

Assignment 1 Joshua Beer

by Joshua Beer

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HND Electrical and Electronic Engineering

Investigation into Three-Phase Induction Motors

**PSDE 5027
Power and
Machines**

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1. Research

1.1 Construction and operation of three-phase cage and wound rotor induction motors

According to Hughes (2002) Asynchronous motors (induction motor) is widely used for domestic and industrial applications. These account for roughly 50 percent of electrical power consumption which is down to the induction motor loads.

The constructions of these motors which are so important can be seen in the figure below.

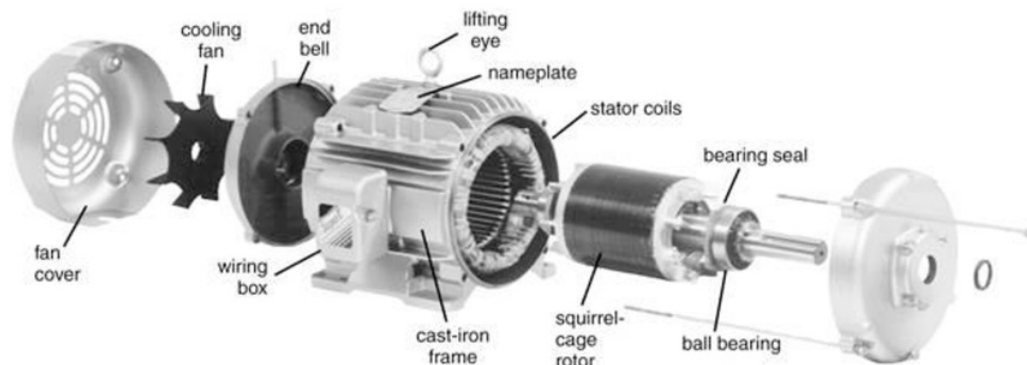


Figure 1 - Three-phase Cage Induction Motor (www.etc.ipfw.edu)

The way in which three-phase motors work is by using three-phases of current to in turn rotate a rotor within the stator coils. This is done by using the e.m.f. (electromotive force) to then create a mechanical turning system which can then be uses to drive or power a system.

The figure above shows the wiring box where the three-phases are wired into which will then create the e.m.f. in the stator coils which will in turn drive the cage rotor and turn the drive shaft to create the mechanical power. The bearings of the drive shaft must be as friction free as possible to therefore have the most energy efficient and free moving motor as possible. The cooling fan will also turn with the motor sucking air in and cooling the coils.

A wound motor differs from a cage motor as it relies on resistance to vary the speed of the motor. This means that it has brushes on the shaft that push against the outside of the inner motor which will vary the speed.

Cage induction motors are more widely used than wound motors, this is because they take less maintenance and are more reliable as they do not need friction to vary the speed.

Hughes states "The stator of an induction motor is similar to that of a synchronous machine, and in the case of a machine supplied with three-phase currents, a rotating, magnetic flux is produced, as already explained." (2002, p. 711)

1.2 Approximate per-phase equivalent circuit of a three-phase wound-rotor induction motor

McFayden states "An ideal transformer of N_1 and N_2 turns respectively represents the air gap. For the rotor side, the induced e.m.f. is affected by the slip (as the rotor gains speed, slip reduces and less emf is induced). The rotor resistance and reactance are represented by R_2 and X_2 ; with X_2 being dependant on the frequency of the inductor rotor e.m.f.s. (2016)

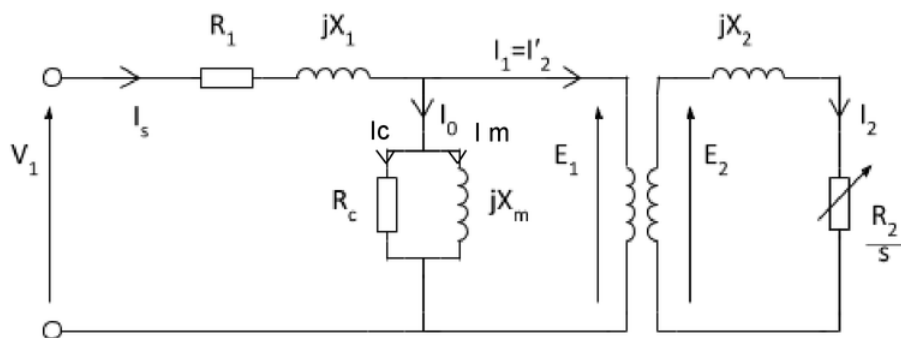


Figure 2 – Exact Equivalent Circuit of an Induction Motor (induction-motor-equivalent-circuit)

Figure 2 shows the equivalent circuit of an induction motor. The left hand side represents the primary side with the right hand side representing the secondary side.

R_1 represents the primary winding resistance

X_1 represents the primary winding leakage reactance

R_2 represents the secondary winding resistance

X_2 represents the secondary winding leakage reactance

R_c represents the open circuit resistance responsible for core losses (hysteresis and Eddy currents)

I_c represents the current that flows into the primary that supplies the core losses

X_m represents the reactance of the core

I_m represents the magnetising current

I_o represents the open circuit primary current

I_2 represents the balancing current in the primary as a ratio of the secondary current for i.e. it supplies and it depends on the load.

I'_2 represents the open circuit primary current

According to McFayden (2016) By removing the dependence on slip for determining the secondary voltage and frequency the simplified equivalent circuit can be drawn below (figure 3). The circuit has been simplified by eliminating the ideal transformer and referring the rotors resistance and reactance to the primary.

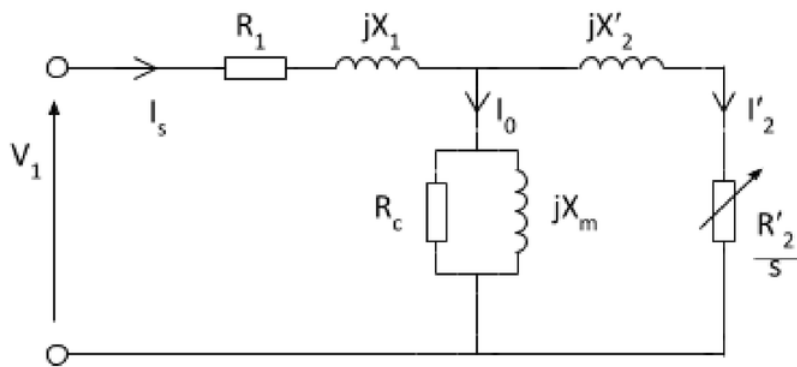


Figure 3 - Approximate Equivalent Circuit (induction-motor-equivalent-circuit)

1.3 Formulae of torque and rotor current to predict the performance of a three-phase induction motor based upon the approximate per-phase equivalent circuit neglecting stator impedance.

The formulae for torque can be found below, first the power losses must be found.

These power losses can be found in the rotor and the rotor windings.

$$\text{Power loss in rotor: } P_{\text{loss}} = \frac{s^2 |E_2|^2 R_2}{(R_2^2 + s^2 X_2^2)}$$

$$\text{Power loss due to heat: } = 2\pi S n_s T$$

$$P_{\text{loss}} = |I_2|^2 R_2$$

By transposing the formulae's for Power loss in rotor and power loss due to heat the following formula is derived:

$$\frac{1}{(2\pi n_s)} \times \frac{s |E_2|^2 R_2}{(R_2^2 + s^2 X_2^2)}$$

By using the equivalent circuit found in 1.2 the formula for rotor current can be found, first the rotor impedance must be found.

Z_2 = Rotor Impedance

If $E_1 = V_1$

$$|E_2| = \frac{N_2}{N_1} \times |E_1|$$

$$\therefore |E_2| = \frac{N_2}{N_1} \times |V_1|$$

$$\therefore |Z_2| = \sqrt{\left(\frac{R_2}{s}\right)^2 + X_2^2}$$

By using this equation above for rotor impedance, the rotor current formula can be derived.

$$|I_2| = \frac{|E_2|}{|Z_2|}$$

$$|I_2| = \frac{|E_2|}{\sqrt{\left(\frac{R_2}{s}\right)^2 + X_2^2}}$$

$$|I_2| = \frac{s|E_2|}{\sqrt{R_2^2 + s^2 X_2^2}}$$

These formulae will be used in the tasks below to calculate results from simulated and practical findings.

1.4 Methods of speed control and braking for cage and wound rotor induction motors typically used in industrial applications.

Speed control for wound motors typically relies on the resistance of the brushes changing to control the speed; this is described in 1.1 above. This is used because it is a simple way of controlling speed but can have high maintenance costs for replacing brushes and man hours doing so.

Speed control for cage motors relies on the varying voltage of the 3 phases. This is because if you give the motor less E.M.F. by reducing the voltage the motor is going to turn slower and thus in reverse by increasing the E.M.F. the motor will turn faster. In industry this would be the preferred modern way of controlling the speed of a motor as it keeps costs low, but isn't suitable for low resistance cage motors as the speed in the stable part of the operating region is limited.

There are three main types of braking for motors, these are:

- Plug
- DC Injection
- Frequency Reduction

Plug braking involves swapping the polarity of two phases and therefore creating a reverse acting E.M.F. for the motor and therefore braking it until its speed reaches zero. This must be used in conjunction with a speed probe otherwise the motor itself will start turning in the opposite direction. This is not a very efficient way of braking and can damage the motor as 4 times the kinetic energy of the motor will be dumped as heat into the motor at the time of switching, this can damage the motor.

Injecting a DC current into two of the phases will cause the rotor to travel faster than the stator field and therefore create a negative torque in a positive direction. This makes the motor generate until it slows down and stops.

Frequency reduction has the same effect as injecting a DC current. By reducing the frequency in which the three phases supply current to the motor the stator field will reduce but the rotor will be faster than this and therefore will brake but will generate while doing so.

2. Simulation

Using the formulae already found above, it was now possible to simulate data needed in order to generate results and to then use these results to make graphs which can then be analysed as to what is happening. These graphs are plotting rotor current and torque against fractional slip. By already finding the torque and rotor current equations, this simplifies this part of the assignment. Data values for the equations were given in the assignment brief, which were as follows:

- Motor Poles: 2
- Synchronous Speed (Frequency): 50 Hz (ns)
- E.M.F: 161.6V (E₂)
- Rotor Resistance 4.8 Ohms (R₂)
- Reactance: 39.6 Ohms (X₂)

The equations found in task 1 and used for the simulation are shown below along with examples.

$$\text{Torque: } \frac{1}{(2\pi n_s)} \times \frac{s |E_2|^2 R_2}{(R_2^2 + s^2 X_2^2)}$$

Example of data using a value of 1 for fractional slip:

$$\frac{3}{(2\pi \times 50)} \times \frac{1 \times 161.6^2 \times 4.8}{(4.8^2 + 1^2 \times 39.6^2)} = 0.75$$

$$\text{Rotor Current: } \frac{s E_2}{\sqrt{R_2^2 + s^2 X_2^2}}$$

Example of data using a value of 0.5 for fractional slip:

$$\frac{0.5 \times 161.6}{\sqrt{4.8^2 + 0.5^2 \times 39.6^2}} = 3.97 A$$

Motor Speed: $\frac{60ns(1 - \text{fractional slip})}{\text{Poles}/2}$

Example of data using a value of 2 for fractional slip:

$$\frac{60 * 50(1 - 2)}{2/2} = -3000$$

These were then simulated using fractional slip values incrementing by 0.2 from -1 to 2. These values were obtained and recorded as seen in figure 4.

Fractional Slip	Motor Speed	Torque	Rotor Current
-1.00	6000.00	-0.75	-4.05
-0.90	5700.00	-0.83	-4.04
-0.80	5400.00	-0.93	-4.03
-0.70	5100.00	-1.06	-4.02
-0.60	4800.00	-1.22	-4.00
-0.50	4500.00	-1.44	-3.97
-0.40	4200.00	-1.75	-3.91
-0.30	3900.00	-2.19	-3.78
-0.20	3600.00	-2.79	-3.49
-0.10	3300.00	-3.09	-2.60
0.00	3000.00	0.00	0.00
0.10	2700.00	3.09	2.60
0.20	2400.00	2.79	3.49
0.30	2100.00	2.19	3.78
0.40	1800.00	1.75	3.91
0.50	1500.00	1.44	3.97
0.60	1200.00	1.22	4.00
0.70	900.00	1.06	4.02
0.80	600.00	0.93	4.03
0.90	300.00	0.83	4.04
1.00	0.00	0.75	4.05
1.10	-300.00	0.69	4.06
1.20	-600.00	0.63	4.06
1.30	-900.00	0.58	4.06
1.40	-1200.00	0.54	4.07
1.50	-1500.00	0.51	4.07
1.60	-1800.00	0.47	4.07
1.70	-2100.00	0.45	4.07
1.80	-2400.00	0.42	4.07
1.90	-2700.00	0.40	4.07
2.00	-3000.00	0.38	4.07

	poles	2
ns	Synchronous speed	50
E2	EMF	161.6
R2	Rotor Resistance	4.8
X2	Locked Rotor Reactance	39.6

Figure 4 - Simulated Results

As stated above these were now used to plot the graph of fractional slip against rotor current and torque, this can be seen in figure 5.

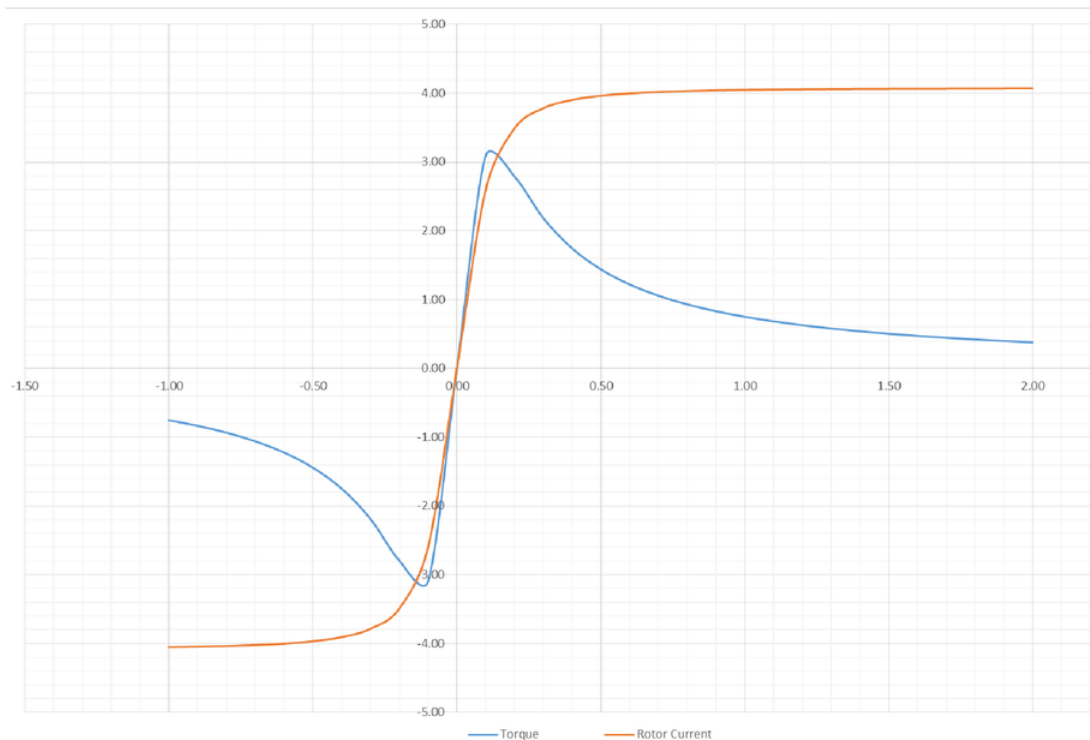


Figure 5 - Fractional Slip against Rotor Current and Torque (Simulated)

The Y axis has no value as both current and torque share the same axis whereas the X axis is showing fractional slip alone.

The graph in figure 5 shows that the motor has a very high start current in the motoring phase of the graph which then levels out to a steady rate when in the braking phase of the graph (about 4 Amps).

Whilst switching from the motoring to the generating phase the graph is a mirror image of each phase until the motor is generating about 4 Amps of current.

$N_r = 0$ when $N_s = 1$ and $N_r = N_s$ when the graph crosses the X axis. This is the motoring region (explained further below)

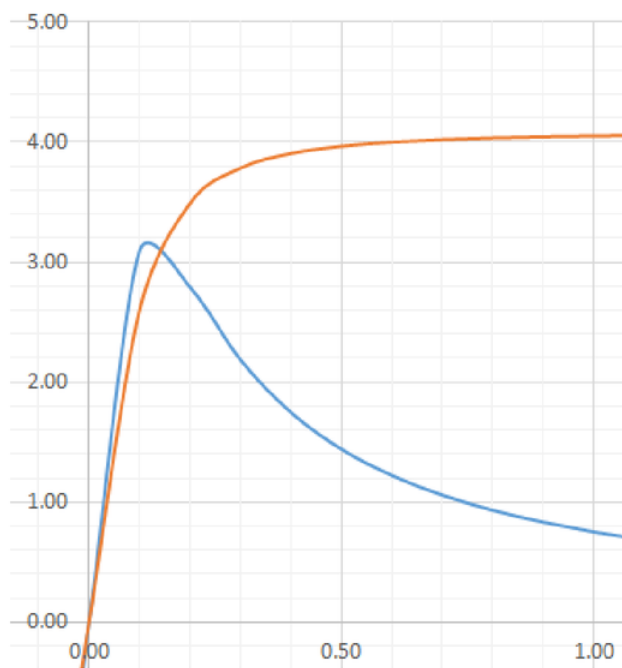


Figure 6 - Simulated Graph (Motoring)

The period in which the motor is motoring is from n_s to 0. This is displayed in figure 6 where n_s (fractional slip) is ranged from 1 to 0 on the graph. The graph is showing the torque increases linearly up until its maximum point until it starts to drop with a decreasing rate. The torque is increasing so rapidly because the motor is running below synchronous speed at this point and is trying to reach synchronous speed. When $N_r < N_s$ the motor is motoring.

Once the motor has reached synchronous speed and is now shown as $N_r = -N_s$ the motor is now braking as the force against the motor is now negative and acting against the stator field, therefore creating a positive torque in a negative direction therefore braking the motor.

This can be seen below in figure 7.

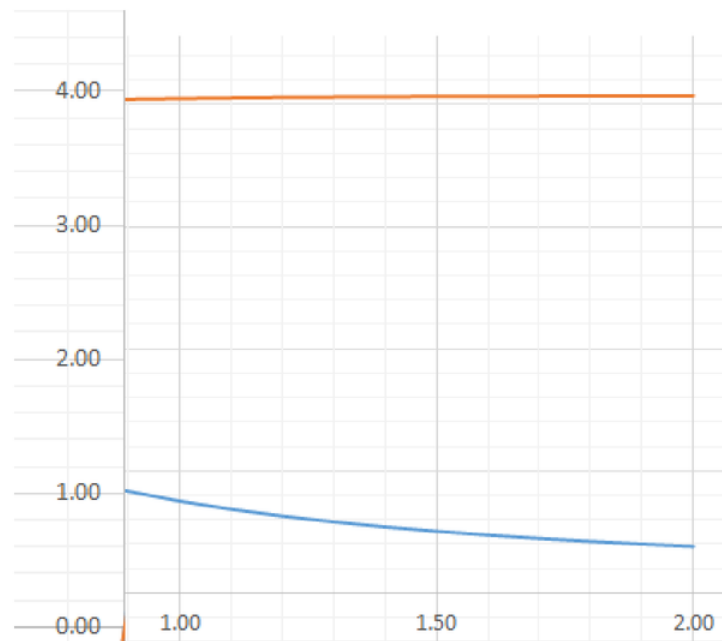


Figure 7 - Simulation Graph (Braking)

The graph above shows the region from $ns = 1$ to 2. This region is the braking region as explained above.

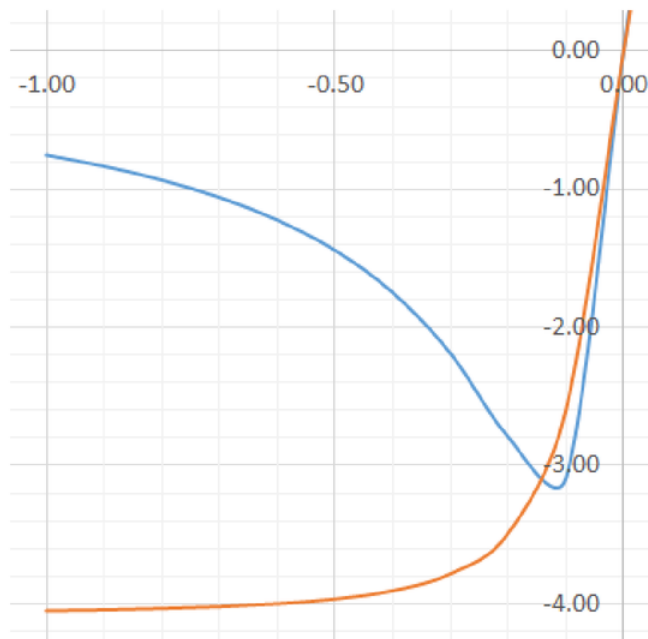


Figure 8 - Simulation Graph (Generating)

Figure 8 shows the region of the simulation in which the motor is generating. When generating, the value for fractional slip (N_s) is negative which means the stator field is being driven faster than the motor can achieve on its own and therefore $N_r > N_s$. This means that the stator field can now generate current which can be put back into the power system.

Torque also goes negative as the motor is not designed to travel faster than synchronous speed and therefore is acting as a brake against the motor and stator field but the motor still generates.

3. Practical Investigation

The practical investigation in this assignment was to carry out an experiment using a three-phase wound rotor induction motor. It was to be wired in delta, with a brake used to simulate load, a VSD was also added to the motor for the generating part of the investigation as this would allow the motor to go above its synchronous speed. Instrumentation will then be used to measure speed, torque, input power, line current, line voltage and power factor. Fractional slip was then calculated along with power for the no load results (both formula are shown below).

There were two parts to this experiment, the generating part where there was no load on the motor and the motoring part where there was a load put on the motor. To gain accurate results which were easier to plot on excel to gain a linear graph the load was increased in decrements so that rotor speed would decrease by 50 each time.

Fractional Slip	P.F	Rotor Speed	VAR	VA	Watts	Current mA	Load	Voltage
0.017	0.53	2950	177	209	110	565	0.00	215
0.033	0.64	2900	175	230	148	621	0.05	215
0.050	0.67	2850	174	233	152	639	0.10	215
0.067	0.75	2800	172	259	195	705	0.20	215
0.083	0.81	2750	170	289	230	779	0.40	215
0.100	0.85	2700	171	326	278	883	0.50	215
0.117	0.87	2650	174	359	314	990	0.70	215
0.133	0.88	2600	175	364	325	1040	0.80	215
0.150	0.90	2550	183	425	371	1130	0.90	215
0.167	0.91	2500	189	451	407	1250	1.00	215

Figure 9 - Practical Results with Load

Fractional Slip	P.F	Rotor Speed	VAR	VA	Watts	Current mA	Voltage	Calculated power
0.000	0.20	3000	196	200	40.6	536	214	39.73
-0.017	-0.02	3050	-213	218	42.1	577	216	-4.53
-0.033	-0.36	3100	-231	248	91.2	657	217	-88.90
-0.050	-0.47	3150	-244	275	128	732	218	-129.91
-0.067	-0.60	3200	-268	334	200	885	218	-200.50
-0.083	-0.65	3250	-286	379	248	998	219	-246.06
-0.100	-0.67	3300	-306	423	294	1120	219	-284.64

Figure 10 - Practical Results with No Load

With no load added to the motor (using the brake) the speed of the motor was increased by 50 each time from synchronous speed (3000 rpm) until the motor could no longer generate as it couldn't be driven any faster by the VSD.

Calculating fractional slip: (Synchronous speed – rotor speed) / synchronous speed

Calculated power (no load): $\sqrt{3}$ x current x voltage x power factor

The results show that fractional slip is increasing/decreasing each time very linearly compared to the rotor speed, this is what we wanted to see by changing the rotor speed linearly.

As the load is increased the speed of the motor decreases as it is gradually braking the motor.

The power, current and VA increase on the motor with a load and the same with the motor with no load.

The power factor decreases on both results as the speed decreases, once the power factor becomes negative, this signals that the motor is now generating.

Using these results the following graphs were produced.

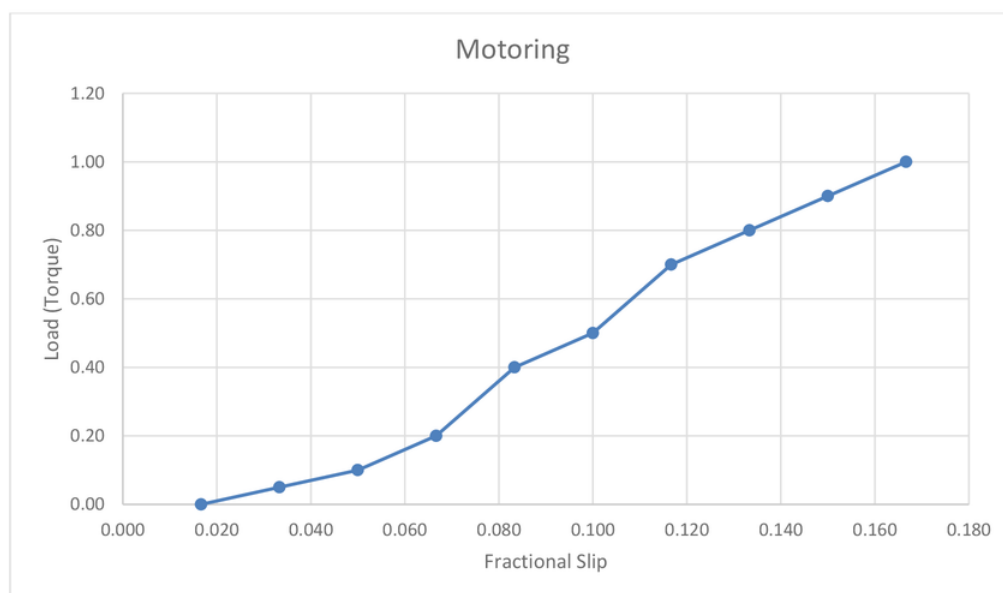


Figure 11 - Practical graph (Motoring) Load against Fractional Slip

Figure 11 above shows that when the load is increased fractional slip also increases. This happens linearly as it does in the simulated graph in figures 5 and 6.

Over this period the load increases very linearly and rapidly as this is therefore the motoring phase.

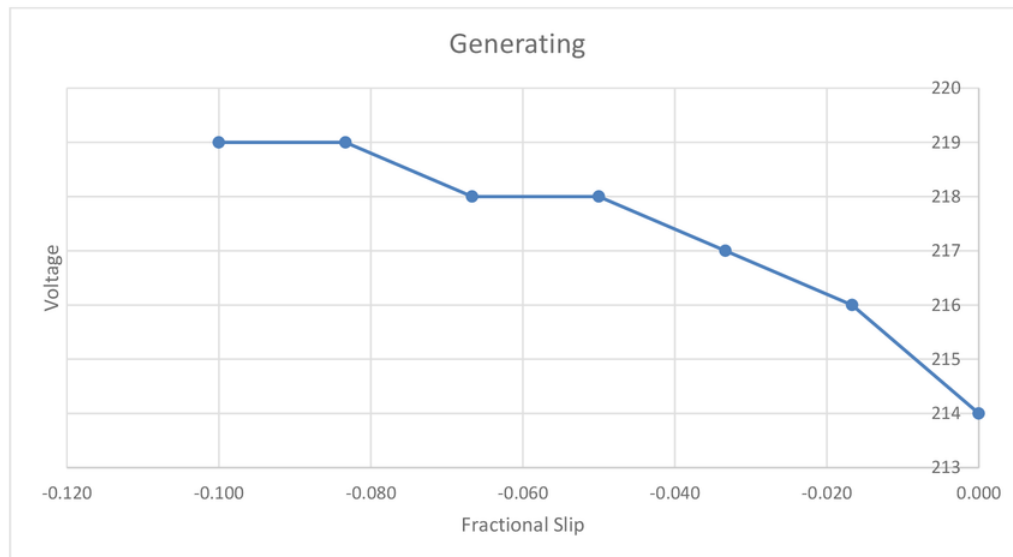


Figure 12 - Practical Graph (Generating) Voltage against Fractional Slip

Figure 12 shows that as the fractional slip decreases the voltages increases, this is because the motor is now being driven faster than synchronous speed by the VSD and is generating voltage to be put back into the power system.

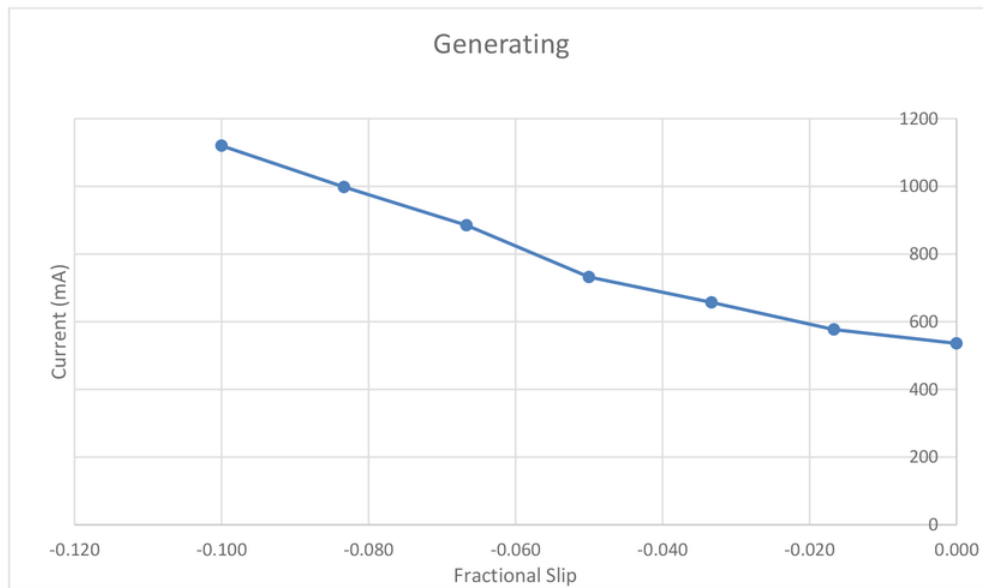


Figure 13 - Practical Graph (Generating) Current against Fractional Slip

Figure 13 shows that as the fractional slip decreases (as explained above) the current increases, this is again because the motor is now generating and current is being supplied back to the system.

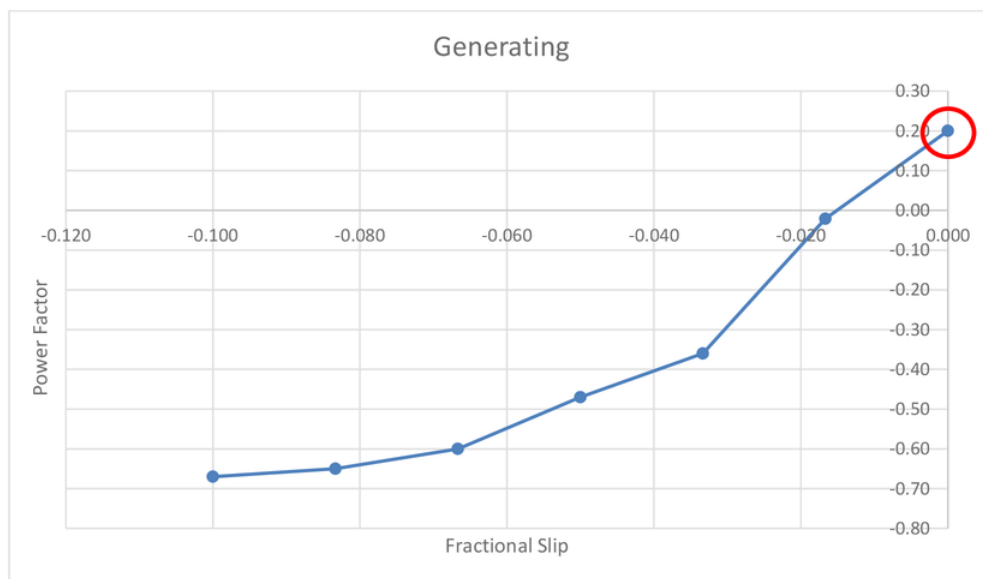


Figure 14 - Practical graph (Generating) Power factor against Fractional Slip

Figure 14 above shows that the first plot on the right (circled) is at the point in which the motor is at synchronous speed and therefore the power factor is still positive as it is still motoring, but once the motor is driven beyond synchronous speed the power factor becomes negative and therefore the motor is generating as $N_r > N_s$.

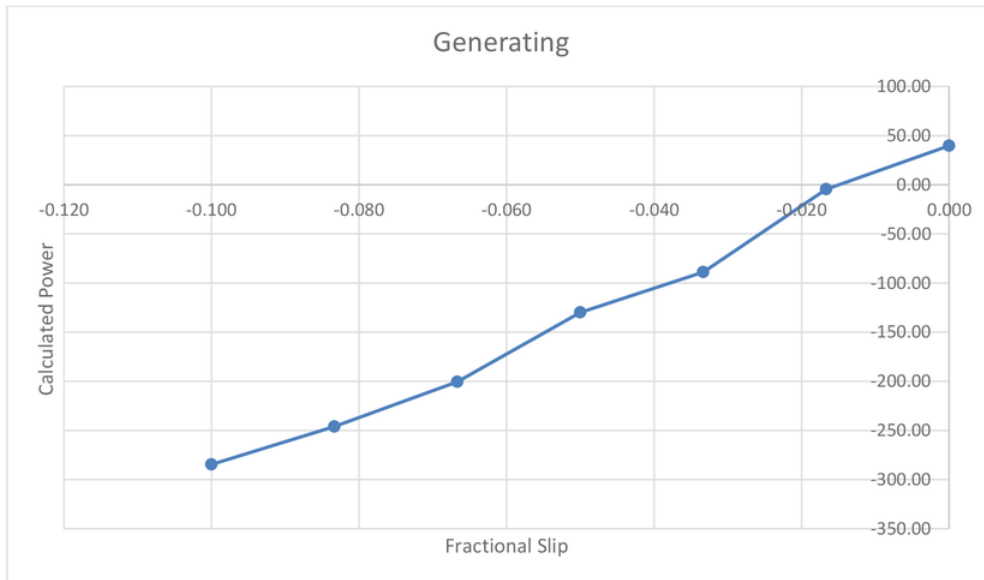


Figure 15 - Practical Graph (Generating) Calculated Power against Fractional Slip

Figure 15 above is very similar to the power factor as when at synchronous speed the value is positive as the value for power factor is also positive but once generating the power factor is negative and therefore so becomes calculated power.

4. Conclusions and Recommendations

By comparing the theory, simulated and practical results a conclusion can be drawn upon whether the results gained were successful and whether they match the theory.

By using the research for the torque and current formulas it was then possible to calculate extra results from the simulated values, these values were then put on a graph and compared to the theory of the induction motor and its equivalent circuits and the speed control and braking of motors.

The graph clearly shows the braking, motoring and generating phases of the motor which is described in the research. These graphs were analysed further and match up again to the results which we expected to gain from the research.

By doing the practical and gaining results from these it was possible to further enhance our knowledge and understanding of motors by again comparing the graphs created (using the formula found in research) to the simulated graphs and research knowledge.

The graphs from the practical results are near perfect compared to the theoretical values and graphs in which we expected to see. The practical results were analysed a bit more in depth and with extra formula to further conclude that the simulated results matched the research.

By doing the research, simulation and practical my understanding of motors has now increased and can now be used in situations where needed in my industry.

5. Citation List

Works Cited

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Assignment 1 Joshua Beer

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

65/100

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GRADING FORM: CSG-RUBIC

JOSHUA BEER**65****RESEARCH-INFORMED LITERATURE**

Section 1: Your research - Good evidence of research and background reading. Further marks were available for a deeper insight into the operation and control of an induction motor. (15/25)

Section 5: Your use of Harvard referencing for citing and listing - Small range of sources listed - almost correctly with correct method of citation. (Select Harvard method within WORD). (2/5)

17**KNOWLEDGE AND UNDERSTANDING**

Section 2 - Explanation of simulation - A brief explanation provided with relevant equations referenced to the theory. (5/10)

Section 3 - Explanation of practical investigation - A good explanation given but further marks were available for a schematic diagram and photos of the setup. (6/10)

11**ANALYSIS**



Section 2: Analysis of simulation - Some analysis carried out but further marks were available for more in-depth analysis comparing results with theory. (5/10) Section 3: Analysis of practical experimental results - Some analysis and comments made on the results with reference to theory. (7/10) Section 4: Overall conclusions and recommendations - good conclusions drawn but no recommendation given. Try to be less subjective in your comments and avoid use of the first person. (6/10)

18

PRACTICAL APPLICATION AND DEP.



Section 2: Presentation of simulation results - Results are well presented in tabular and graphical form. (5/5) Section 3: Presentation of practical results - Results and well presented. (5/5)

10

SKILLS FOR PROFESSIONAL PRAC.



All sections - A well presented and structured report, generally well written. (9/10)

9