-1.325	-2.65	15.4
6	50.00	-0.008	-0.008	1.137	-8.719	-0.174	14.5
7	58.33	0.106	0.106	1.074	1.170	2.34	13.7
8	66.66	0.215	0.215	1.016	2.371	4.74	13.0
9	75.00	0.332	0.332	0.956	3.666	7.33	12.2
10	83.33	0.433	0.433	0.906	4.788	9.58	11.5
11	91.66	0.546	0.546	0.846	6.038	12.1	10.8
12	100.00	0.661	0.661	0.794	7.308	14.6	10.1
13	108.33	0.777	0.777	0.737	8.582	17.2	9.4
14	116.66	0.894	0.894	0.687	9.875	19.8	8.8

Table 6: Smith Motor Calculated Capacitance

100% Load Design (Smith Motor) Measurements

Equipment:

WT130 Digital Power Wattmeter (EE 6230)
Dynamometer (EE 4519)
Three-Phase Squirrel Cage Induction Motor: 4 - Voltage
Capacitors
2 Fluke Meters

Capacitor Values Used:

C2-6 = 7.39uF , C1-4 = 14.7uF , C4-6 = 10.1

Data - 100% Smith Motor Load Design											
Torque (in-lb)	Speed (RPM)	V_{LINE} (V)	I_{INE} (A)	P_{IN} (W)	V(1-4) (V)	V(2-5) (V)	V(3-6) (V)	I(1-4) (A)	I(2-5) (A)	I(3-6) (A)	Power Factor
0.06	1792	206.4	0.596	115	131.7	113.5	135.4	1.62	0.45	1.83	0.935
1	1788	206.2	0.681	132	130.9	114	134.8	1.6	0.46	1.76	0.940
2	1785	206.2	0.762	149	130.1	114.4	133.7	1.588	0.49	1.68	0.948
3	1781	206.1	0.843	166	129.3	114.8	132.8	1.575	0.54	1.62	0.955
4	1777	206.4	0.945	185	128.2	115.8	131.6	1.557	0.62	1.54	0.948
5	1771	206.1	1.023	204	127.2	115.9	130.3	1.537	0.7	1.49	0.968
6	1766	206.4	1.115	223	126	116.3	128.8	1.517	0.79	1.44	0.969
7	1762	206.1	1.208	243	124.3	116.9	126.9	1.493	0.88	1.4	0.976
8	1756	206.1	1.303	264	123.1	117.4	124.9	1.467	0.99	1.37	0.983
9	1751	206	1.408	285	121.8	117.8	123.1	1.445	1.1	1.36	0.983
10	1744	205.8	1.521	311	120.7	118	120.9	1.422	1.22	1.38	0.994
11	1738	205.8	1.625	335	119.1	118.2	118.9	1.4	1.34	1.4	1.001
12	1730	205.8	1.755	358	118	118.5	116.7	1.38	1.47	1.46	0.991
13	1722	205.8	1.883	386	116.5	118.5	11434	1.361	1.61	1.53	0.996

Table 7: Data for the 100% Smith Motor Load Design

Power Factor (PF) = P_{in} / (V_{in} * I_{in})
$Power_{out}$ (W) = $1.184*10^{-2}$ (W) * speed(RPM) * Torque(in-lb)
Efficiency = $Power_{out}$ / $Power_{in}$

75% Load Design (Smith Motor) Measurements

Equipment:

WT130 Digital Power Wattmeter (EE 6230)
Dynamometer (EE 4519)
Three-Phase Squirrel Cage Induction Motor: 4 - Voltage
Capacitors
2 Fluke Meters

Capacitor Values Used:

C2-6 = 3.14uF , C1-4 = 7.39uF , C4-6 = 12.17

Data - 75% Smith Motor Load Design											
Torque (in-lb)	Speed (RPM)	V_{LINE} (V)	I_{INE} (A)	P_{IN} (W)	V(1-4) (V)	V(2-5) (V)	V(3-6) (V)	I(1-4) (A)	I(2-5) (A)	I(3-6) (A)	Power Factor
0.01	1793	206.9	0.53	91.2	129.2	114	130	1.345	0.6	1.648	0.832
1	1790	206.9	0.6	109.5	128.3	114.6	129.1	1.335	0.62	1.58	0.882
2	1785	206.9	0.665	127.3	127.5	115.1	128.1	1.322	0.67	1.508	0.925
3	1780	206.9	0.754	146.3	126.3	115.7	126.6	1.304	0.72	1.436	0.938
4	1776	206.8	0.835	165	125.2	116.4	125.3	1.286	0.79	1.389	0.956
5	1771	206.9	0.93	186	123.8	117.1	123.6	1.265	0.87	1.338	0.967
6	1767	207	1.036	208.7	122.5	117.5	121.8	1.241	0.97	1.3	0.973
7	1762	206.8	1.129	227.2	121.4	118	120.3	1.227	1.05	1.288	0.973
8	1755	206.8	1.248	252.1	120	118.4	118.4	1.204	1.17	1.289	0.977
9	1751	206.8	1.364	274.1	118.8	118.7	116.6	1.186	1.27	1.309	0.972
10	1742	206.7	1.49	301.7	117.5	118.9	114.6	1.116	1.4	1.351	0.980
11	1735	206.7	1.618	327.9	116.2	119	112.4	1.146	1.53	1.3413	0.980
12	1728	206.4	1.746	335.9	114.8	119.1	110.1	1.124	1.67	1.5	0.932

Table 8: Data for the 75% Smith Motor Load Design

Power Factor (PF) = P_{in} / (V_{in} * I_{in})
$Power_{out}$ (W) = 1.184*10^{-2} (W) * speed(RPM) * Torque(in-lb)
Efficiency = $Power_{out}$ / $Power_{in}$

58.33% Load Design (Smith Motor) Measurements

Equipment:

- WT130 Digital Power Wattmeter (EE 6230)
- Dynamometer (EE 4519)
- Three-Phase Squirrel Cage Induction Motor: 4 - Voltage
- Capacitors
- 2 Fluke Meters

Capacitor Values Used:

C2-6 = 1.00uF , C1-4 = 2.05uF , C4-6 = 13.23

Data – 58.33% Smith Motor Load Design											
Torque (in-lb)	Speed (RPM)	V_{LINE} (V)	I_{INE} (A)	P_{IN} (W)	V(1-4) (V)	V(2-5) (V)	V(3-6) (V)	I(1-4) (A)	I(2-5) (A)	I(3-6) (A)	Power Factor
0.02	1793	206.8	0.689	85.4	126.5	114.5	126.4	1.213	0.72	1.489	0.599
1	1789	206.5	0.726	100.7	125.8	114.9	125.2	1.199	0.74	1.4	0.672
2	1786	206.8	0.778	119.7	124.8	115.6	124.1	1.184	0.79	1.359	0.744
3	1780	206.6	0.845	139.1	123.5	116.3	122.4	1.166	0.85	1.298	0.797
4	1776	206.5	0.925	159.1	122.2	116.9	120.9	1.146	0.92	1.257	0.833
5	1770	206.4	1.021	181.7	120.8	117.4	119.2	1.26	1.01	1.22	0.862
6	1765	206.5	1.121	204.3	119.5	117.9	117.6	1.108	1.1	1.21	0.883
7	1759	206.5	1.226	226.2	118.3	118.2	115.9	1.089	1.19	1.216	0.893
8	1753	206.3	1.335	250.6	117.1	118.5	114.3	1.072	1.3	1.243	0.910
9	1747	206.6	1.448	276.3	115.9	118.9	112.5	1.055	1.41	1.293	0.924
10	1740	206.6	1.583	303.7	114.8	119	110.3	1.035	1.53	1.362	0.929
11	1731	206.4	1.723	330.4	113.6	119.2	108.3	1.016	1.66	1.45	0.929
12	1723	203.2	1.862	358.9	112	119.2	105.9	0.993	1.8	1.55	0.949

Table 9: Data for the 58.33% Smith Motor Load Design

Power Factor (PF) = P_{in} / (V_{in} * I_{in})
$Power_{out}$ (W) = $1.184*10^{-2}$ (W) * speed(RPM) * Torque(in-lb)
Efficiency = $Power_{out}$ / $Power_{in}$

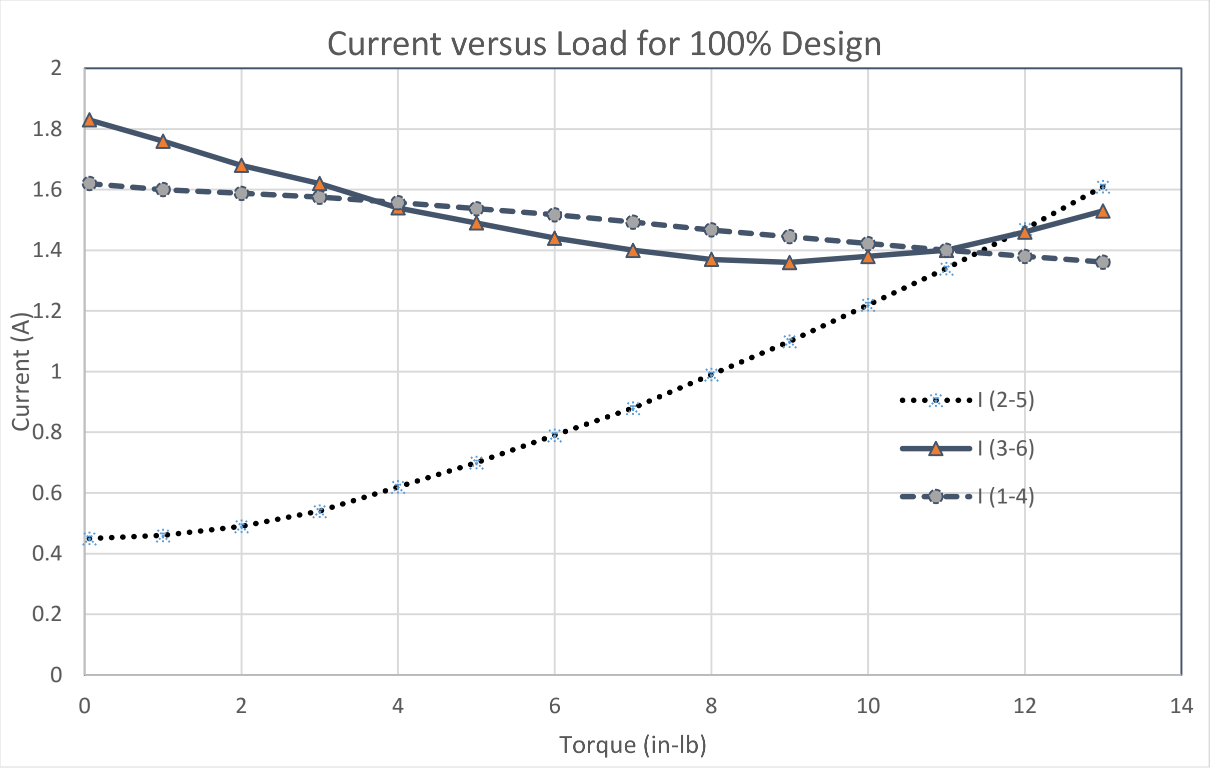


Figure 4: Current vs. Load (100%)

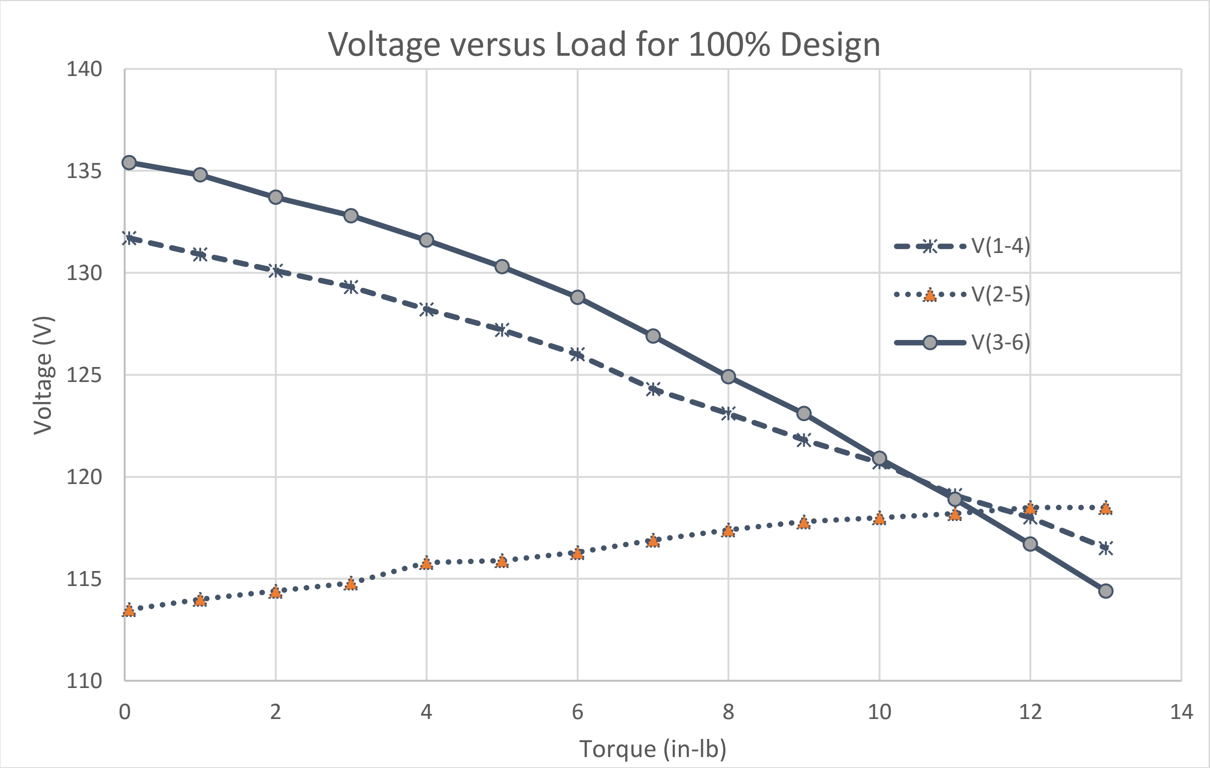


Figure 5: Voltage vs. Load (100%)

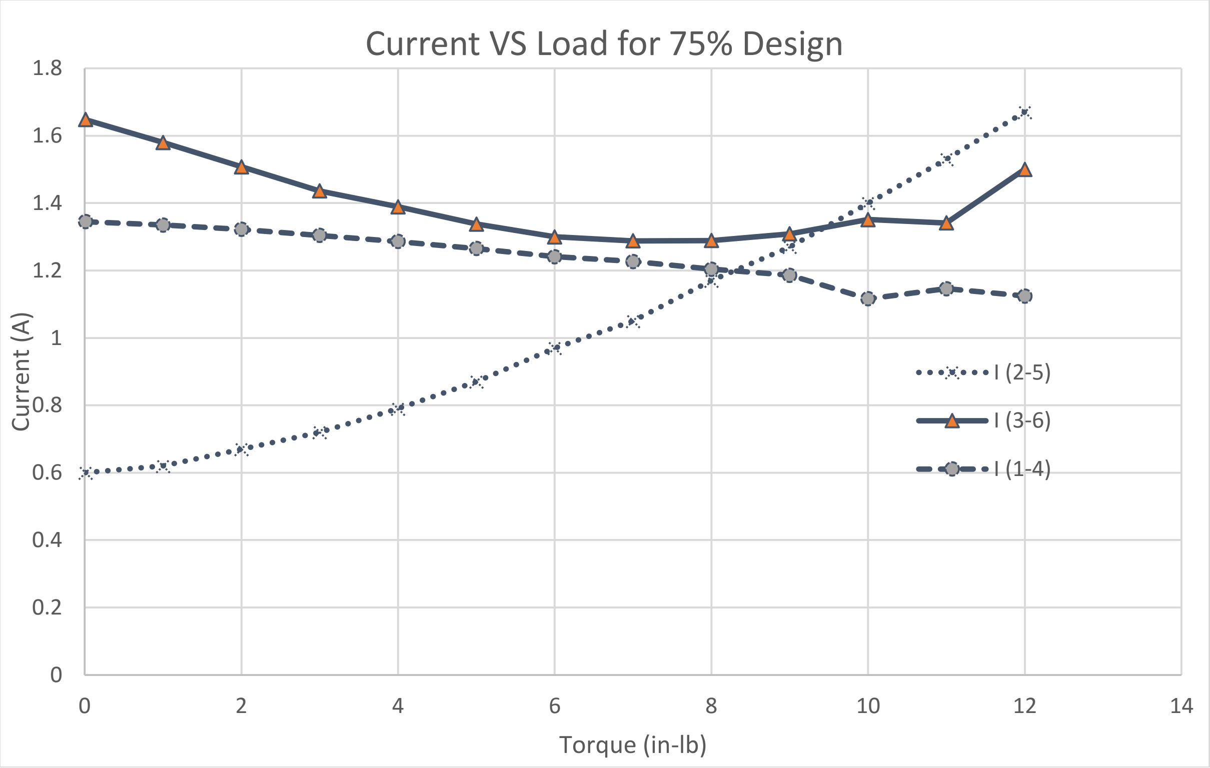


Figure 6: Current vs. Load (75%)

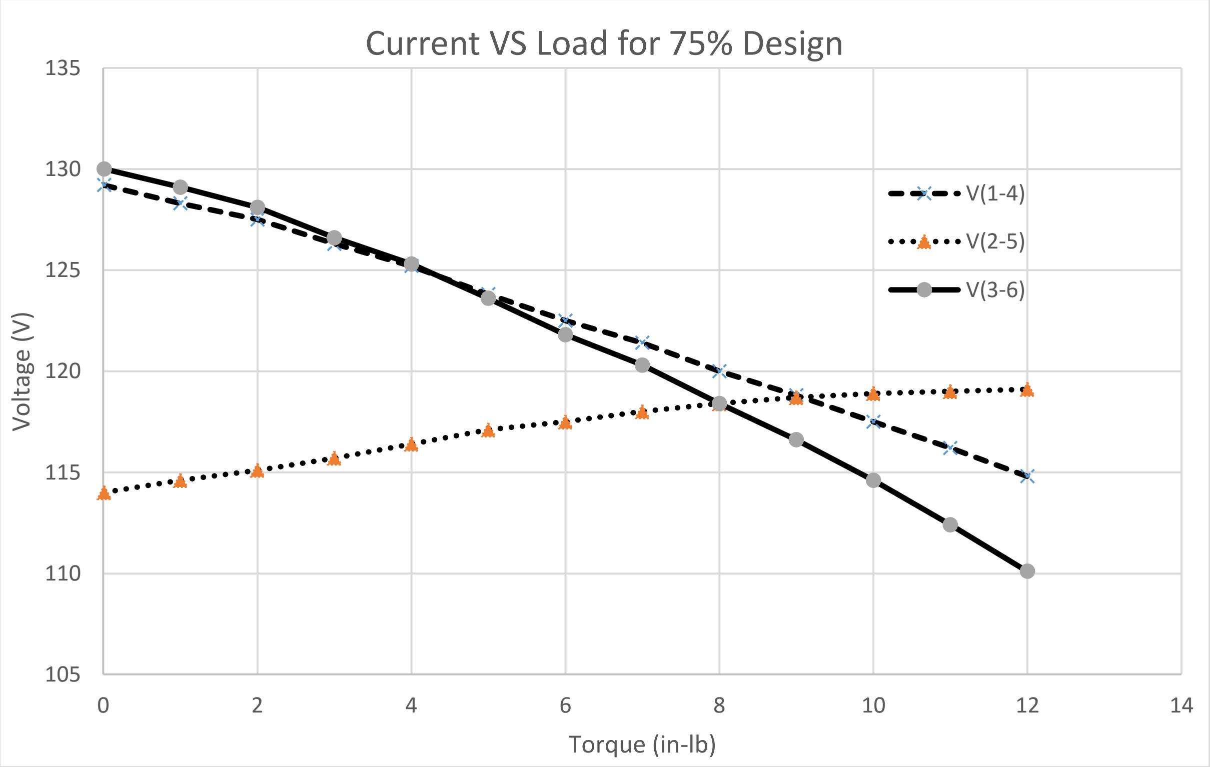


Figure 7: Voltage vs. Load (75%)

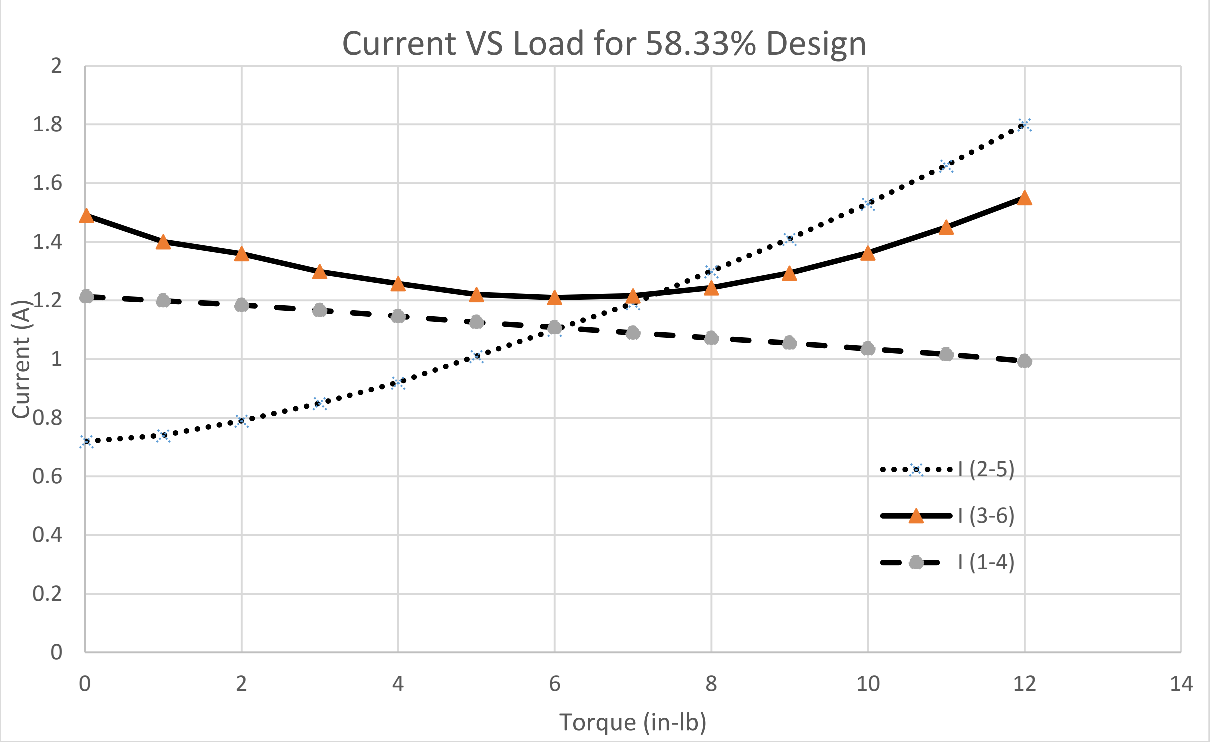


Figure 8: Current vs. Load (58.33%)

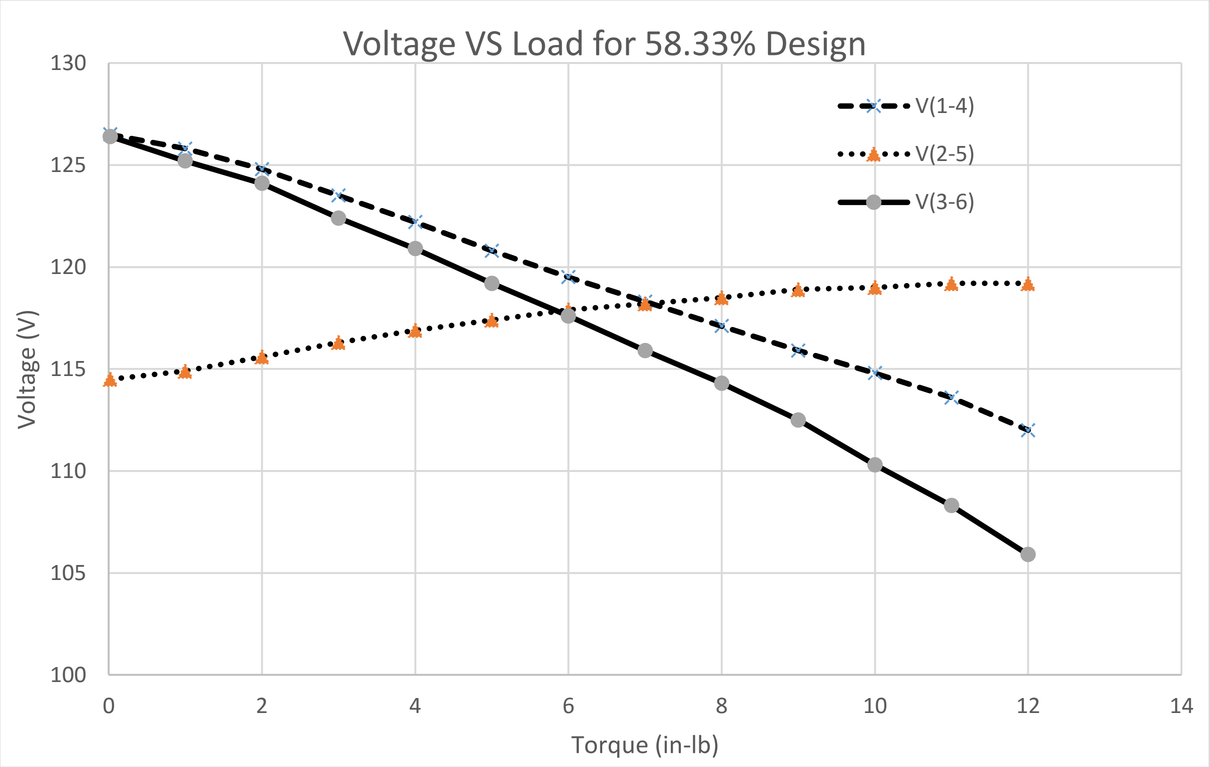


Figure 9: Voltage vs. Load (58.33%)

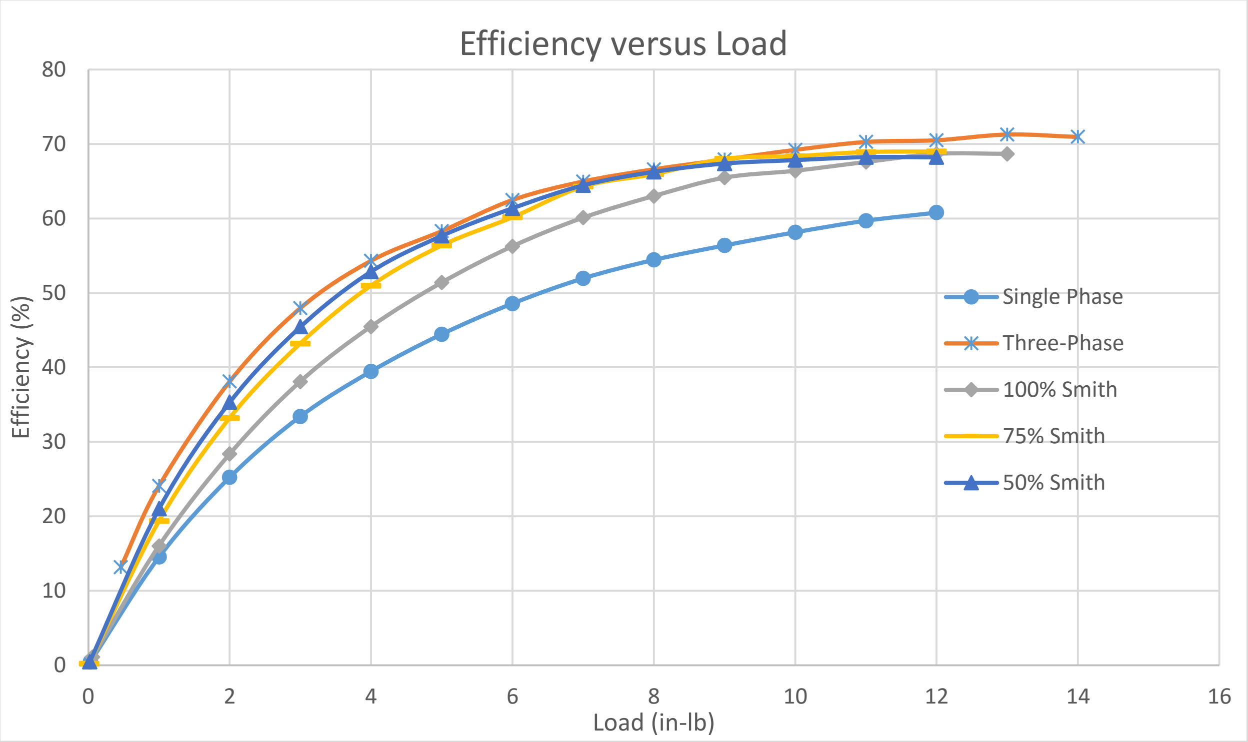


Figure 10: Efficiency vs. Load Comparison

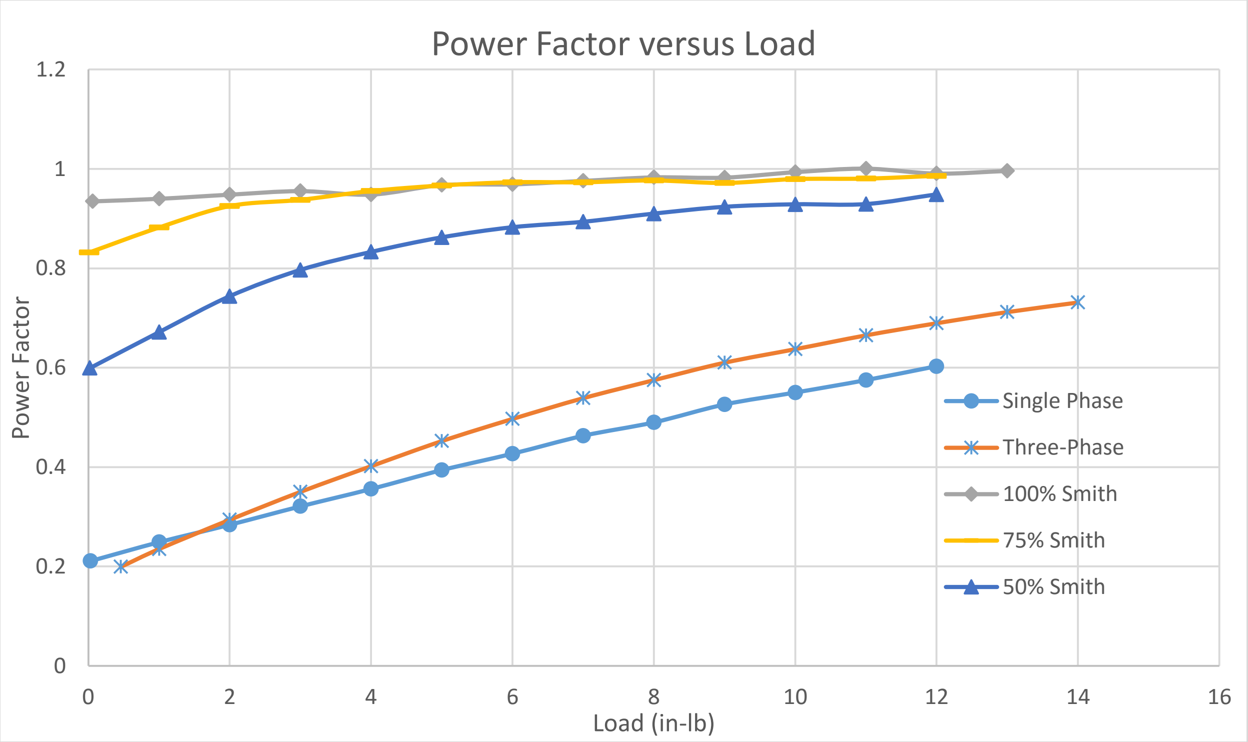


Figure 11: Power Factor vs. Load Comparison

Test 1 Discussion

As we can confirm from figures 10, the efficiency of the Smith Motor is greater than the single phase induction motor, but less efficient than the three phase motor. On average, the Smith Motor is about 10 percent more efficient than the single phase induction motor. Depending on the load design and operation, the Smith Motor is between 1 to 2 percent less efficient that the three phase motor. From the efficiency graph, we see that the 58.33% design load is more efficient that the 100% load until about 10 to 11 in-lb. When designing the control system, this efficiency factor will play a part as to choose which load design to start with.

Another factor contributing to the design choices is the balancing of the system. Figures 4 and 5 show that the voltage and current are balanced at about 12 in-lb for the 100% load design. Figures 6 and 7 show that the voltage and current are balanced at about 9 in-lb for the 75% load. Figures 8 and 9 show that the voltage and current are balanced at about 7 in-lb. Ideally, I will want the currents and voltages to be balanced at any load the machine operates at. For my design, I want the voltages and currents to be balanced at 7 in-lb and 12 in-lb. Thus, the 58.33% load design seems like the logical choice to begin with - switching to the 100% load design.

The last factor that contributes to the design choices is the current ratings. The motor is rated to operate at a maximum of 1.8 amps. From figure 4, we see that the current at no-load for the 100% load design is slightly higher than 1.8 amps. The best choice to begin operating the motor will be at the 58.33% load, as it falls under the maximum current ratings.

VI. DESIGN

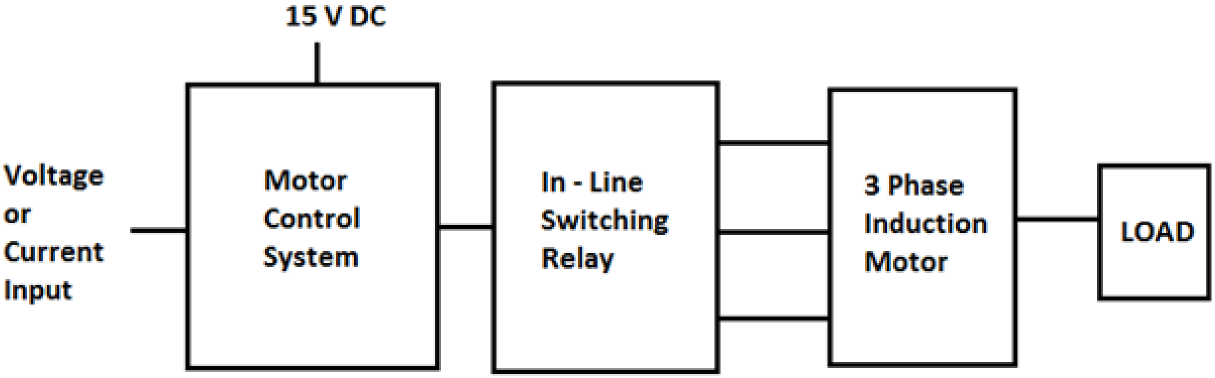
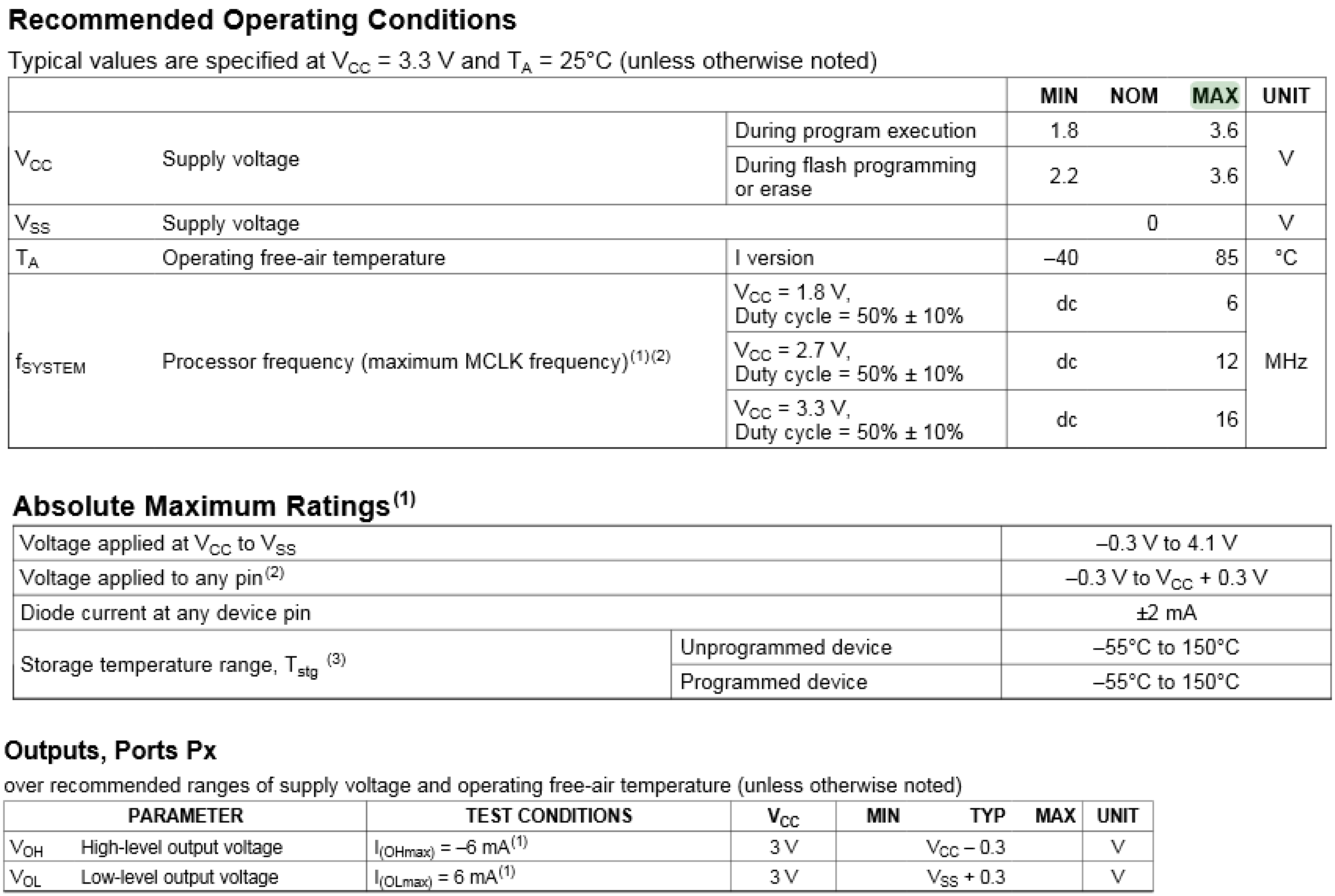


Figure 12: High Level Block Diagram

For my design, I must first choose how I want to operate the control system. In this project, I have chosen to use a microprocessor (MSP430G2553) to serve as the center of the control system. The microprocessor has an internal analog-to-digital converter that reads in different levels of voltage. Thus, the input signal to the microcontroller must be in volts. The control system must read in data from either the current or voltage provided by a leg of the motor, convert it to usable data, and activate switches based on the input. The microprocessor needs to handle the voltage and current coming into the input ports. Knowing this information will allow me to use a transformer to reduce the voltage or a current sensor that converts current into voltage as an input signal. This must be done without destroying the microprocessor. The microprocessor's datasheet shown in figure 9 will help with choosing the proper transformer or current sensor for the input. The transformer or current sensor cannot be chosen using only the microprocessor's datasheet, but must also use the current characteristics of the motor during operation.



Recommended Operating Conditions

Typical values are specified at V_{CC} = 3.3 V and T_A = 25°C (unless otherwise noted)

			MIN	NOM	MAX	UNIT
V_{CC}	Supply voltage	During program execution	1.8		3.6	V
		During flash programming or erase	2.2		3.6	
V_{SS}	Supply voltage			0		V
T_A	Operating free-air temperature	I version	–40		85	°C
f_{SYSTEM}	Processor frequency (maximum MCLK frequency)(1)(2)	V_{CC} = 1.8 V, Duty cycle = 50% ± 10%	dc		6	MHz
		V_{CC} = 2.7 V, Duty cycle = 50% ± 10%	dc		12	
		V_{CC} = 3.3 V, Duty cycle = 50% ± 10%	dc		16	

Absolute Maximum Ratings(1)

Voltage applied at V_{CC} to V_{SS}		–0.3 V to 4.1 V
Voltage applied to any pin(2)		–0.3 V to V_{CC} + 0.3 V
Diode current at any device pin		±2 mA
Storage temperature range, T_{stg} (3)	Unprogrammed device	–55°C to 150°C
	Programmed device	–55°C to 150°C

Outputs, Ports Px

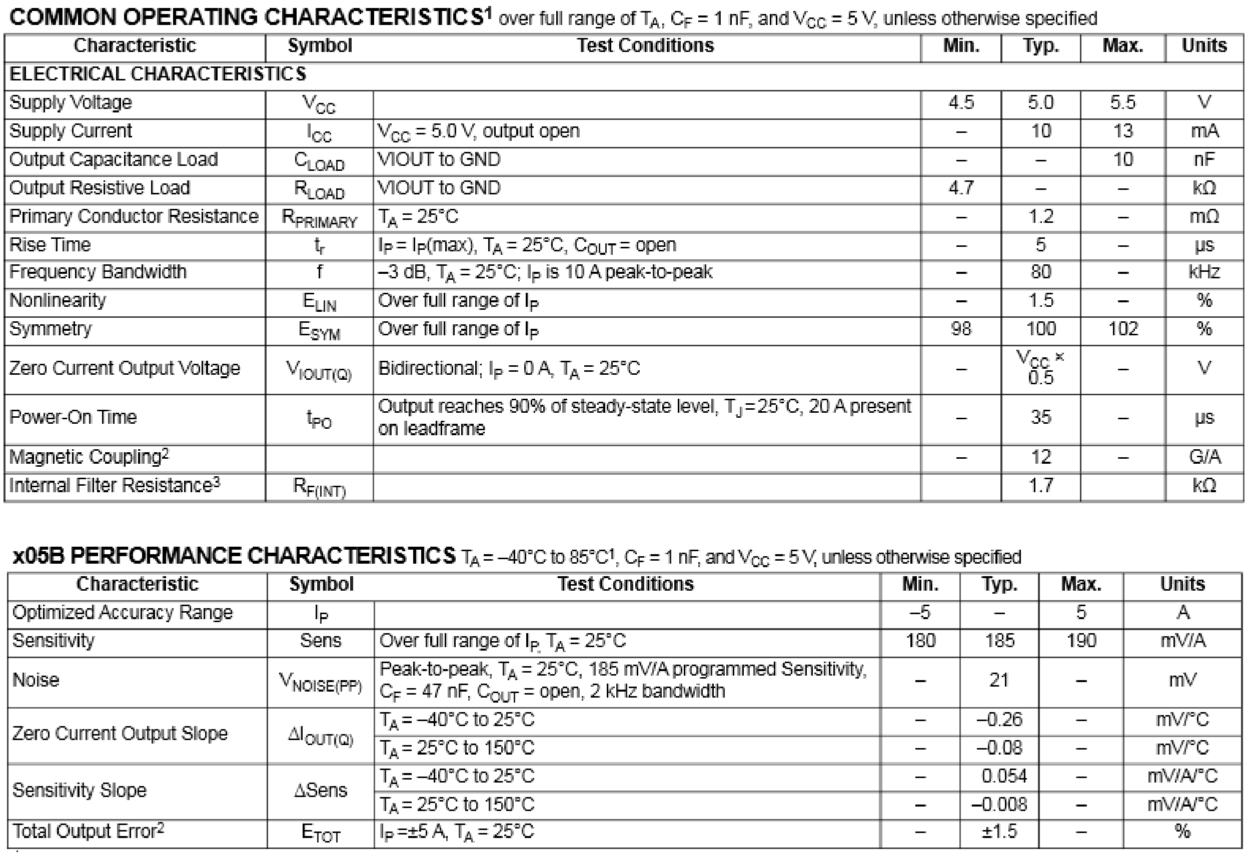
over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V_{CC}	MIN	TYP	MAX	UNIT
V_{OH}	High-level output voltage	$I_{(OHmax)}$ = –6 mA(1)	3 V		V_{CC} – 0.3		V
V_{OL}	Low-level output voltage	$I_{(OLmax)}$ = 6 mA(1)	3 V		V_{SS} + 0.3		V

Figure 13: MSP430 Datasheet Information

In this project, sensitivity is important because the project requires a control system that reads in data (current or voltage) and performs switches accordingly. If the sensitivity of the change is small or insignificant, the control system will have a harder time identifying changes made in the system. Thus, a highly sensitive input is desired. Choosing voltage or current is almost arbitrary. The voltage can be used due to its sensitivity, but will require a transformer to reduce the voltage for the control system to handle. Figures 4, 6, and 8 show that the leg current I (2-5) can be used due to its sensitivity, but requires a current sensor that will output voltage. Between the current sensor and transformer, I chose the current sensor because it is cheaper and more readily available in the market.

As shown in MSP430 Datasheet, the voltage applied to any pin can range from -0.3 volts to 4.1 volts. Thus, the current sesnor must output voltages within that range. I chose to read the input data from the current of leg 2-5 because *Sparkfun* has a current sensor (Hall Effect-Based Linear Current Sensor ACS712) that can measure up to 4 amps while outputting 185 millivolts per amp. Figure 14 shows the common operating characteristics as well as the performance characteristics of the current sensor.



COMMON OPERATING CHARACTERISTICS[1] over full range of T_A, C_F = 1 nF, and V_{CC} = 5 V, unless otherwise specified

Characteristic	Symbol	Test Conditions	Min.	Typ.	Max.	Units
ELECTRICAL CHARACTERISTICS						
Supply Voltage	V_{CC}		4.5	5.0	5.5	V
Supply Current	I_{CC}	V_{CC} = 5.0 V, output open	–	10	13	mA
Output Capacitance Load	C_{LOAD}	VIOUT to GND	–	–	10	nF
Output Resistive Load	R_{LOAD}	VIOUT to GND	4.7	–	–	kΩ
Primary Conductor Resistance	$R_{PRIMARY}$	T_A = 25°C	–	1.2	–	mΩ
Rise Time	t_r	I_P = I_P(max), T_A = 25°C, C_{OUT} = open	–	5	–	μs
Frequency Bandwidth	f	–3 dB, T_A = 25°C; I_P is 10 A peak-to-peak	–	80	–	kHz
Nonlinearity	E_{LIN}	Over full range of I_P	–	1.5	–	%
Symmetry	E_{SYM}	Over full range of I_P	98	100	102	%
Zero Current Output Voltage	$V_{IOUT(Q)}$	Bidirectional; I_P = 0 A, T_A = 25°C	–	V_{CC} × 0.5	–	V
Power-On Time	t_{PO}	Output reaches 90% of steady-state level, T_J = 25°C, 20 A present on leadframe	–	35	–	μs
Magnetic Coupling[2]			–	12	–	G/A
Internal Filter Resistance[3]	$R_{F(INT)}$			1.7		kΩ

x05B PERFORMANCE CHARACTERISTICS T_A = –40°C to 85°C[1], C_F = 1 nF, and V_{CC} = 5 V, unless otherwise specified

Characteristic	Symbol	Test Conditions	Min.	Typ.	Max.	Units
Optimized Accuracy Range	I_P		–5	–	5	A
Sensitivity	Sens	Over full range of I_P, T_A = 25°C	180	185	190	mV/A
Noise	$V_{NOISE(PP)}$	Peak-to-peak, T_A = 25°C, 185 mV/A programmed Sensitivity, C_F = 47 nF, C_{OUT} = open, 2 kHz bandwidth	–	21	–	mV
Zero Current Output Slope	$\Delta I_{OUT(Q)}$	T_A = –40°C to 25°C	–	–0.26	–	mV/°C
		T_A = 25°C to 150°C	–	–0.08	–	mV/°C
Sensitivity Slope	ΔSens	T_A = –40°C to 25°C	–	0.054	–	mV/A/°C
		T_A = 25°C to 150°C	–	–0.008	–	mV/A/°C
Total Output Error[2]	E_{TOT}	I_P = ±5 A, T_A = 25°C	–	±1.5	–	%

Figure 14: Current Sensor Operating and Performance Characteristics

This current sensor is ideal because it operates at 5 voltages like the MSP430. The current sensor provides a maximum of 3.15 volts into the pin of the microprocessor. It can also handle the amount of current that flows through it.

In order for the microprocessor to read the analog data from the current sensor, it must be converted to a digital signal. The microprocessor has an internal analog-to-digital converter (ADC) known as the ADC10. The characteristics of the ADC is important and I will need to access the datasheet in order to determine if the internal ADC has enough resolution to read the data that will be coming from the current sensor. But first I need to know what the current sensor will read. The following figure shows the currents of leg 2-5 for each percent design.

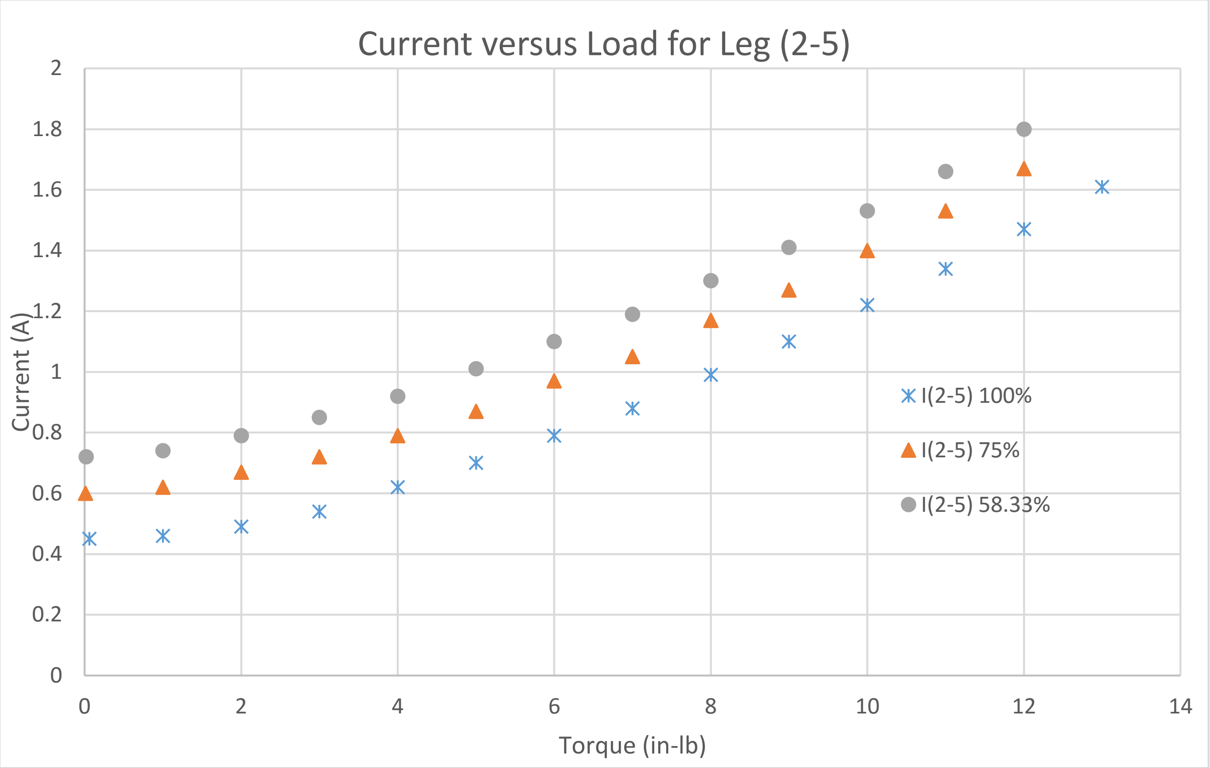
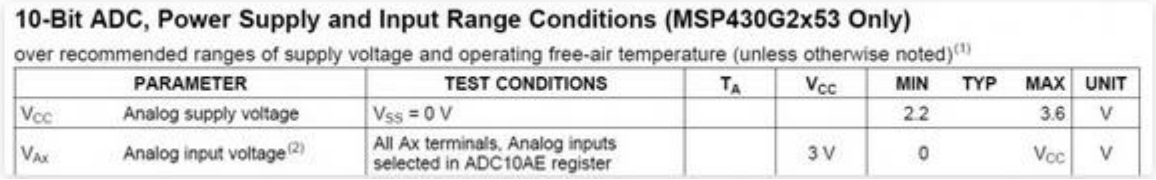


Figure 15: Leg Current (2-5) for each Load Design

Figure 15 shows the current that will be flowing through leg 2-5 for each design. To optimize the sensitivity needed for the microprocessor, a greater change is needed. Using the 58.33% load design to begin with and changing to the 100% load will optimized the sensitivity. The current sensor will read in currents from 0 amps to a maximum of 1.8 amps. The next step is to choose at what load the switch should activate. Figure 8 shows that the currents are balanced at 7 in-lb for the 58.33% load design and Figure 4 shows that the currents are balanced at 12 in-lb for the 100% load. For my design I will choose to activate the relay switch at 8 in-lb.

Note that if the design must switch from the 58.33% load design to the 100% load design at 8 in-lb, the current will drop from about 1.275 amps to 1 amps. If a simple switch is used, the microprocessor itself will have a problem because it will read a lower current after the switch and continuously switch between the two states. This pose a problem for the motor as continuous abrupt changes in current can damage the motor. Like a hysteresis inverter, the microprocessor will need to switch ON when the current exceeds 1.275 amps and switch OFF when the current falls below 0.9 amps. Based on the input reading, the current sensor will output certain voltages. To see if the ADC10 has enough resolution to effectively read the current sensor output values, I will need to access the datasheet. Figure 16 below shows the characteristics of the ADC10.



10-Bit ADC, Power Supply and Input Range Conditions (MSP430G2x53 Only)

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)(1)

PARAMETER		TEST CONDITIONS	T_A	V_{CC}	MIN	TYP	MAX	UNIT
V_{CC}	Analog supply voltage	V_{SS} = 0 V			2.2		3.6	V
V_{Ax}	Analog input voltage(2)	All Ax terminals, Analog inputs selected in ADC10AE register		3 V	0		V_{CC}	V

Figure 16: ADC10 Characteristics

The resolution may be calculated using figure 16. The ADC10 has 10 bits and ranges from 0 to 3.6 voltages.

10 bits → 2^{10} = 1024 bits or steps →

Resolution = 3.6 Volts / 1024 steps = 3.5 mV per step

Table 10 on the following page shows the conversion from input current, to output voltage, then to a digital value. From this table we see that the microprocessor’s ADC10 has enough resolution to provide for the changes in current.

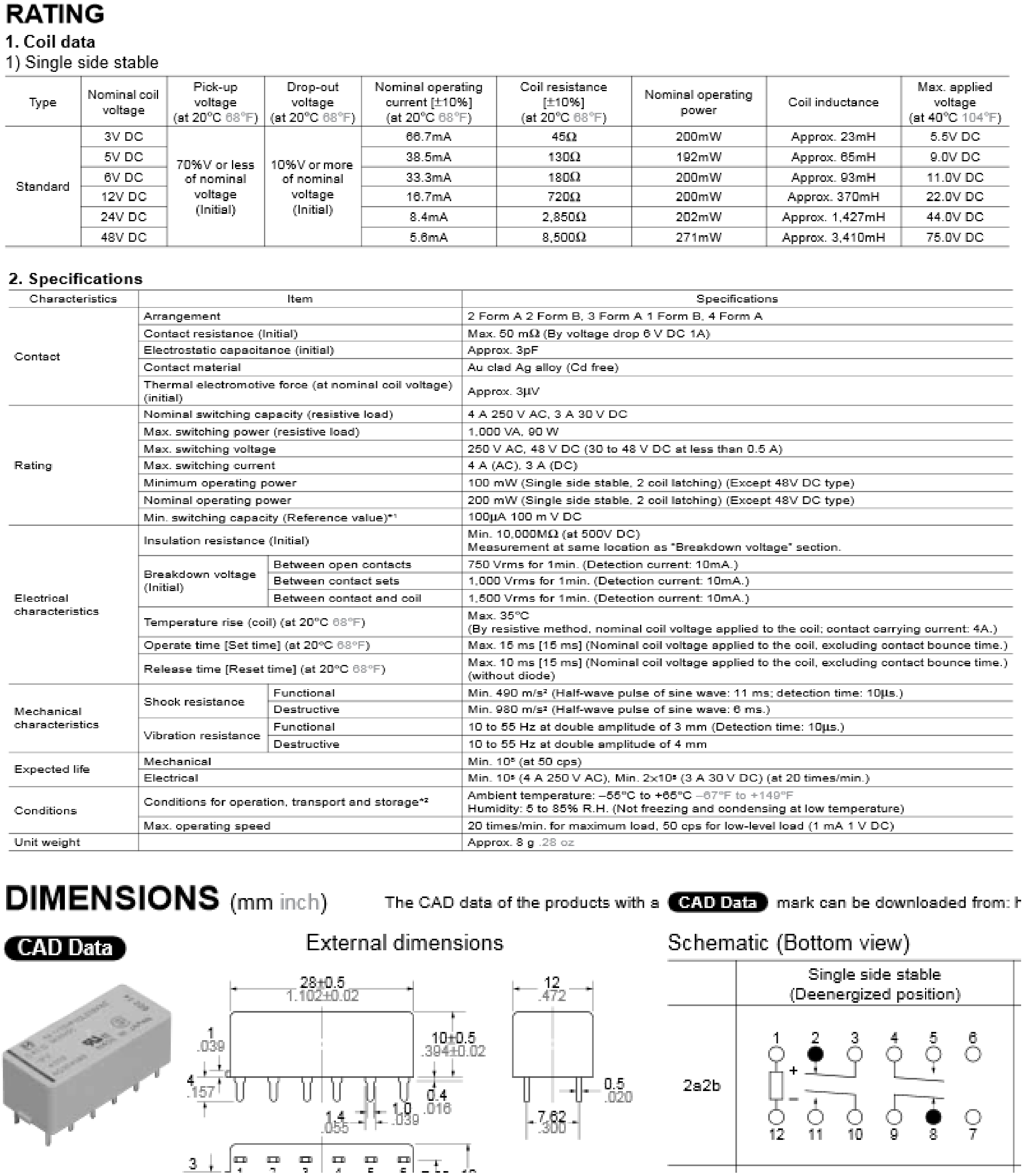
Input Current (A)	Output Voltage (mV)	Effective Output Voltage	Output Digital Value (#/1024)
0	0	2.530	720
0.2	37	2.567	730
0.4	74	2.604	741
0.75	139	2.669	759
0.85	157	2.687	764
0.9	167	2.697	767
1.25	231	2.761	785
1.3	241	2.771	788
1.8	333	2.863	814
2	370	2.900	825
2.5	463	2.993	851

Table 10: Current Sensor Conversion

The output digital value was calculated using the following equation [3.6 Volts (X / 1024) = Effective Output Voltage] Solving for X will give the output digital value. The digital values at which the control system is designed to switch are at 767 and 785, a difference of 18 steps. This difference is large enough to provide consistent switching.

The final step of the control system design is choosing a relay switch that can be activated from output voltage of the microcontroller while handling the amount of current and voltage running through the motor. From figure 13, we see that the output pin outputs 3.3 volts. And from figures 4 through 9 the max voltage is about 135 volts and the max current is 1.8 amps. A multi-switching relay is desired as there must be at least four switches, one for the starting current, and one for each current leg. The Aromat S2EB-3V is rated to activate at 3 volts while handling up to 4 amps and 250 Volts (AC). Upon receiving 3 volts, the relay switch opens and closes two switches each as shown in the datasheet in figure 17. The control system will use one relay switch for the starting cap and another for the three legs.

Figure 18 shows a black box diagram of the control system interacting with the motorized system. This is the final stage for the design. The following report is about simulating and testing the current sensor, microprocessor, and relay switch.



RATING

1. Coil data

1) Single side stable

Type	Nominal coil voltage	Pick-up voltage (at 20°C 68°F)	Drop-out voltage (at 20°C 68°F)	Nominal operating current [±10%] (at 20°C 68°F)	Coil resistance [±10%] (at 20°C 68°F)	Nominal operating power	Coil inductance	Max. applied voltage (at 40°C 104°F)
Standard	3V DC	70%V or less of nominal voltage (Initial)	10%V or more of nominal voltage (Initial)	66.7mA	45Ω	200mW	Approx. 23mH	5.5V DC
	5V DC			38.5mA	130Ω	192mW	Approx. 65mH	9.0V DC
	6V DC			33.3mA	180Ω	200mW	Approx. 93mH	11.0V DC
	12V DC			16.7mA	720Ω	200mW	Approx. 370mH	22.0V DC
	24V DC			8.4mA	2,850Ω	202mW	Approx. 1,427mH	44.0V DC
	48V DC			5.6mA	8,500Ω	271mW	Approx. 3,410mH	75.0V DC

2. Specifications

Characteristics	Item		Specifications
Contact	Arrangement		2 Form A 2 Form B, 3 Form A 1 Form B, 4 Form A
	Contact resistance (Initial)		Max. 50 mΩ (By voltage drop 6 V DC 1A)
	Electrostatic capacitance (initial)		Approx. 3pF
	Contact material		Au clad Ag alloy (Cd free)
	Thermal electromotive force (at nominal coil voltage) (initial)		Approx. 3μV
Rating	Nominal switching capacity (resistive load)		4 A 250 V AC, 3 A 30 V DC
	Max. switching power (resistive load)		1,000 VA, 90 W
	Max. switching voltage		250 V AC, 48 V DC (30 to 48 V DC at less than 0.5 A)
	Max. switching current		4 A (AC), 3 A (DC)
	Minimum operating power		100 mW (Single side stable, 2 coil latching) (Except 48V DC type)
	Nominal operating power		200 mW (Single side stable, 2 coil latching) (Except 48V DC type)
	Min. switching capacity (Reference value)*1		100μA 100 m V DC
Electrical characteristics	Insulation resistance (Initial)		Min. 10,000MΩ (at 500V DC) Measurement at same location as "Breakdown voltage" section.
	Breakdown voltage (Initial)	Between open contacts	750 Vrms for 1min. (Detection current: 10mA.)
		Between contact sets	1,000 Vrms for 1min. (Detection current: 10mA.)
		Between contact and coil	1,500 Vrms for 1min. (Detection current: 10mA.)
	Temperature rise (coil) (at 20°C 68°F)		Max. 35°C (By resistive method, nominal coil voltage applied to the coil; contact carrying current: 4A.)
	Operate time [Set time] (at 20°C 68°F)		Max. 15 ms [15 ms] (Nominal coil voltage applied to the coil, excluding contact bounce time.)
	Release time [Reset time] (at 20°C 68°F)		Max. 10 ms [15 ms] (Nominal coil voltage applied to the coil, excluding contact bounce time.) (without diode)
Mechanical characteristics	Shock resistance	Functional	Min. 490 m/s² (Half-wave pulse of sine wave: 11 ms; detection time: 10μs.)
		Destructive	Min. 980 m/s² (Half-wave pulse of sine wave: 6 ms.)
	Vibration resistance	Functional	10 to 55 Hz at double amplitude of 3 mm (Detection time: 10μs.)
		Destructive	10 to 55 Hz at double amplitude of 4 mm
Expected life	Mechanical		Min. 10⁸ (at 50 cps)
	Electrical		Min. 10⁵ (4 A 250 V AC), Min. 2×10⁵ (3 A 30 V DC) (at 20 times/min.)
Conditions	Conditions for operation, transport and storage*2		Ambient temperature: –55°C to +65°C –67°F to +149°F Humidity: 5 to 85% R.H. (Not freezing and condensing at low temperature)
	Max. operating speed		20 times/min. for maximum load, 50 cps for low-level load (1 mA 1 V DC)
Unit weight			Approx. 8 g .28 oz

DIMENSIONS (mm inch) The CAD data of the products with a **CAD Data** mark can be downloaded from: h

Figure 17: S2EB Aromat Relay Switch

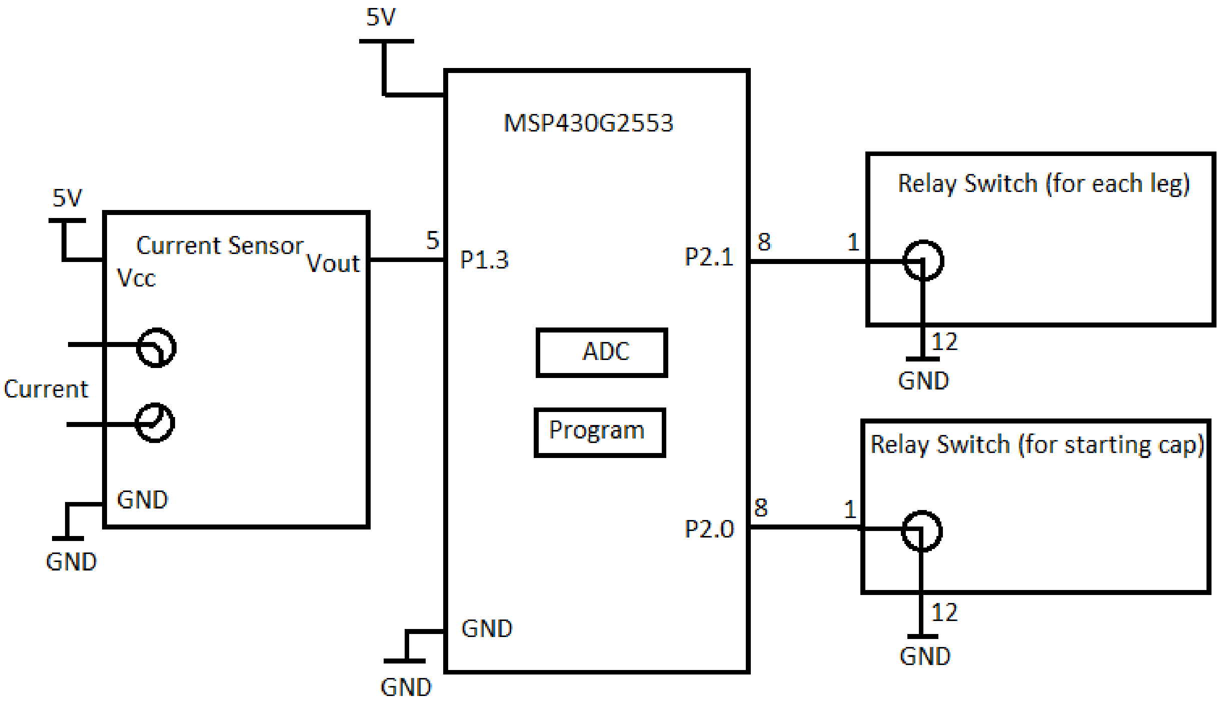


Figure 18: Control System Black Box Diagram

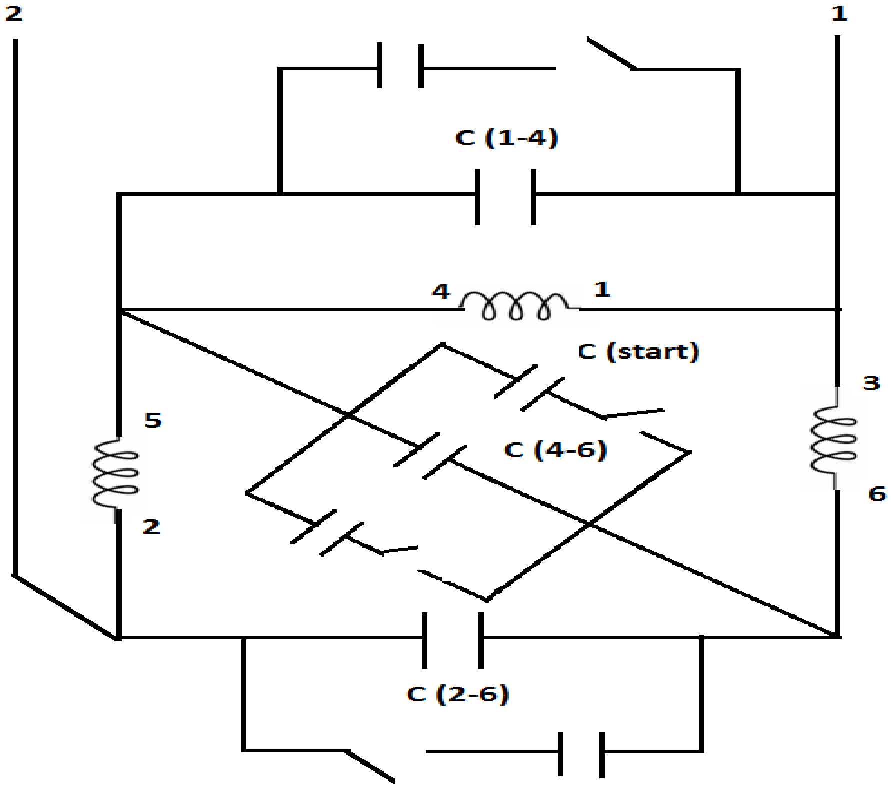


Figure 19: Motor Connection Diagram

VII. TESTING PART 2

Before integrating the system, testing each individual component of the system is critical. This section outlines the tests done for the microprocessor, the current sensor, and the relay switch. These tests were done isolated from each other using some other way of simulating the signal that will be seen for the specific component.

MSP430G2553 Results with Simulated Input

The MSP430 was programmed for initial simulated values. With the assumption that the current sensor outputs 0 volts at 0 amps, and 185 mV/ 1A thereafter, the simulated input values were 166 mV for 0.9 amps and 235 mV for the 1.25 amps. The MSP430 behaved as expected. When the voltage reached 235 mV (67 bits), the output pin turned on, theoretically activating the relay switch. When the votlage went below 166 mV (47 bits), the switch deactivate. This is what the program is designed to do.

MSP430G2553 Coding

```
#include <msp430.h>
#include <stdio.h>
#include <stdlib.h>
int ADC_startcap = 10;           // Low number to see if motor is on
int ADC_low = 47;                // ~ 0.9 amps equivalent
int ADC_high = 67;               // ~ 1.275 amps equivalent
int value = 0;                   // variable
int Flag = 0;                    // Flag
// main.c
int main(void)
{
      WDTCTL = WDTPW | WDTHOLD;               // Stop watchdog timer
      BCSCTL1 = CALBC1_1MHZ;                  // Set range   DCOCTL = CALDCO_1MHZ;
      BCSCTL2 &= ~(DIVS_3);                   // SMCLK = DCO = 1MHz
      P1SEL |= BIT3;
      ADC10CTL1 = INCH_3;                     // Channel 3, ADC10CLK/3
      ADC10CTL0 = SREF_0 + ADC10SHT_3 + ADC10ON + ADC10IE;
                                              // Vcc & Vss as reference, Sample and
                                              hold for 64 Clock cycles, ADC on,
                                              ADC interrupt enable
      ADC10AE0 |= BIT3;                       //ADC input enable P1.3
      P2DIR |= BIT0 + BIT1 + BIT2;            //Sets P2.0 and P2.1 as outputs
```

```
                                        //P2.0 for starting caps and P2.1 for
                                        switching caps
    P2OUT &= 0x00;                      //make sure P2.0 and P2.1 are off (low)
    _enable_interrupts();
    while(1)
    {
        __delay_cycles(1000);           // Wait for ADC Ref to settle
        ADC10CTL0 |= ENC + ADC10SC;     // Sampling and conversion start
        __bis_SR_register(CPUOFF + GIE); // Low Power Mode 0 with interrupts
enabled
        value = ADC10MEM;
        if (value < ADC_startcap) {     //If the motor is not on
            P2OUT &= ~BIT0;             //keep the starting capacitor connected
        }
        else {
            P2OUT |= BIT0;              //else (if on) take off starting
capacitor
        }

        if ((value > ADC_high) && (Flag == 0)) {        //if the current exceeds
                                            1.275 amps and is in state 0
            P2OUT |= BIT1;                          //activate the relay
                                        switch, switching from 58.33% load
                                        design to 100% load design
            Flag = 1;                               //switch into state 1
        }
            else if ((value > ADC_low) && (Flag == 1)) {  //if the current is
                                            above 0.9 amps and is in state 1
                P2OUT |= BIT1;              //keep the switch activated
                Flag = 1;
            }
            else if ((value < ADC_low) && (Flag == 1)) {
                                            //if the current
                                            falls below 0.9 amps and
                                            is in state 1
                P2OUT &= ~BIT1;             //deactivate the switch,
                                            switching back to 58.33%
                                            load design
                Flag = 0;                   //switch back to state 0
            }
            else if ((value < ADC_high) && (Flag == 0)) {
                                            //if value is below 1.275 amps
                                            and is in state 0
                P2OUT &= ~BIT1;             //the switch deactivated
                Flag = 0;
                }
}


//ADC10 interrupt service routine
#pragma vector=ADC10_VECTOR
__interrupt void ADC10_ISR (void){
    __bic_SR_register_on_exit(CPUOFF);          // Return to active mode }
}
```

S2EB Aromat Relay Switch Results with Simulated Input

The relay switch had two test. The first test was to see if the switch operated correctly given 3 volts. Supplying 3.02 volts to the input of the relay switch was enough to cause all four switches to occur. The second test was to see if the relay switch can withstand the amount of current and voltage runnig through it. Simulating a simple circuit by providing high voltage and about 1.6 amps of current to the pins, the switch did not burn up or show any signs of destruction, passing the test.

Current Sensor Results

When powering the current sensor without any connections, the nominal output voltage of the current sensor was 2.531 volts. Providing 1 amp through the current sensor will cause the output voltage to rise 185 mV – a total of 2.716. The result of this test was 2.714, an error of less than 2%. This 2% error is insignificant as it should not affect the digital value. The current sensor was also tested running 1.5 amps through the sensor. Once again, the error was less than 2%.

VIII. TESTING PART 3

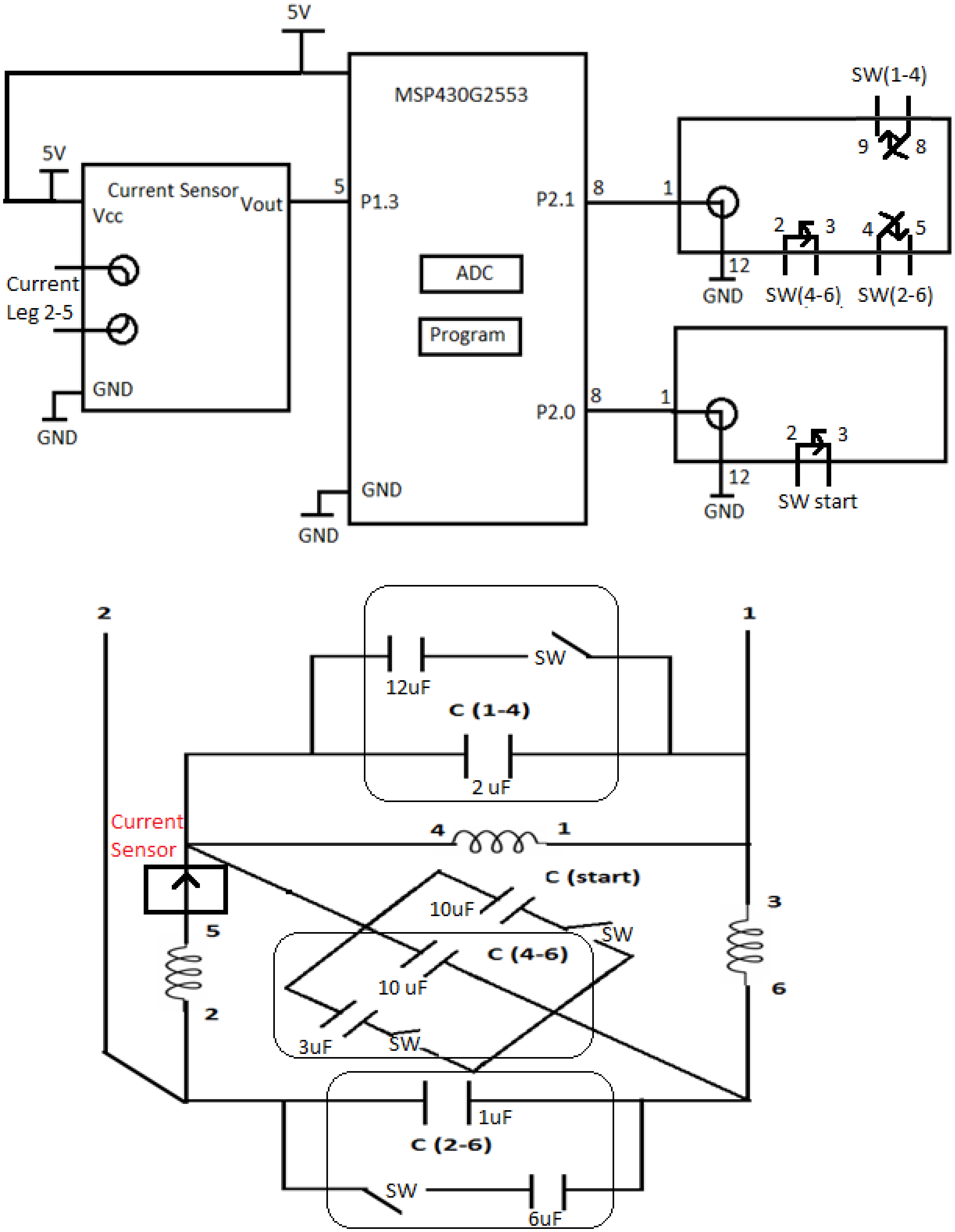


Figure 20: System Integration Design

With any design, expecting the fully integrated system to work on the first try is hopeful. With each attempt, debugging and re-simulating is key to getting the system to work. Unfortunately for this project, I was not able to get the system to work as designed due to the lack of time and resource. Much of my time of debugging and simulating were put into the coding of the microprocessor, obtaining repeatability from the motor design, and retesting of each component. The following of this section deals with the process I took trying to debug the system.

For my system integrated design, refer to figure 20. In this design, the lines connecting the relay switch to the circuit were 18 gage wires. Any connection to the microcontroller were 22 gage male-male or male-female wires. The reason for choosing these gaged wires is to handle the amount of current and voltage across the line. Figure 20 also shows a detailed schematic of how the control system interacted and connected to the Smith Motor design. When running the test for the first time, the starting capacitor switched off, but the switches for the legs did not trigger. This happened because the code had to be recalibrated using the correct effective output voltage as shown in table 10. The initial coding assumed 0 volts at 0 amps. By making the following changes,

```
int ADC_low = 767;               // ~ 0.9 amps equivalent
int ADC_high = 785;              // ~ 1.25 amps equivalent
```

I was able to get the switches for the legs to work, but it kept switching between in and out the two states continuously. The values were too close and I needed to increase the hysteresis range.

Thus I changed the design to trigger above 1.3 amps and below 0.85 amps.

```
int ADC_low = 764;                 // ~ 0.85 amps equivalent
int ADC_high = 788;                // ~ 1.3 amps equivalent
```

This change was enough for the system design to work, but it did not work as well as I had hoped. This change to the code made it so that it should switch to the 100% design at 1.3 amps, but this change was not stable until 1.51 amps. Once in the 100% design, the switch back to the 58.33% design turned back at 0.92 amps. The following table and figures are the results for this design. Note that the table runs from 0 in-lb to 12 in-lb and back to 0 in-lb. The data for both 8 and 9 in-lb were highlighted because the switch flicker between the two states. Thus the data for these are that of the 58.33% load design.

	Data – System Integrated Smith Motor Design										
Torque (in-lb)	Speed (RPM)	VLINE (V)	IINE (A)	PIN (W)	V(1-4) (V)	V(2-5) (V)	V(3-6) (V)	I(1-4) (A)	I(2-5) (A)	I(3-6) (A)	Power Factor
0.02	1794	206.6	0.702	85.6	125.9	114.2	126.2	0.71	1.469	1.19	0.590
1	1790	206.6	0.729	100.5	125.2	114.6	125	0.73	1.38	1.176	0.667
2	1786	206.6	0.783	119.4	124.1	115.3	123.9	0.79	1.329	1.157	0.738
3	1782	206.6	0.848	139.2	124.9	116	122.2	0.85	1.268	1.139	0.795
4	1777	206.6	0.927	159	121.3	116.6	120.7	0.92	1.227	1.12	0.830
5	1771	206.6	1.025	181.4	119	117.1	119	1.00	1.19	1.234	0.857
6	1765	206.6	1.123	204.2	118.9	117.6	117.4	1.09	1.19	1.082	0.880
7	1758	206.6	1.229	225.7	117.6	117.9	115.9	1.18	1.196	1.066	0.889
8	1753	206.6	1.335	250	117.1	118.5	114.3	1.3	1.243	1.072	0.906
9	1747	206.6	1.448	276.3	115.9	118.9	112.3	1.41	1.293	1.055	0.924
10	1743	206.6	1.512	309	120.3	117.7	120.6	1.2	1.34	1.398	0.989
11	1737	206.6	1.621	334	118	117.9	118.6	1.32	1.36	1.376	0.997
12	1730	206.6	1.749	357	118.5	118.2	116.4	1.45	1.42	1.356	0.988
11	1737	206.6	1.62	334	119	117.9	118.6	1.32	1.36	1.377	0.998
10	1743	206.6	1.518	312	120.6	117.7	120.6	1.21	1.34	1.399	0.995
9	1750	206.6	1.402	284	121.7	117.5	122.9	1.09	1.32	1.423	0.980
8	1757	206.6	1.297	264	123	117.1	124.7	0.97	1.35	1.444	0.985
7	1758	206.6	1.228	226	117.6	117.9	115.7	1.18	1.186	1.066	0.891
6	1765	206.6	1.123	203	118.9	117.6	117.4	1.09	1.18	1.085	0.875
5	1771	206.6	1.024	182	119	117.1	119	1.01	1.19	1.237	0.860
4	1777	206.6	0.926	158	121.3	116.6	120.7	0.91	1.227	1.123	0.826
3	1782	206.6	0.848	139	124.9	116	122.2	0.83	1.278	1.143	0.793
2	1786	206.6	0.782	119	124.1	115.3	123.9	0.77	1.339	1.161	0.737
1	1790	206.6	0.73	101	125.2	114.6	125	0.73	1.38	1.176	0.670
0.02	1794	206.6	0.701	86	125.9	114.2	126.2	0.71	1.469	1.19	0.594

Table 11: Integrated Smith Motor Design System Data

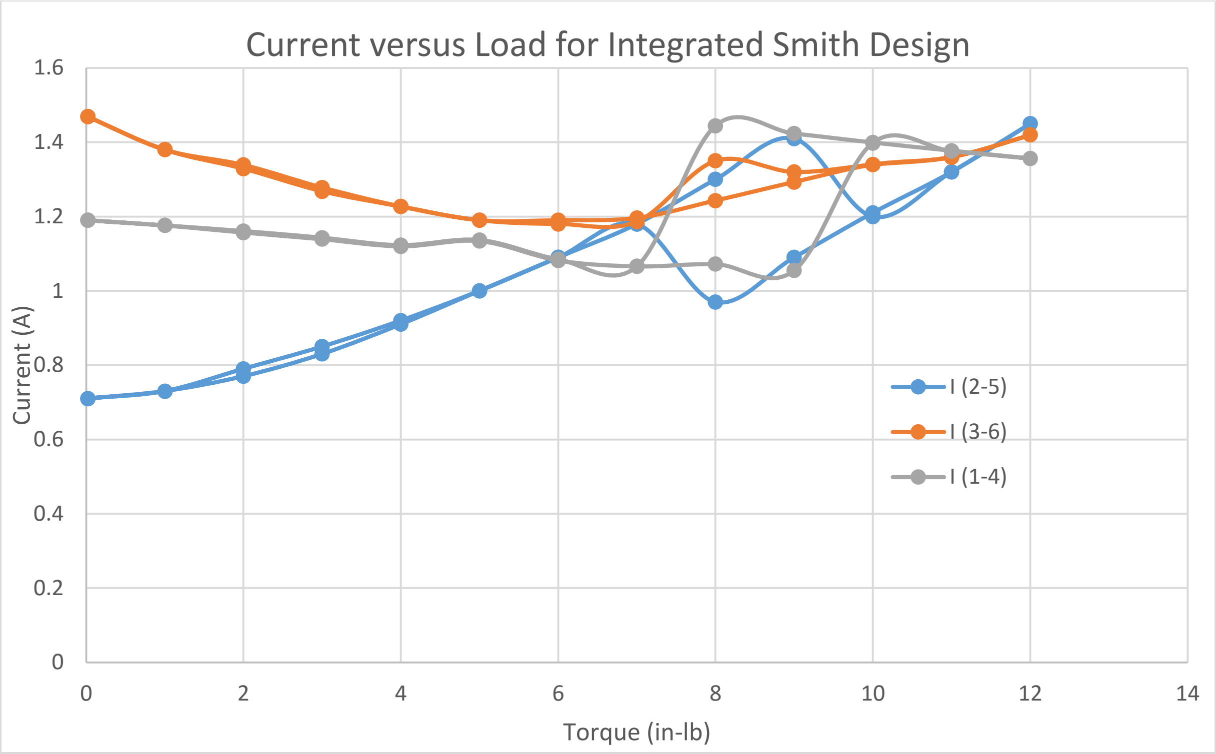


Figure 21: Current vs. Load (Integrated Smith)

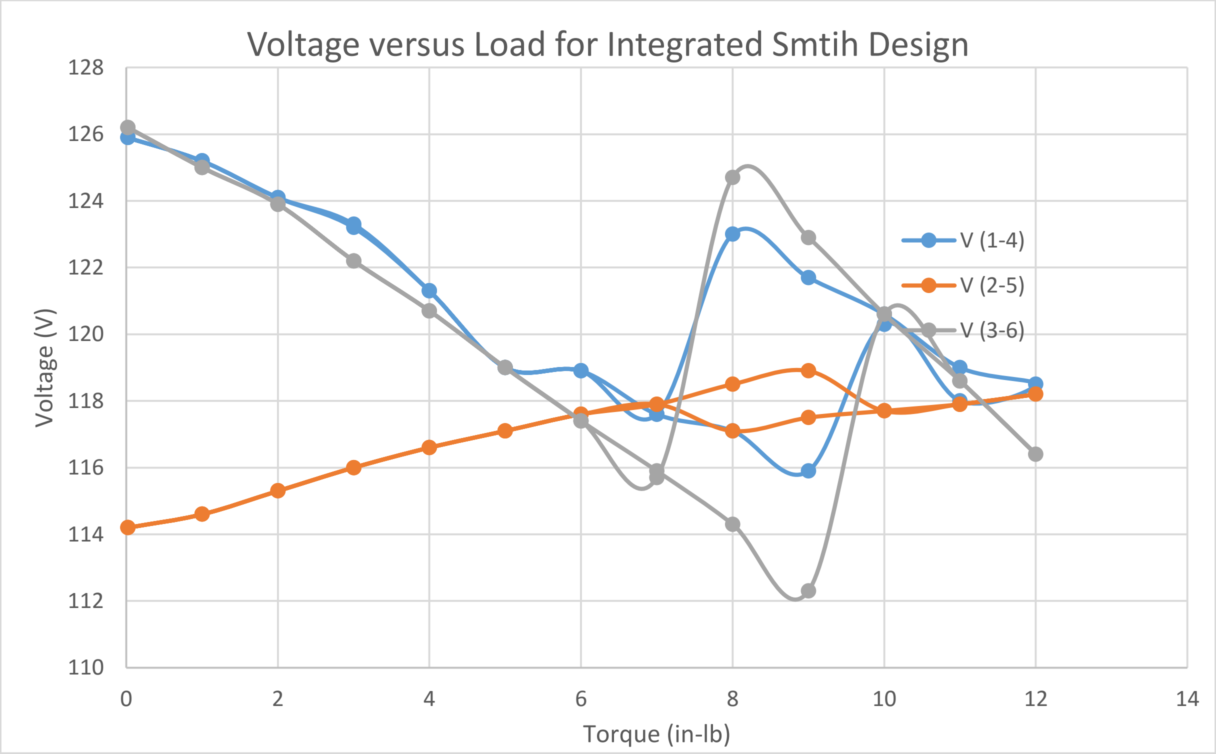


Figure 22: Voltage vs. Load (Integrated Smith)

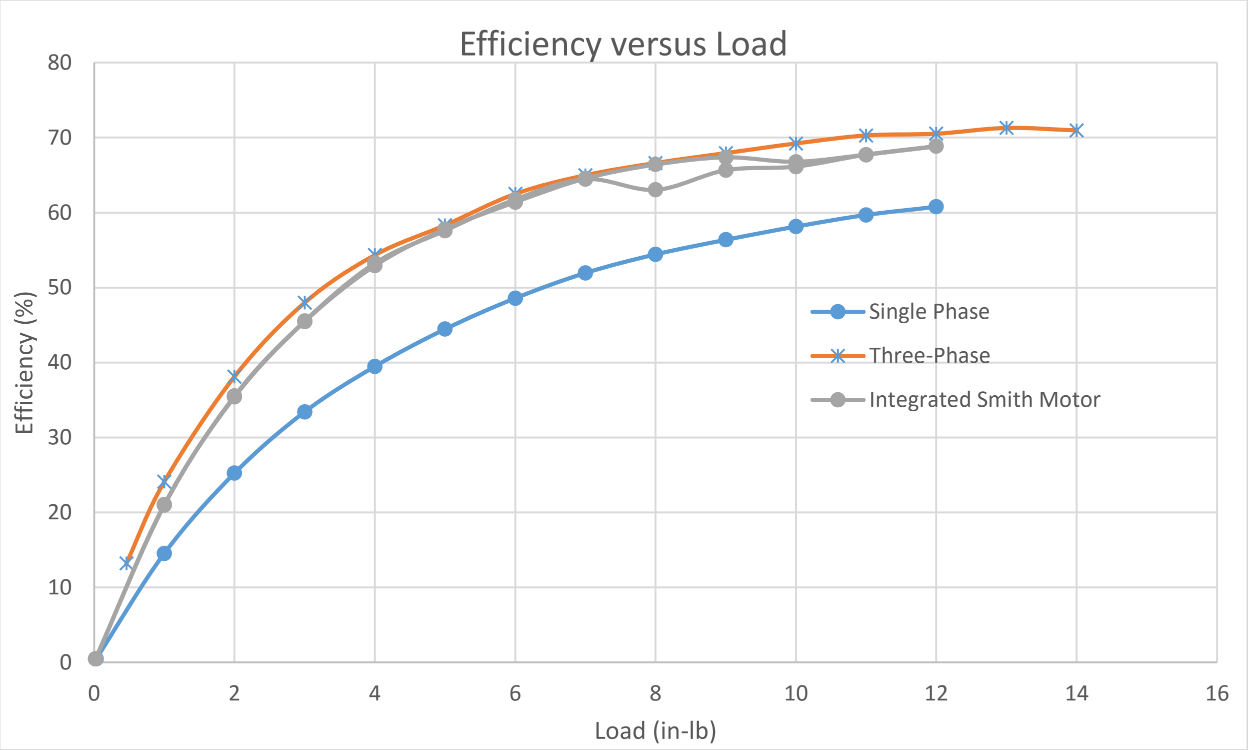


Figure 23: Efficiency vs. Load (with Integrated Smith)

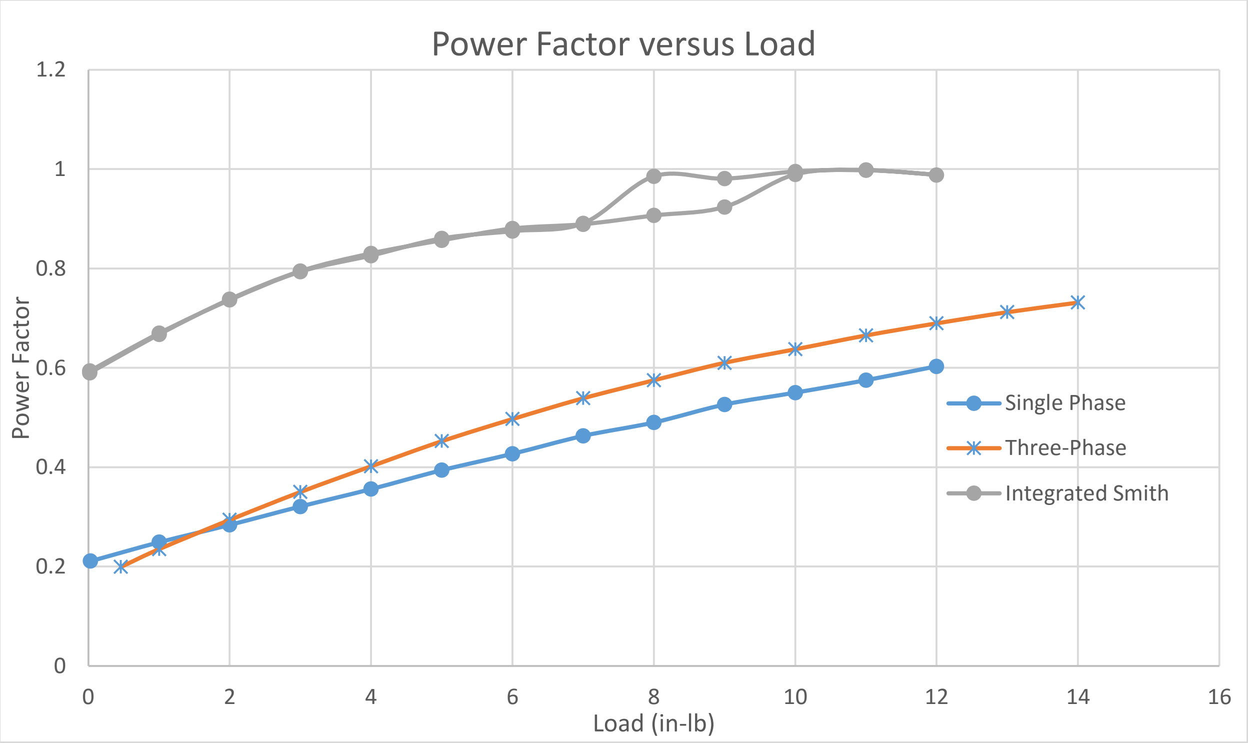


Figure 24: Power Factor vs. Load (with Integrated Smith)

IX. Conclusion

The advantage of the Smith Motor is an increase in efficiency while operating using a single phase power supply. Its disadvantage is its limitation as a single permanent design. Calculations must be made to choose the capacitor values that allow the motor to operate at a certain load. If the capacitor network is designed to operate at full load, a no-load to the motor will cause a winding current to exceed the current rating of the motor - leading to uneven aging in the windings. This is the biggest disadvantage, but can be solved by using the control system. In figure 20, the control system adds or removes capacitance parallel to the existing capacitors in order to follow the load the motor operates at.

Figures 21 through 24 show the current, voltage, efficiency, and power factor characteristics of the integrated Smith Motor test. Each of these graphs displayed a hysteresis-like pattern. This pattern was expected as designed. The current and voltage values are similar to those of the initial standard runs with only a small margin of error. The efficiency of the integrated Smith Motor design was slightly less efficient than the 58.33% load design, but comes with a tradeoff. Although it is less efficient, figures 21 and 22 show that the circuit is more balanced.

In figure 11 of section V, the power factor of the Smith Motor is much closer to unity than both the single phase motor and the three phase motor. Figure 24 shows that this trend still exists after integrating the control system. Power factor is the amount of real power divided by the apparent power. The closer the power factor is to unity, the less amount of reactive power the motor draws. Utility companies will pay for the reactive power of individual customers. A large industrial company will have to pay for their own use of reactive power. They are also required to limit the amount of reactive power they consume. The reduction of reactive power saves money for both the customer and the utility company.

The point at which the switch activates and deactivates is not exactly how it was designed. I was expecting activation at 1.3 amps and deactivation at 0.85 amps, but the design did not activate until 1.51 amps and deactivated at 0.92 amps. Another problem with this data or experimental run is the motor kept switching in and out of the 58.33% and 100% load designs when the torque was between 8 to just below 10 in-lb, which can be problematic for the motor's windings. The last problem this design had was switch back the starting capacitor. I ran this test restarting the program on the microcontroller each time. Although there were bugs, the design essentially did what it needed to do. The following section "Resolution" talks about some fixes I tried as well as other fixes that can be made for future reference.

X. Resolution

The first and second problem with the Integrate Smith Motor design was the switching points of the hysteresis-like design. I believe this problem is due to the sensitivity of the current sensor. The current sensor outputs about 185 mV per amp, which is equivalent to 3.5 mV per step. Theoretically, the design should be able to handle the small change in voltage, but errors can come from the wearing of the motor, the fluctuations of the current sensor's standard output point, or the small output margin of the current sensor.

The last problem dealt with the starting capacitor. To fix this I added the following code,

```
int ADC_startcap_high = 830;
int ADC_startcap_low = 740;
int ADC_Max = 822;
int ADC_low = 758;
int FlagStartCap = 0;

if ((FlagStartCap == 0) && ((value > ADC_startcap_high) || (value <
ADC_startcap_low))) {
                    P2OUT &= ~BIT0;
                    FlagStartCap = 0;
             }
                    else if ((FlagStartCap == 0) && (value < ADC_Max) && (value >
ADC_startcap_low)) {
                          P2OUT |= BIT0;
                          FlagStartCap = 1;
                    }
                    else if ((FlagStartCap == 1) && ((value < ADC_startcap_low) ||
value > ADC_Max)) {
                          P2OUT &= ~BIT0;
                          FlagStartCap = 0;
                    }
                    else if ((FlagStartCap == 1) && (value < ADC_Max) && (value >
ADC_startcap_low)) {
                          P2OUT |= BIT0;
                          FlagStartCap = 1;
                    }
```

Adding this to code check to see if the current is too high or if the current is at zero (motor off) When it sees these values, the starting capacitor will close. When falls within the maximum and minimum current Leg 2-5 reads, it will remove the starting capacitor. Theoretically this should work, but when I tried it on the circuit it was having problems. I believe the problem once again is due to the current sensor. I was not able to get a consistent reading out of the sensor. After retrying the design several times, I was unable to get the design to run without the control system – trying to re-establish the standard.

Some changes I recommend for future studies on the Smith Motor design is to get a more sensitive current sensor. 185 mV per amp is too little and can cause reading problems for the ADC10 of the microprocessor. Obtaining a more sensitive sensor will put the range of the hysteresis further apart, reducing the error that can be made at the output of the current sensor or the input of the microprocessor. Another change I recommend is cleaning up the coding. Although I believe my coding is sufficient, the coding itself can be improved. Working with teachers who have coding experience may be helpful. The last recommendation I have on improving the system is obtaining a relay switch that runs more smoothly and possibly extras. When running the tests, the relay switch made a lot of ticking noise, which brings me to believe that the relay switch may have been damaged during the tests.

I made many changes during the debugging of the control system. Eventually I tried establishing a standard point by running both the 100% and 58.33% load designs. I was not able to repeat the data obtained from the tests done last quarter and the beginning of this quarter. My final recommendation for this would be to try to do all these tests in one quarter.

XI. MARKET RESEARCH

Table 12: Problem, Solution, and Drawbacks of the Project

Problem	Solution	Drawback
Efficiency, Size, and Cost	Use a more efficient single phase induction motor	As efficiency increases, so does cost. The cost of a three phase induction motor cost as much as a single phase induction motor
	Use a three phase induction motor	A three phase induction motor requires modification to run from a single phase power source. Installing a three phase power supply is expensive
	Use a phase converter	Buying a phase converter is very costly to the point where utility companies charge more
	Use a solid state inverter as the extra design to the Smith Motor	A solid state inverter costs well above $40
	Use a rotary phase converter to power a three phase induction motor	This technique requires another motor, hence adding to the weight and size of the product.
	Use a digital phase inverter to drive the three phase induction motor	A digital phase inverter will make changes to the phase, causing the power factor to decrease
	Make a control design that use smaller components	Smaller components typically cost more and are harder to work with. The tradeoff would be price for size
	Build a Control Design using common components (The goal of this Senior Project)	This would be the best solution - Using common component to make the circuit easily repairable; prioritizing efficiency and cost over size.

With this motor operating up to 208 volts, the markets this project will be aiming to attract are companies that make home appliances. Some examples are mini-refrigerators, air conditioning units, washing machines, and fans. These home appliances are used very often and a 10% increase in efficiency will allow of owners to reduce their electricity bill. According to the US Department of Energy, Americans use an average of $1,340 annually. This means saving up to $134 a year.

The purpose of this project is to use the Smith Motor in place of a single-induction motor in order to get higher efficiency without having to install a three phase power source. Though the three phase induction motor cost an average of 10% more than a single phase induction motor, users will reduce their electricity bill and eventually save more money in the long run.

Table 13: Marketing Considerations

Marketing Considerations	Answers to Considerations
Who are the market leaders? List the companies/organizations that play in this market.	Gentec, Ace, NAPCES, Enco, Arco, General Electric (Leads sales in phase converters) Leaders: Gentec, General Electric Competitive solutions in Table 2.
How big is the market?	Phase converters are used to convert from single phase to three phase and vice versa. The demand for it is not large, but many projects may require it.
Which part of the market is addressable to the project?	Many machines and appliance may require the use of phase converters to power the motor. This is where the project design shines in may be useful as it is cheaper than the standard phase converter

Marketing Considerations	Answers to Considerations
What is the project's leverage?	The project does not require a $500 phase converter. Instead, it relies on small analog circuit design that cost less than $40. A fourth capacitor is added to balance the voltage and current in order to improve the power factor and efficiency. The control system will fit in a 5x5x5 inch box.
What are its window of opportunity?	Electronics and machinery are always being improved, thus the window of opportunity for this product is any time. Saving energy is saving money, thus the sooner the better, allowing its efficiency to be tested in real life scenarios.
How big of an effort will it take to get into the market?	Currently provided with a three phase squirrel induction motor, the amount of time exceeds the cost of the design. The cost is expected to be less than $40. The expected amount of time for this project is approximately 175 man-hours (based on previous projects)
Who are key partners for success?	Key partners would be large appliance companies such as KitchenAid, Whirlpool, General Electric, or Kenmore. These companies sell many household appliances that may utilize the Smith Motor.
Is the existing sales organization capable of selling this into the market?	Yes, these companies are already big name brands. Implementing the Smith Motor may actually cost less since larger appliances rely on three phase connections. For smaller appliances, the cost will go up, but the efficiency also goes up. Over time people will save money
Who are some key potential customers?	Key potential customers are the same as needed partners (KitchenAid, Whirlpool, General Electric, Kenmore). These companies can buy the design and implement them into their appliances.

Competing Designs

The present solution is to apply a phase converter in order to power the three phase induction motor as shown in Figure 25. The problem is that the phase converter can range at a cost of $150 to $500.

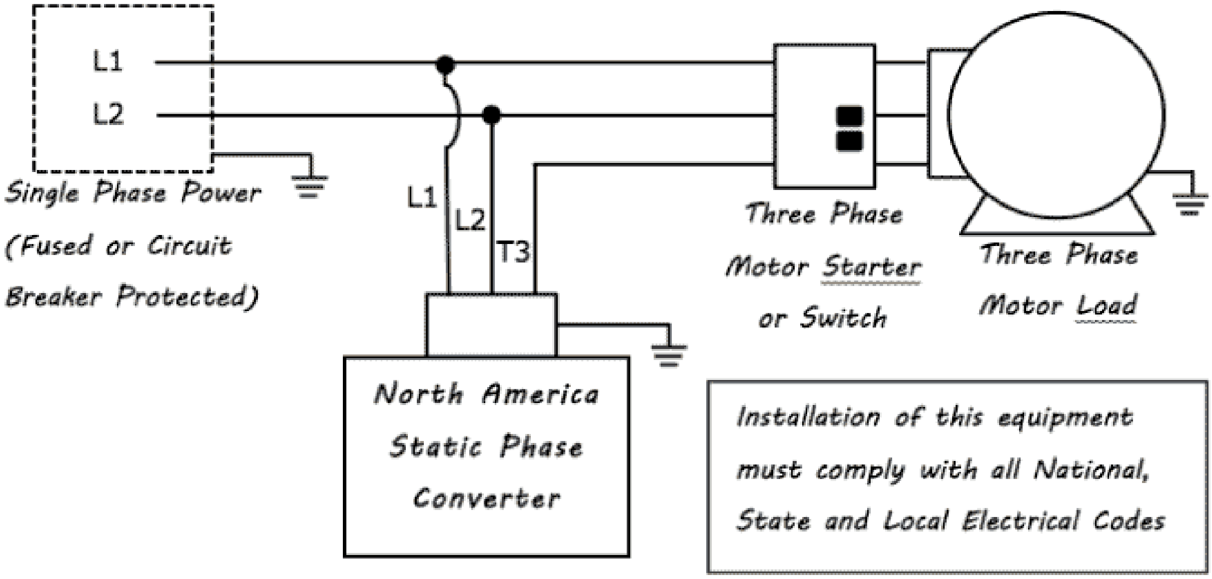


Figure 25: Standard Phase Converter Setup

Rotary phase converters cost even more than a typical phase converter, ranging from about $5,000 to $8,000. Installing a three phase power source costs nearly $500 an outlet, making it very expensive. The installation for three phase power is not offered to homes because they require a large amount of load that homes cannot fulfill. Thus, this senior project gives an alternate design solution that performs the same task as a phase converter and a single phase induction motor.

XII. SCHEDULE

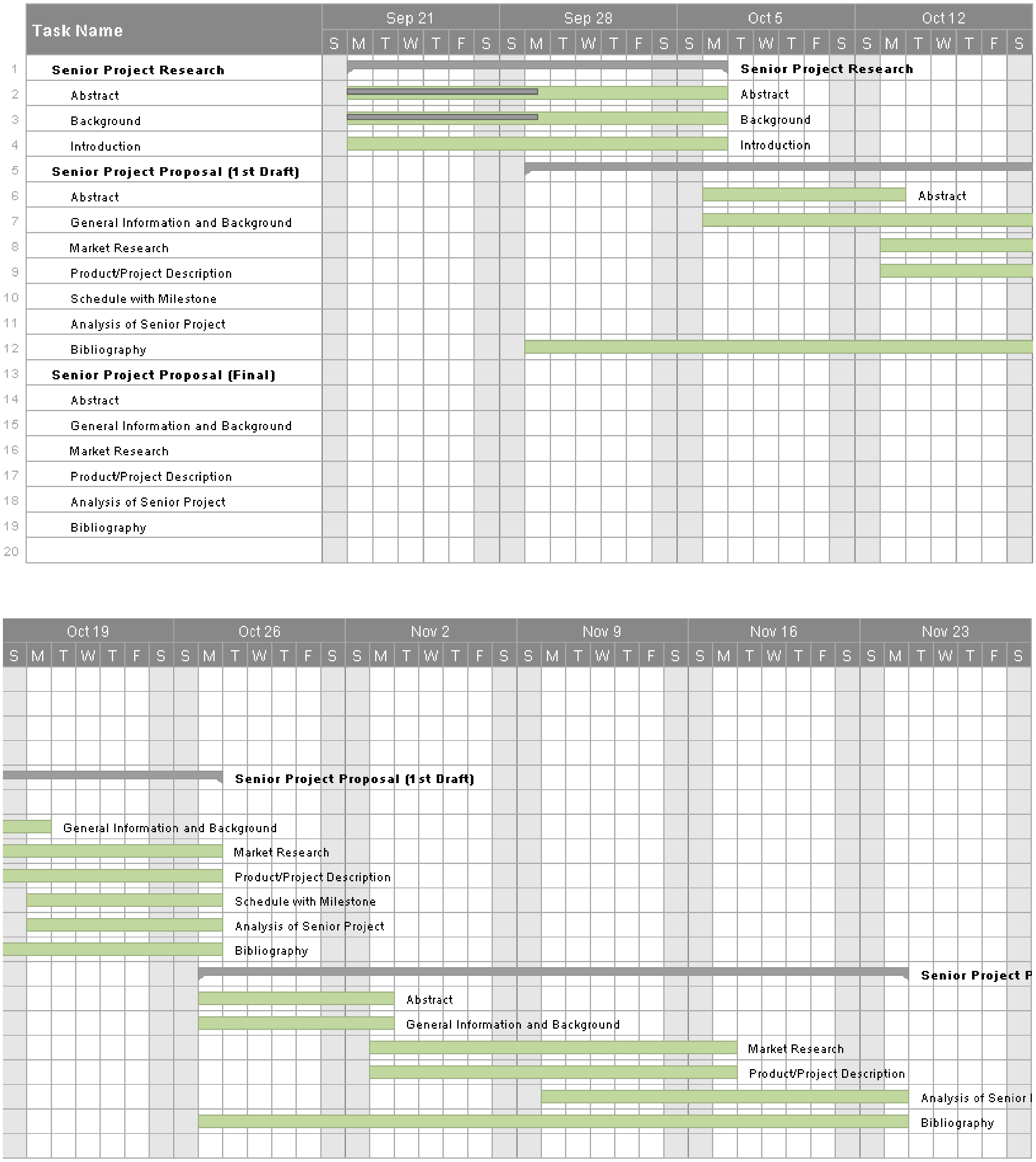
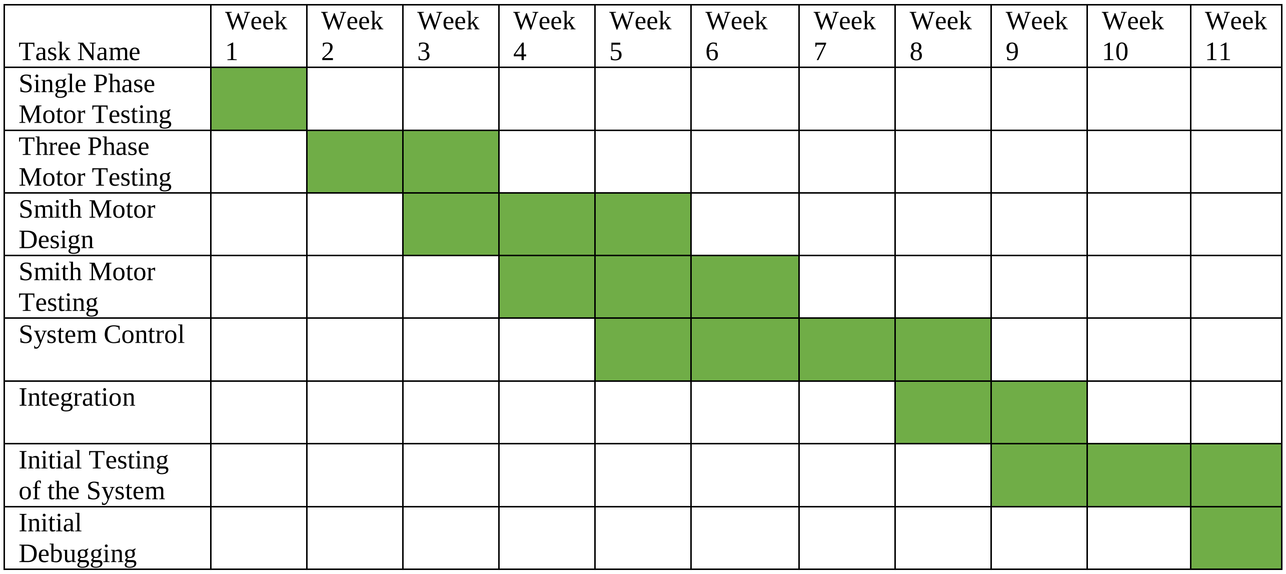
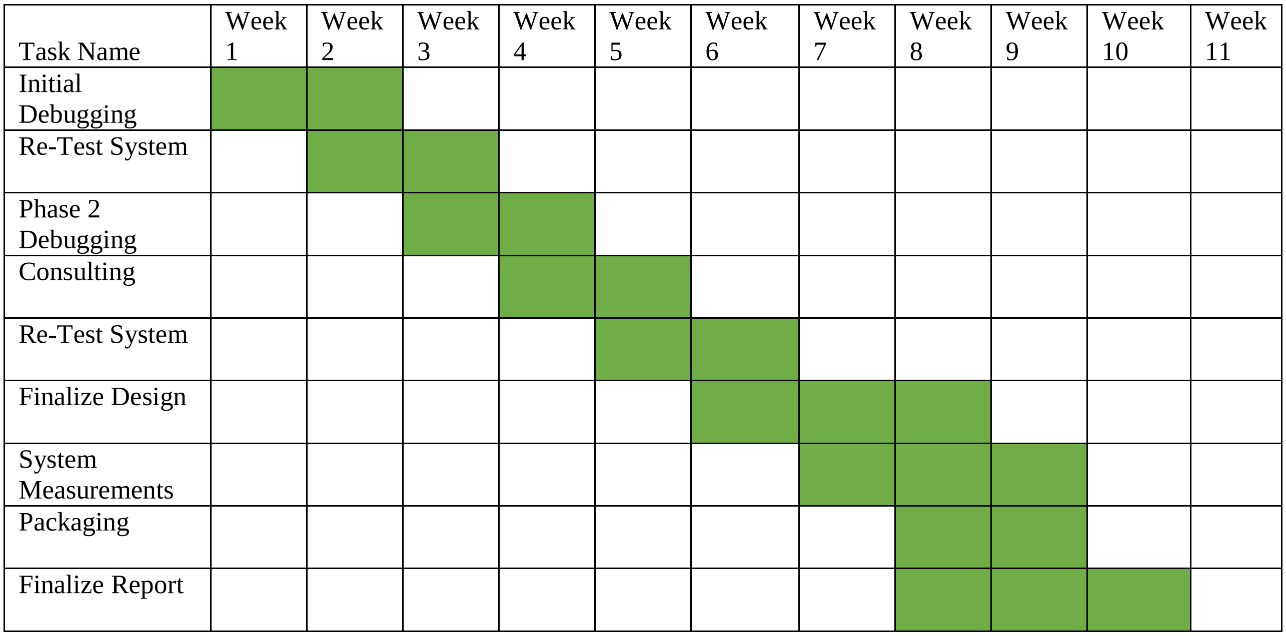


Figure 26: Gantt Chart for Fall Quarter 2014



Task Name	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11
Single Phase Motor Testing	🟩										
Three Phase Motor Testing		🟩	🟩								
Smith Motor Design			🟩	🟩	🟩						
Smith Motor Testing				🟩	🟩	🟩					
System Control					🟩	🟩	🟩	🟩			
Integration								🟩	🟩		
Initial Testing of the System									🟩	🟩	🟩
Initial Debugging											🟩

Figure 27: Gantt Chart for Spring Quarter 2015



Task Name	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11
Initial Debugging	🟩	🟩									
Re-Test System		🟩	🟩								
Phase 2 Debugging			🟩	🟩							
Consulting				🟩	🟩						
Re-Test System					🟩	🟩					
Finalize Design						🟩	🟩	🟩			
System Measurements							🟩	🟩	🟩		
Packaging								🟩	🟩		
Finalize Report								🟩	🟩	🟩	

Figure 28: Gantt Chart for Fall Quarter 2015

XIII. Bibliography

Market Research

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XIV. Apendix A. Senior Project Analysis

Project Title: Utilization of the Comparative Studies on the Smith Single Phase Motor

Student: Kevin Hua

Advisor: Professor Ali Shaban

1. Study of Functional Requirements

This project utilizes past studies on the Smith Motor and requires a design to be developed in order to allow a three phase induction motor to operate from a single phase power source. The design will allow the Smith Motor to be used practically for difference appliances. The motor will function from half load to full load torque.

2. Primary Constraints

The primary constraint of this project is developing the circuitry that will allow the Smith Motor to be useful. The major problem of the Smith Motor in itself is its limitations. The Smith Motor design forces it to operate at a certain load. If the user wants to change the percent load the motor is operating at, the user must change the capacitors. Thus, the need of a circuit that can add or reduce the shunt capacitor value is needed.

3. Economic

If the design was to be funded by a large company, the initial investment may seem hefty due to the expense of buying three phase induction motors compared to single phase induction motor. But overall, the power factor of the three phase induction motor will increase, reducing reactive power and increasing the efficiency. This will allow for buyers to save energy. This project would be most useful for appliances or machines that are commonly used.

4. If Manufactured on a commercial base

If manufactured on a commercial base, the cost of the material for the circuitry will be less than $20, as shown as a requirement. Assuming this circuit is used for all large home appliances, it was calculated that owners will save up to $134 annually. In about two months, the efficiency of the machine already saves enough to cover the circuit. It will take a few more years to cover the fee of having to use a three phase induction motor instead of a single phase induction motor.

5. Environmental

The purpose of this project is to increase the power factor and increase the efficiency. That alone will be good for the environment. Although it is not a source of renewable energy, it is an action of energy improvement. Looking at it from a broader view, creating the ICs can be an environmental issue. The release of gases can be add more pollution into the air.

6. Manufacturability

The design can be easily manufactured if common components are used as stated. This way replacements and repairs can easily be done. If funded by a large company, a mass production can easily be done and implemented in many home appliances.

7. Sustainability

Due to its efficiency improvement, that alone resents makes it sustainable. The energy saved can be used for other needs. In the grand scheme other things, if this is implemented everywhere, it means that 10% of the world's home energy usage will be saved. That alone will be good for the environment and improves energy management. Looking at it from a broader view, creating the ICs can be an environmental issue.

8. Ethical

Due to the way ICs are made, this can present an ethical issue. In a study done in 2013, the creations of ICs use silicon and are often times produced in third world countries. This present and ethical issue the people living in the third world country due to the amount of pollution release in the air during manufacturing.

9. Health and Safety

As shown in the ethical issue, the health and safety of the creation of the ICs may present a problem. The project in itself, the goal to save energy and reduce reactive energy, is safe to implement. The only other slight problem may be the heating of the coils may be of some danger. But if designed accurately and cautiously, heating will not be a problem (as long as the current does not go above the rated current of the motor).

10. Social and Political

Socially, the idea of saving energy is what we yearn for. Our resources are depleting and we need to find ways of renewable energy or improvement in efficiency. Politically it does not present a problem. It cannot be used for a dangerous product.

11. Development

The development is central in the circuitry of the design. Most of the data and measurements have already been done on the Smith Motor. Although this project does require retaking measurements for the Smith Motor, the development will be centered on the control system.