Single-Phase High Efficiency Motor Testing

A Senior Project

presented to

the Faculty of the

Electrical Engineering Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

by

Marc Perez

December, 2012

Table of Contents

List of Figures

List of Tables

Abstract

A three-phase induction motor has higher efficiency than the single-phase motor counterpart. It is possible to run a three-phase motor with a single-phase source to develop a single-phase high efficiency system. The single-phase high efficiency motor, or SHE-motor, uses capacitor banks to operate at a balanced three phase induction motor using a single phase source. Unfortunately, this design has been limited, as it can only be balanced for one load configuration at a time. This provides the system to have maximum system performance. Due to this limitation in operations, it has proven to be non-ideal in commercial applications. It is seen that conventional three-phase induction motors are more practical and better suited for field applications.

Introduction

As seen from previous studies of the Smith motor, the benefit of using the configuration to run a three phase induction motor from a single phase source has higher efficiency compared to their single-phase counterparts. The result of this is an efficiency that is 3% higher than the conventional single-phase motor. By using a specific circuit design, as seen in figure 1, a set of balanced currents and voltages were supplied to each winding of the motor, at a specific load. Also, the SHE-motor nearly achieved a unity power factor rating.

A big disadvantage of this design is that the capacitor network is specific to certain loads. To supply different loads, capacitor values must be recalculated and then replaced to operate correctly. In addition, unbalanced motor voltages may have resulted in reduced torque and speed. This would have increased the chances of having unbalance currents, leading to improper operations of the SHE-motor. As seen in testing, when the load on the motor goes from no load to full load, there are irregular operations that occur in the motor. This could be due to some losses through the motor such as temperature.

A three-phase motor has an efficiency of about 74%, while a single-phase motor runs at 64%. Being able to run a three-phase motor with a single-phase source will provide efficiency higher than a conventional single-phase motor and operate close to a three-phase motor efficiency. Through the use of capacitors, it is possible to supply the motor with the necessary winding voltages and currents. This will allow the motor to run at a higher efficiency than a single-phase motor that will operate closely to unity power factor.

Design

The motor used during this experiment was a three phase induction motor, produced by the Hampden Engineering Corporation. It is a four pole machine, with horse power, model IM-100-6. The motor provides access to twelve terminals to be able to modify the three-phase connections. The SHE-motor design goal was to supply balance voltages and currents in the three windings at the different specific load points. The windings for the motor were renamed to match the circuit roles. There is the Center Leg (CL), the Line Leg (LL), and the Driven Leg (DL). Figure 1 shows the circuit diagram configuration for the Smith motor for a single load point.

The original design of the SHE-motor was designed for balanced operations at 100% load and 66. 64% of rated load. As seen through observations of starting the motor at no load for the 100% load design, the current in the center leg exceeded the rated current of the motor; the motor is rated at 1.8 amps. The 100% load design data can be viewed in figure 2. With the excessive current passing through the winding causes overheating for the motor, and ages the windings quicker than expected. Thus, calculations for 66.64% of rated load were done to limit the current for the Center leg. This expanded the range of balanced voltages and currents. As seen in figure 3, the 66.64% load design provides closer balanced winding currents at no load. This also allowed a wider range for the motor to operate through a higher load range with balanced voltages and currents.

Taking information gathered from conventional three-phase tests, the capacitor values were calculated for balanced operations. Below are the calculations for each capacitor at 100% load:

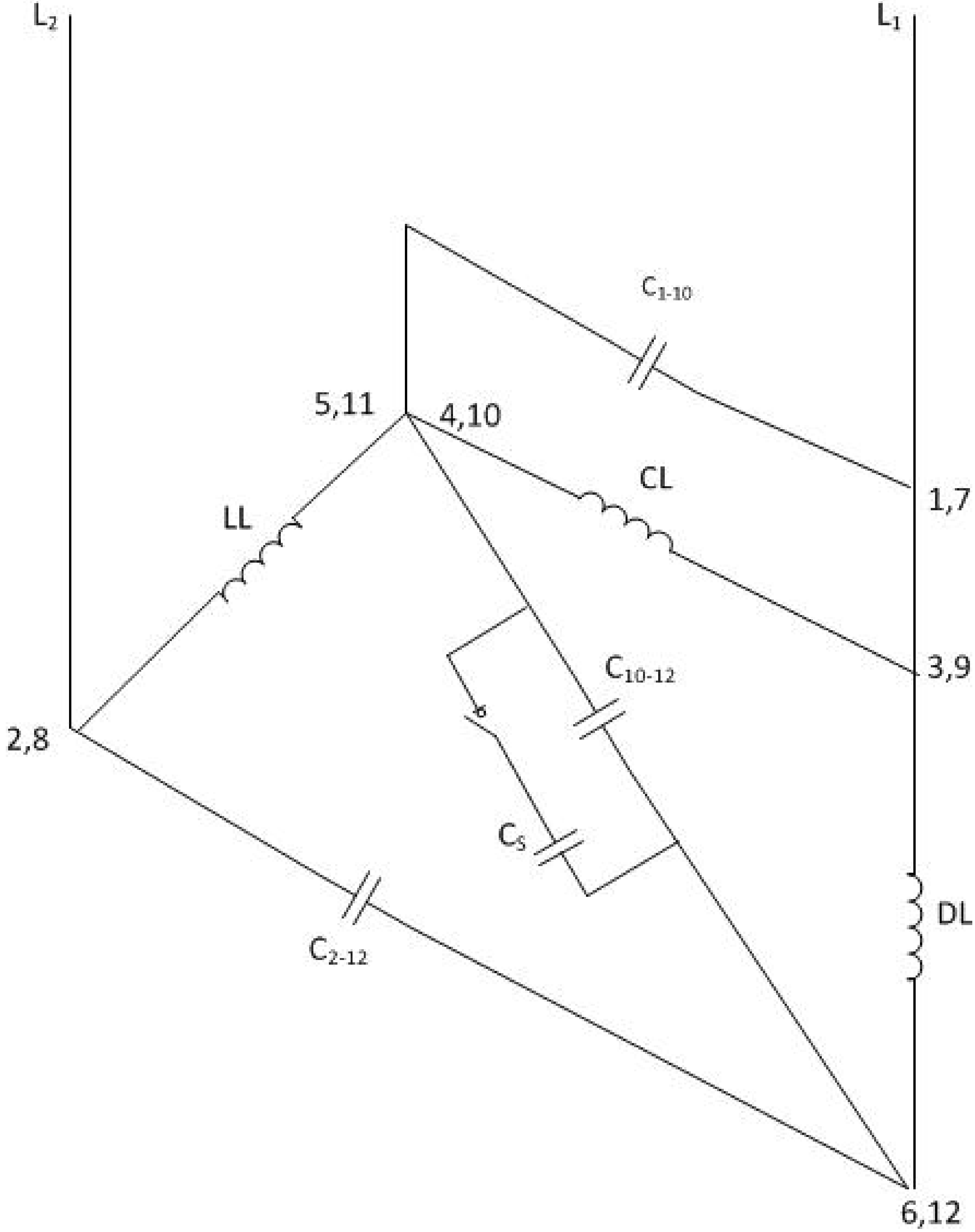

Figure 1: SHE-Motor Configuration

Calculations:

$$Z_C = \frac{V_C}{I_C} = \frac{-j}{\omega C}$$

$$C = \frac{I_C}{\omega V_C} = \frac{I_C}{2\pi f(V_C)}$$

$$\boldsymbol{C_{2-12}} = \frac{I_{C1}}{2\pi f(|V_{2-12}|)}$$

$$\boldsymbol{C_{10-1}} = \frac{I_{C2}}{2\pi f(|V_{10-1}|)}$$

$$\boldsymbol{C_{10-12}} = \frac{I_{C3}}{2\pi f(|V_{10-12}|)}$$

During three-phase operation at 100% rated load:
I = 1.398A
Φ=47.85°

$$I_{C1} = I_{30}$$
$$I_{C1} = 2Isin(60° - \phi)$$
$$I_{C1} = 2(1.398)\sin(60° - 47.85°)$$
$$I_{C1} = 0.588A$$

$$I_{C1} = I_{C2}$$
$$I_{C2} = 0.588A$$

$$I_{C3} = I_{60}$$
$$I_{60} = 2Isin(\phi - 30°)$$
$$I_{60} = 2(1.398)\sin(47.85° - 30°)$$
$$I_{60} = 0.857A$$
$$|V_{2-12}| = \sqrt{|V_{2-1}|^2 + |V_{3-12}|^2}$$
$$|V_{2-1}| = |V_S| = 208V$$
$$|V_{3-12}| = |V_{10-1}| = |V_P| = |V_{2-11}|$$

$$|V_{2-11}| = \frac{|V_{2-1}|}{2\cos(30°)}$$

$$|V_{2-11}| = \frac{208}{2(0.866)} = 120V$$

$$|V_{2-12}| = \sqrt{208^2 + 120^2}$$
$$|V_{2-12}| = 240V$$

$|V_{11-12}| = \sqrt{|V_{2-12}|^2 - |V_{2-11}|^2}$
$|V_{2-12}| = 208V$

$$\boldsymbol{C_{2-12}} = \frac{0.588}{377(240)} = 6.5\mu F$$
$$\boldsymbol{C_{10-1}} = \frac{0.588}{377(|120|)} = 12.99\mu F$$
$$\boldsymbol{C_{10-12}} = \frac{0.857}{377(208)} = 10.9\mu F$$

Similarly, calculations for 66.64% of rated load were calculated for balanced operations.

Before experimenting on the SHE-Motor, tests on a conventional three-phase motor and a single-phase motor were performed. The data taken from the two motors were used to compare the data taken from the SHE-motor. What was hoped for was to have the SHE-motor run at efficiency higher than a conventional single-phase motor and close to the efficiency of a conventional three-phase motor.

Calibration, Testing, and Results

The first initial test taken was the conventional three-phase motor. I ran the motor and loaded it from 0% to 120% of the load. I recorded data for the initial test and used it to compare to the data taken from the SHE-motor. Full load was taken to be at 12 lb-in. At that point, efficiency is found to be at 73.8%. Below is the data taken:

Table 1: Three-Phase Data

Torque (lb-in)	Speed (RPM)	V (V)	I (A)	P (W)	PF	Pout	Efficiency
0.64	1794	205.1	1.026	61.9	0.168	13.571	21.924
1	1793	205.9	1.026	71.8	0.196	21.193	29.517
2	1789	205.7	1.034	93.7	0.254	42.292	45.135
3	1785	205.8	1.056	117.2	0.311	63.296	54.007
4	1779	205.6	1.071	139.7	0.366	84.111	60.208
5	1776	205.7	1.1	163	0.415	104.962	64.394
6	1770	205.6	1.126	186	0.464	125.528	67.488
7	1765	205.5	1.163	210	0.507	146.036	69.541
8	1761	205.4	1.203	234	0.547	166.520	71.162
9	1755	205.5	1.242	257	0.582	186.697	72.645
10	1749	205.6	1.292	284	0.617	206.732	72.793
11	1744	205.4	1.342	308	0.646	226.755	73.622
12	1738	205.3	1.398	334	0.671	246.518	73.808
13	1732	205.1	1.454	359	0.696	266.139	74.133
14	1726	205.1	1.511	385	0.718	285.618	74.187

Similarly, the single-phase motor was used to compare to the SHE-motor. The motor used was a Hampden MFM-100, multi-function machine: single-phase AC. This was loaded from only 0% to 100%. Below is the data taken:

Table 2: Single-Phase Data

Torque (lb-in)	Speed (RPM)	V (V)	I (A)	P (W)	PF	Pout	Efficiency
0.64	1795	114.6	4.95	121.9	0.215	13.579	11.139
1	1794	114.5	4.925	127.7	0.231	21.205	16.605
2	1791	114.4	4.935	151.4	0.268	42.339	27.965
3	1788	114.4	4.961	172.1	0.308	63.402	36.840
4	1785	114.4	4.988	195.8	0.343	84.395	43.103
5	1781	114.4	5.033	217.2	0.377	105.257	48.461
6	1778	114.3	5.075	239.2	0.412	126.096	52.716
7	1774	114.2	5.092	260.4	0.448	146.781	56.367
8	1771	114.1	5.226	284.7	0.478	167.466	58.822
9	1767	114.1	5.292	309.8	0.513	187.973	60.676
10	1764	113.9	5.393	332.5	0.541	208.505	62.708
11	1759	113.8	5.55	358	0.566	228.705	63.884
12	1755	113.6	5.69	385	0.595	248.929	64.657

At full load, the efficiency of the single-phase motor is 64.66%. The SHE-motor is expected to have a higher efficiency than the single-phase motor, and get as close as possible to the efficiency of the three-phase motor.

Taking the data from full load and data from 66.64% load of the three-phase motor, the capacitors below were used to run the SHE-motor using a single-phase source.

Table 3: Capacitor Bank Values

Capacitors	66.64% load	100% load
C_{2-12} (μF)	2.67	6.5
C_{10-1} (μF)	5.35	12.99
C_{11-12} (μF)	13.09	10.9

Taking the capacitor values, the circuit in figure 1 was implemented and testing had been done. Similar to the three-phase motor test, the SHE-motor was loaded from 0% to 120%.

Table 4: 100% Load Design Data

Torque (lb-in)	Speed (RPM)	V_{14} (V) (CL)	V_{25} (V) (LL)	V_{36} (V) (DL)	I_{14} (A) (CL)	I_{25} (A) (LL)	I_{36} (A) (DL)
0.21	1795	133	112	132	1.76	0.5	1.65
1	1791	132	112	132	1.68	0.51	1.64
2	1787	131	113	131	1.6	0.54	1.62
3	1783	130	113	130	1.52	0.58	1.6
4	1779	129	114	129	1.46	0.66	1.59
5	1775	128	114	127	1.4	0.74	1.57
6	1769	127	115	126	1.36	0.84	1.54
7	1765	125	115	124	1.32	0.92	1.52
8	1759	124	116	122	1.3	1.04	1.5
9	1753	122	116	120	1.29	1.14	1.47
10	1747	120	116	118	1.3	1.24	1.42
11	1739	118	116	116	1.34	1.39	1.4
12	1731	117	116	114	1.39	1.52	1.38
13	1722	116	116	111	1.48	1.67	1.36
14	1711	114	116	108	1.59	1.84	1.34

Table 5: 100% Load Design Data

Torque (lb-in)	V_{source} (V)	I_{source} (A)	P_{in} (W)	PF	angle (deg)	P_{out} (W)	Efficiency (%)
0.21	205	0.601	118	0.954	17.446	4.463	3.782
1	204.8	0.688	135	0.958	16.665	21.205	15.708
2	204.8	0.781	154	0.965	15.204	42.316	27.478
3	204.4	0.865	171	0.966	14.984	63.332	37.036
4	204.4	0.956	190	0.972	13.590	84.253	44.344
5	204.4	1.047	209	0.976	12.578	105.080	50.278
6	204.1	1.142	228	0.981	11.187	125.670	55.118
7	204.1	1.232	247	0.986	9.599	146.283	59.224
8	204.5	1.341	270	0.99	8.110	166.612	61.708
9	203.7	1.439	291	0.993	6.783	186.800	64.192
10	203.8	1.552	314	0.995	5.732	206.845	65.874
11	203.2	1.669	338	0.997	4.439	226.487	67.008
12	203.2	1.792	363	0.998	3.624	245.940	67.752
13	203	1.927	390	0.999	2.563	265.050	67.962
14	204	2.082	424	0.999	2.563	283.615	66.890

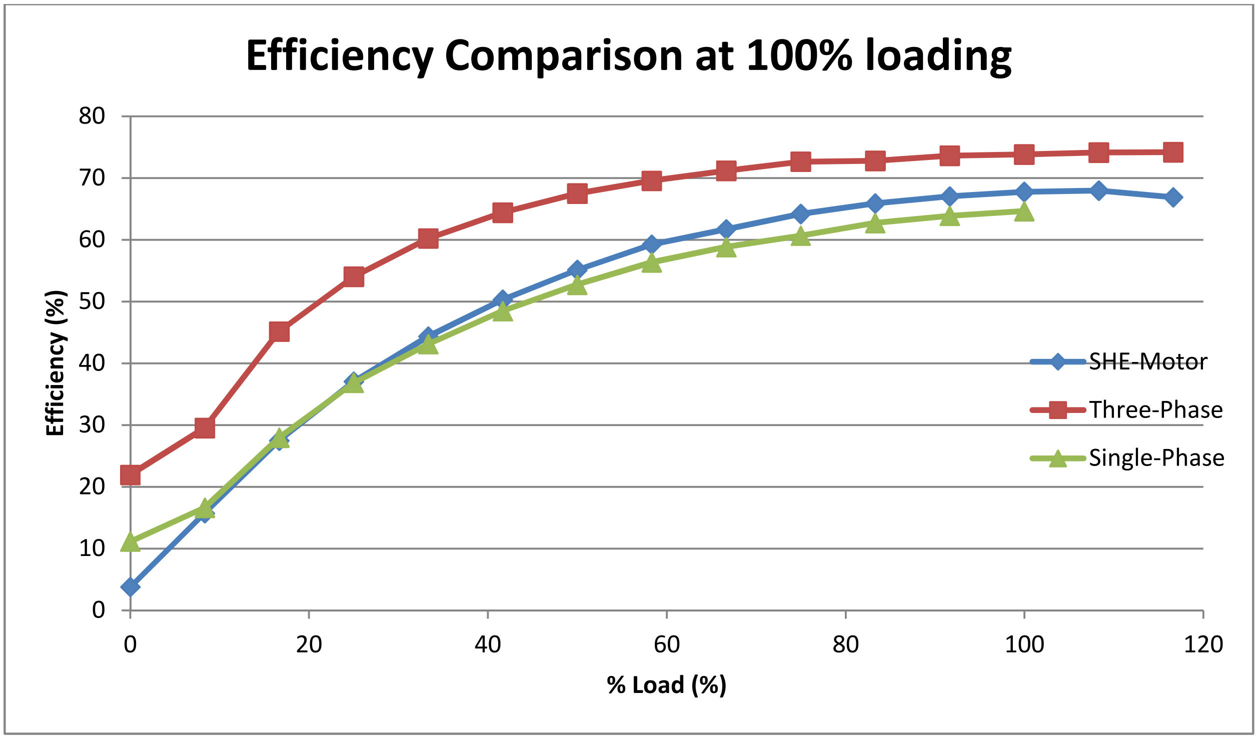

Figure 2: Efficiency at 100% load design

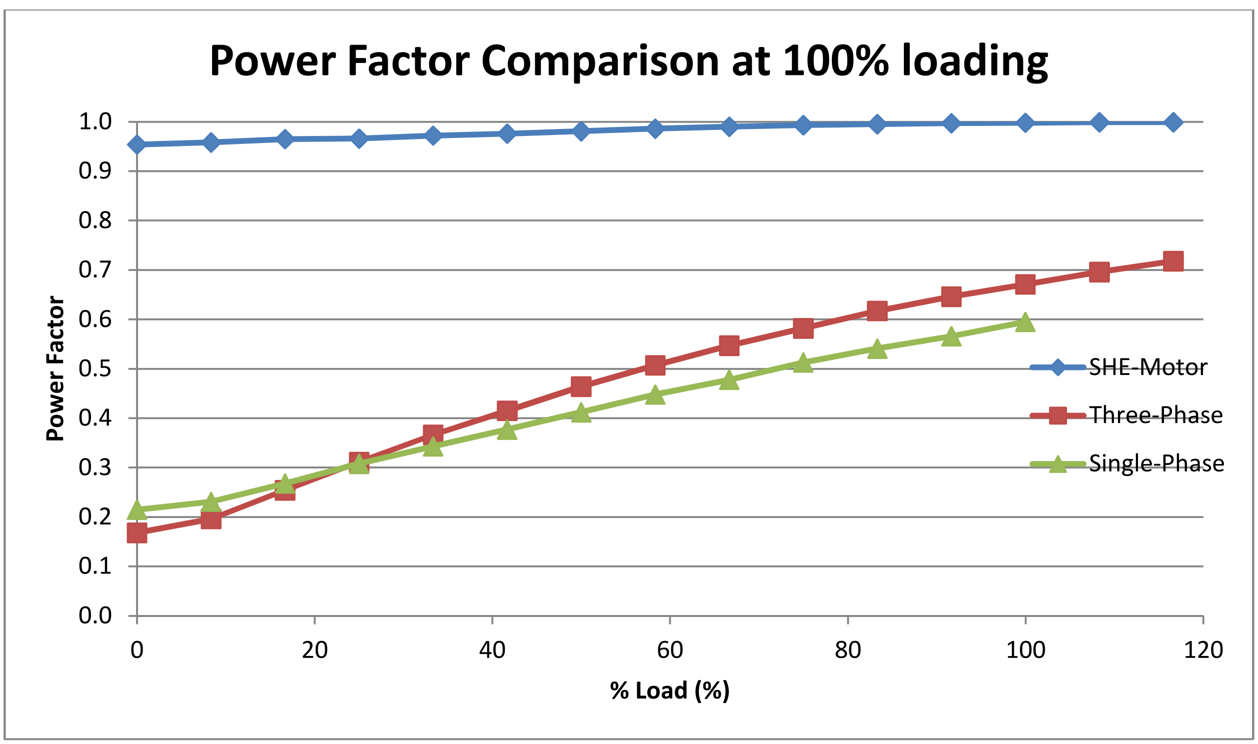

Figure 3: Power Factor at 100% load design

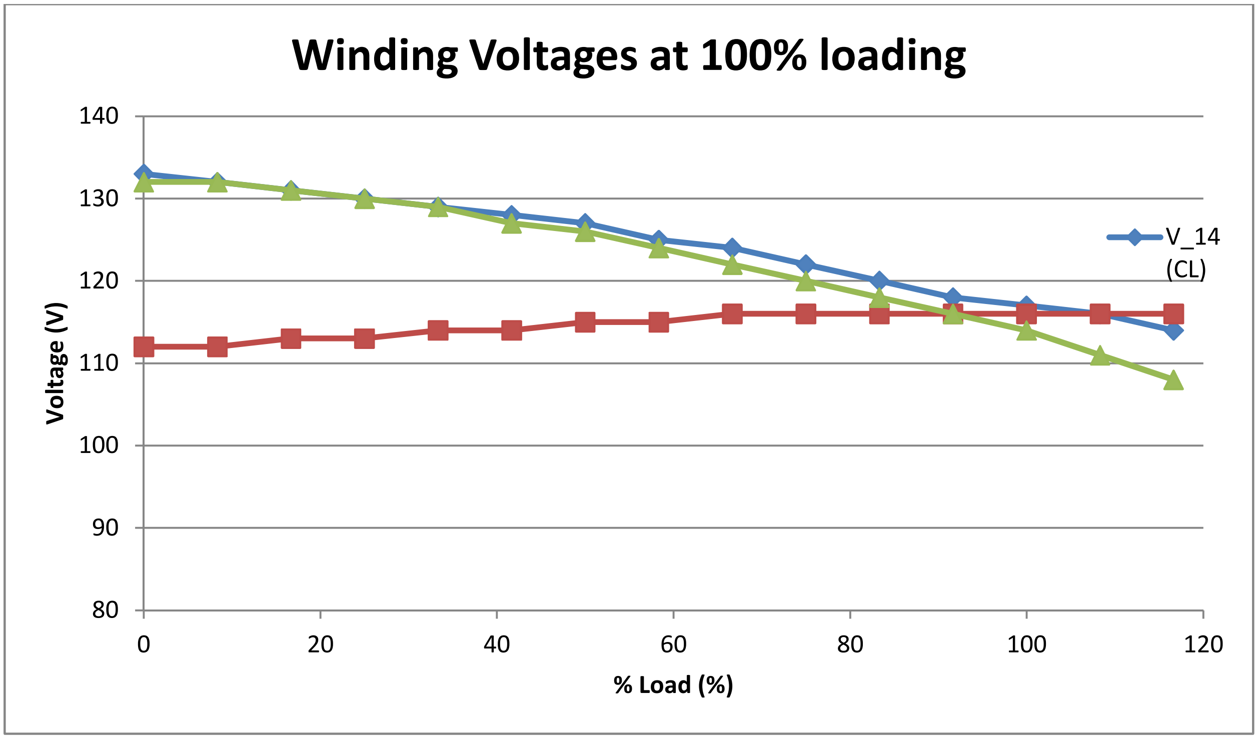

Figure 4: Winding Voltages at 100% load design

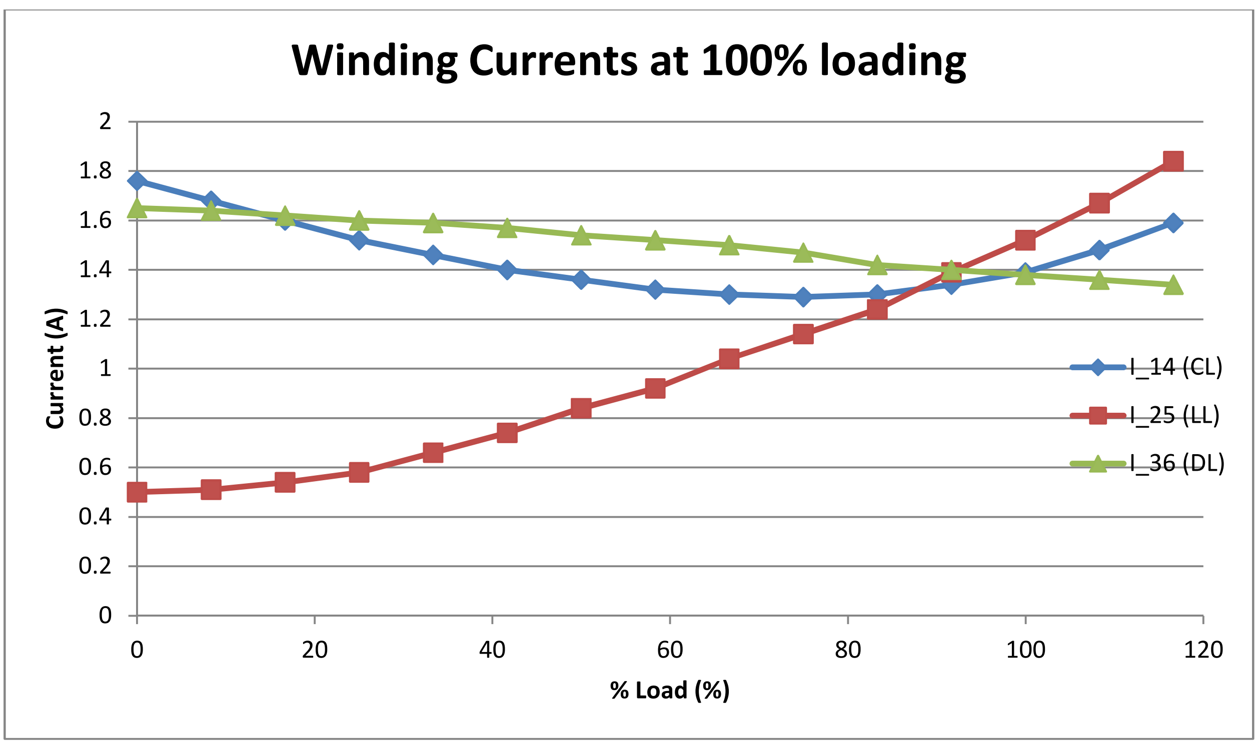

Figure 5: Winding Currents at 100% load design

Table 6: 66.64% Load Design Data

Torque (lb-in)	Speed (RPM)	V_{14} (V) (CL)	V_{25} (V) (LL)	V_{36} (V) (DL)	I_{14} (A) (CL)	I_25 (A) (LL)	I_36 (A) (DL)
0	1796	130	113	128	1.53	0.64	1.4
1	1792	130	113	127	1.47	0.68	1.4
2	1787	128	114	126	1.4	0.72	1.38
3	1783	127	114	125	1.34	0.78	1.36
4	1778	126	115	123	1.28	0.85	1.34
5	1773	124	116	122	1.24	0.93	1.31
6	1768	123	116	119	1.2	1.03	1.28
7	1763	121	117	118	1.18	1.11	1.26
8	1756	120	117	116	1.2	1.24	1.24
9	1750	118	117	114	1.24	1.35	1.22
10	1743	117	117	112	1.29	1.48	1.19
11	1734	115	117	110	1.37	1.62	1.17
12	1726	114	118	107	1.46	1.76	1.14
13	1714	112	118	104	1.61	1.95	1.11
14	1702	110	118	101	1.75	2.12	1.09

Table 7: 66.64% Load Design Data

Torque (lb-in)	V_{source} (V)	I_{source} (A)	P_{in} (W)	PF	angle (deg)	P_{out} (W)	Efficiency (%)
0	205.2	0.583	100	0.832	33.695	0.000	0.000
1	205.1	0.637	115	0.881	28.237	21.217	18.450
2	205.2	0.712	134	0.919	23.220	42.316	31.579
3	204.8	0.792	153	0.942	19.610	63.332	41.394
4	204.8	0.885	174	0.957	16.863	84.206	48.394
5	204.9	0.981	194	0.964	15.421	104.962	54.104
6	205	1.085	215	0.968	14.534	125.599	58.418
7	204.5	1.183	235	0.972	13.590	146.117	62.178
8	204.4	1.314	262	0.974	13.094	166.328	63.484
9	204.4	1.427	285	0.975	12.839	186.480	65.432
10	204.1	1.554	309	0.976	12.578	206.371	66.787
11	204.1	1.699	338	0.975	12.839	225.836	66.815
12	203.9	1.837	365	0.974	13.094	245.230	67.186
13	203.5	2.022	400	0.973	13.344	263.819	65.955
14	203.2	2.179	431	0.971	13.832	282.124	65.458

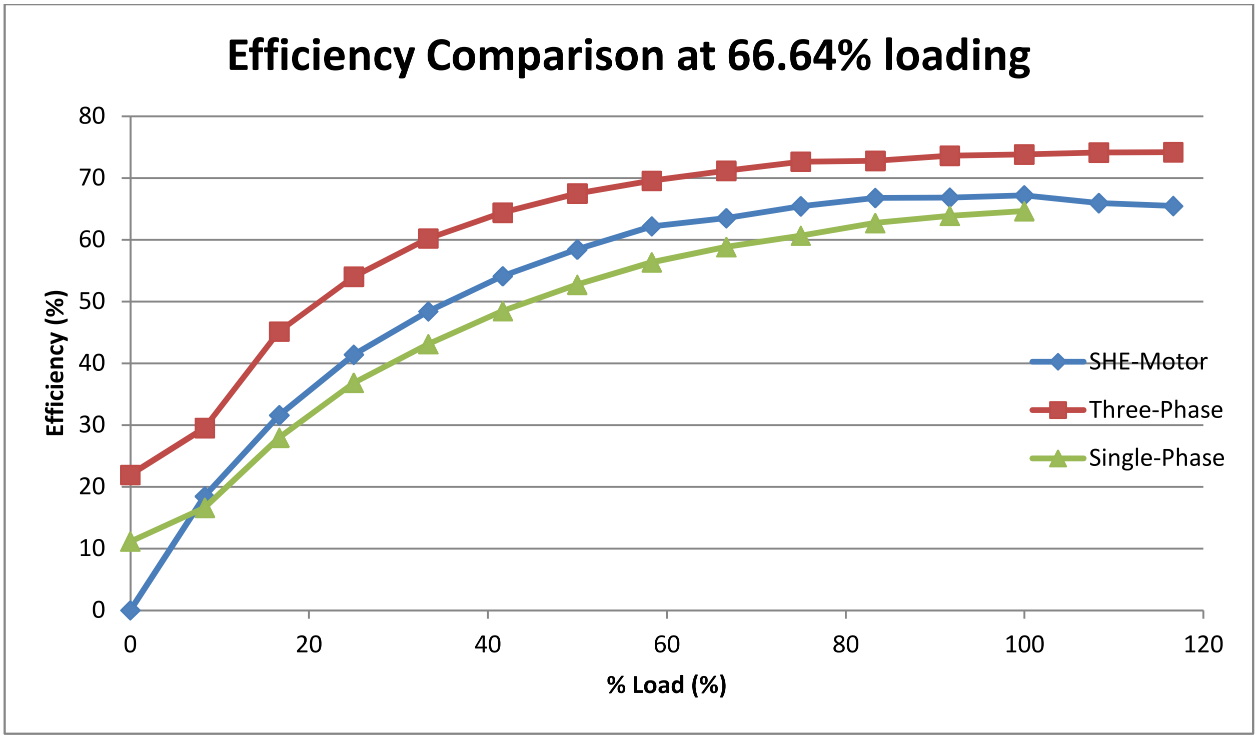

Figure 6: Efficiency at 66.64% load design

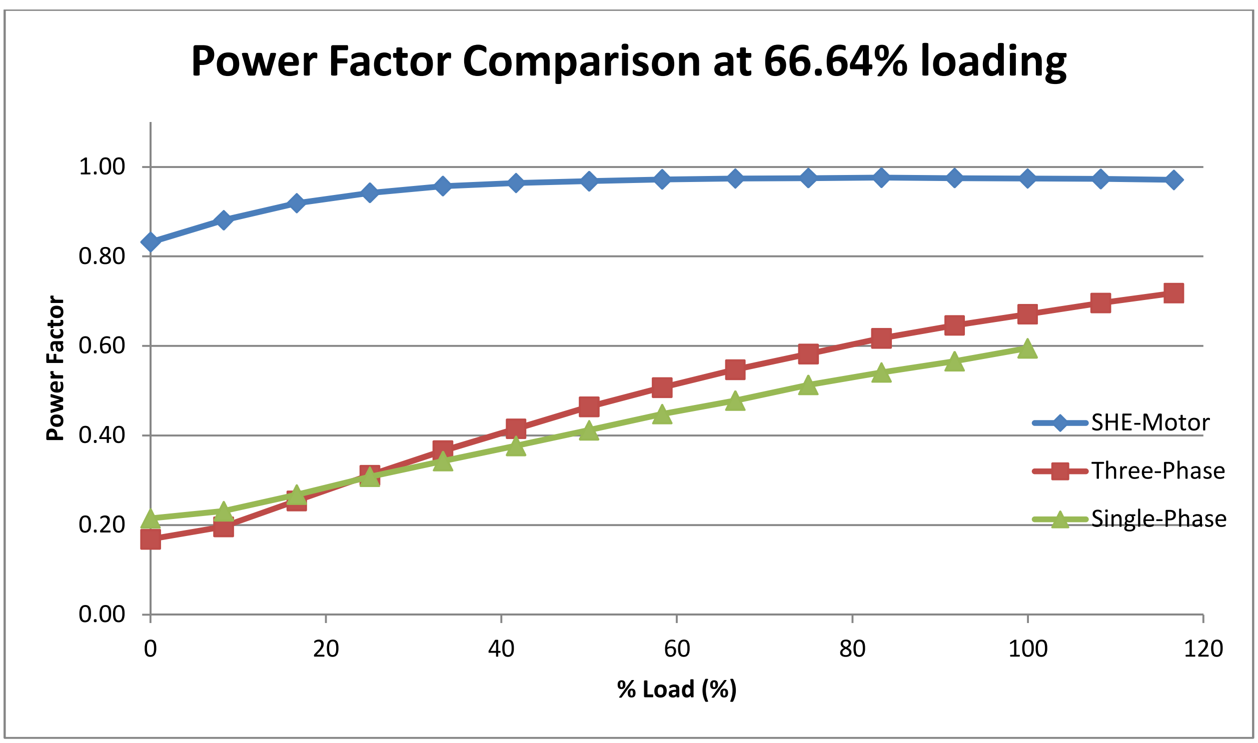

Figure 7: Power Factor at 66.64% load design

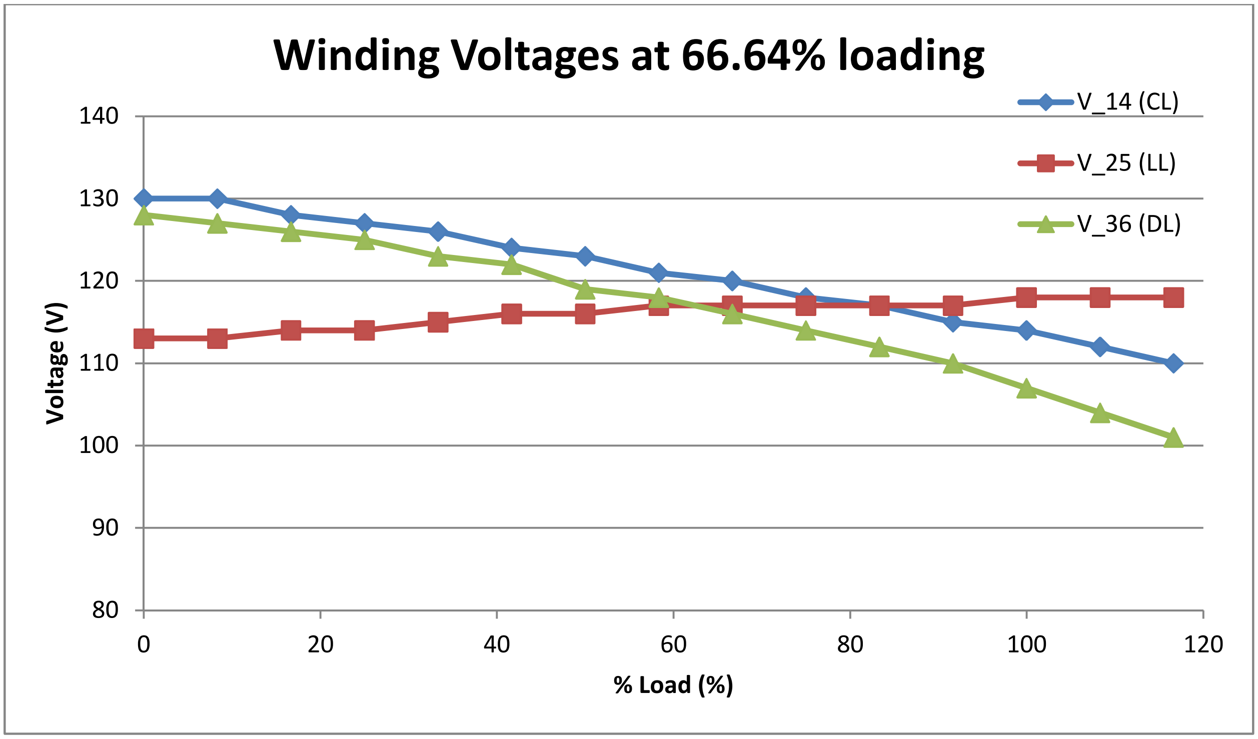

Figure 82: Winding Voltages at 66.64% load design

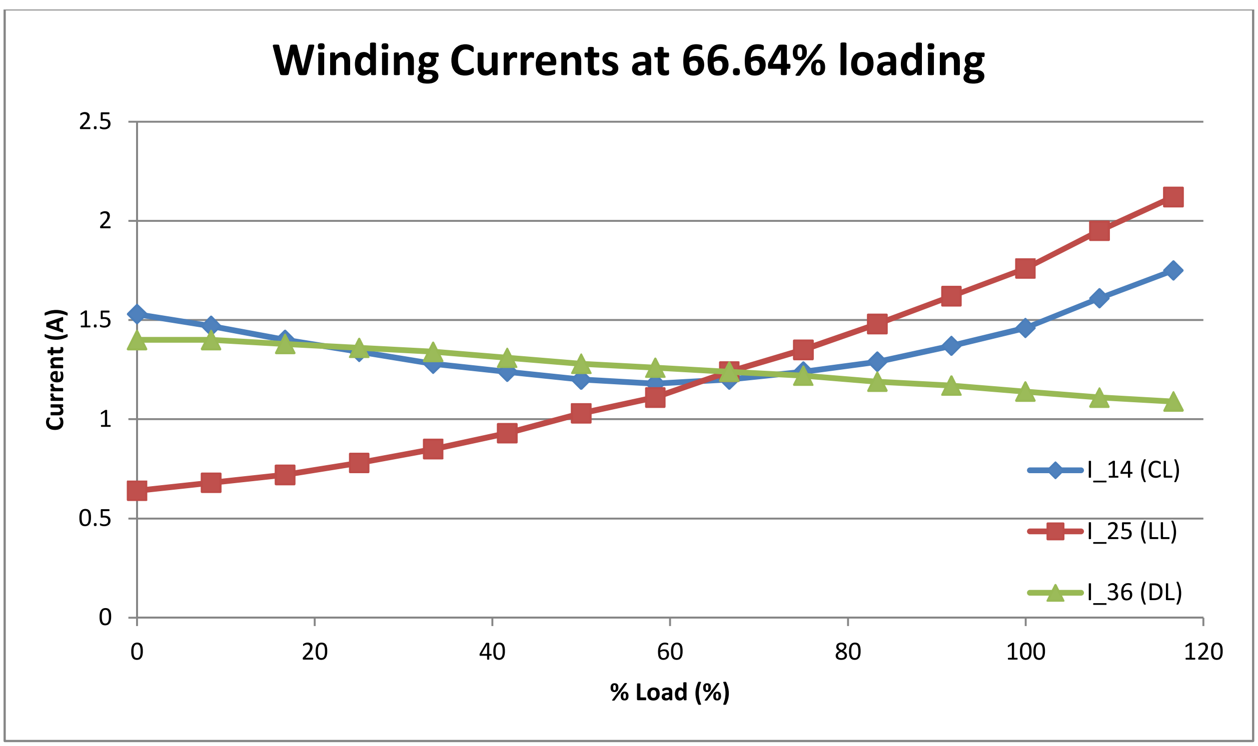

Figure 9: Winding Currents at 66.64% load design

The testing of the SHE-motor was done many times due to invalid data that was recorded. The cause may have been from user error, misreading the meters, as well as the motor itself acting abnormally. Initially, the efficiency found from the SHE-motor was too low to be even considered useful. Both efficiencies of the SHE-motor and single-phase motor were essentially the same with both having about 64%. In order to remedy the issue, many different things were changed. First, the motor was changed since there was only two of its kind. When the results yielded the same issue, the dynameter was then changed. This resulted in a three percent increase in efficiency. Unfortunately, re-running the single-phase motor test yielded the same results it did the first time. Originally when I connected the SHE-motor at full load, and measured it at 12 lb-in, it had given an efficiency of 69.7%. However, when loading the motor from 0% to 120%, the result ended in being 67%. As a hypothesis, the motor may be losing power due to the generation of heat, as it takes time to gather data and loading the motor.

After the full-load testing had been performed, the 66.64% load with capacitor bank values was taken from table 3. The motor could not start on its own and needed help with a starting capacitor. Thus, connecting a 10μF capacitor in parallel to the capacitor at $C_{10\text{-}12}$, when the motor had begun to run, the C_S was removed and testing had begun. When loaded to about 66.64%, the efficiency is about 63.5%. At that same load point for the single-phase motor, it has an efficiency of 58.8%. Although it is only a 5% increase, nonetheless, it proves that the SHE-motor is still more resourceful than its single-phase counterpart. The "half-load" testing of the SHE-motor provided me less trouble than the "full-load" testing did. However, I did need to redo the "half-load" testing an additional time due to the fact that a data point was irregular.

Discussion

Some things that could be looked into for further testing is heat generated in the motor while it is functioning. This may lead toward answers that could solve why the efficiency drops. This test will be used to measure the motor winding temperatures.

Another test that can be looked into is harmonics injected into the motor. Analyzing how harmonics affect the SHE-motor would determine how extensive voltage and current failures will be. This can also lead towards a new study of how to protect the system, preventing harmonics from occurring. However, since there are capacitor banks used to run the SHE-motor, the capacitors will most likely lead toward most harmonic issues.

Overall, the project was a lot of fun. I did want to run the harmonics test on the motor to understand the effects of injecting different harmonics into the system. This would have given me a better understanding of how the SHE-motor is affected negatively. It would have been my contribution to the compilation of tests done on the SHE-motor.

Conclusion

The SHE-motor proved to be a more efficient machine compared to the conventional single-phase motor under the same operating conditions. As seen through the data and tests performed, the SHE-motor configuration is capable of removing a conventional single-phase motor from operation and be used as a replacement. The power factor of both load configurations were also close to unity. This is caused by the introduction of capacitors to compensate for the inductive motor windings. With the introduction of reactive power into the system, the power factor is brought closer to unity opposed to having a power factor of about 0.7 to 0.8 for a conventional three-phase motor.

The SHE-motor is quite limited in this configuration. Although it is more efficient to run a SHE-motor over a conventional single-phase motor, it is limited since it is only balanced at the load point specific to the capacitor values implemented. The SHE-motor is meant to operate only at constant loads. The reason for using a lesser load of 66.64% was due to the fact that the starting current for 100% in the center leg exceeded the current rating of the motor. Thus, initially, the induction motor will start with the 66.64% load then switch to 100% for normal operation.

References

1. Otto Smith, High Efficiency Single Phase Motor. 91 SM 392-1 EC, IEEE Power Engineering Society, May 21, 1990

2. David Mar, A Study of the Smith Single Phase Motor and its Power Quality. Senior Project, Cal Poly, SLO 1993

3. Jon Morris, Automated switching of the Smith motor configuration. Thesis, Cal Poly, SLO 1994

Appendix A

Equipment Data

Motor Data: Hampton 3ph, □ horsepower, induction motor model IM-100-6, 1725 RPM, cont. duty, 208V, 1.6A/1.8A.

Hampden 1ph, 1/3 horsepower, single-phase AC motor, 1725 RPM, cont., 115V, 5.8A