

Scott Dedoncker Ass 1 Power & Machines Final Submission

by Scott Dedoncker

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HND Electrical & Electronic Engineering

PSDE 5027: Power & Machines



Assignment 1

Investigation into Three-Phase Induction Motors

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1. Research

1.1 Construction, Winding & Operation of Induction Motors

Three phase induction motors are a widely used piece of equipment in engineering and industry in general, and there are many reasons for this, positive and negative. These motors harness the rotation of an e.m.f (electromagnetic field) to create a rotating force in order to drive a process.

The construction of a three-phase induction motor is complex to say the least. The two types that will be discussed here are cage and wound three phase induction motors. Figure one shows a cut away view a basic three-phase induction motor, courtesy of Clearwater Tech. The main power supply comes from the terminal box on each of the three phases and then supplies the motor windings generating the e.m.f on the stator coils that then rotates the rotor and drive shaft.

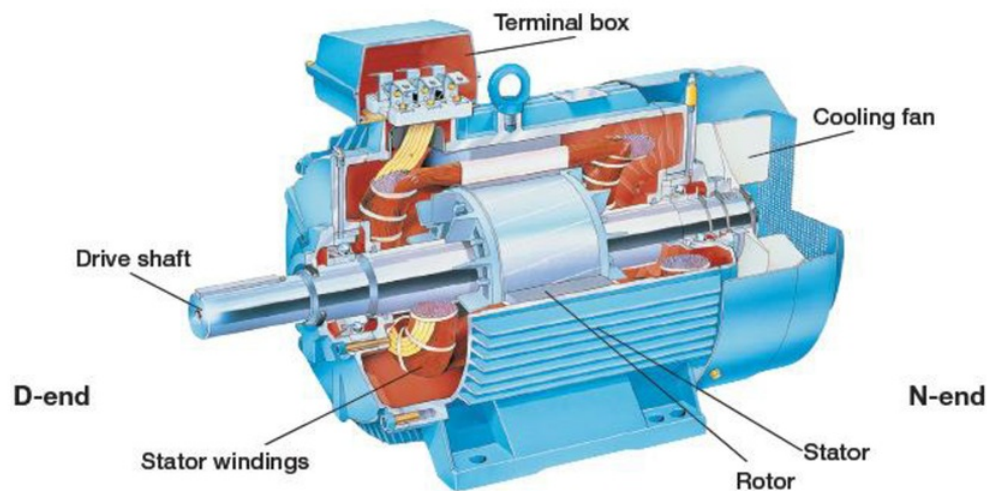


Figure 1 - Induction Motor (Clearwater Tech)

According to Hughes (Hughes, 2006) the cage rotor induction motor is the most widely used type of induction motor, however being best suited for applications that require a constant speed. A cage motor has a rotor that is designed like a cage, with two or more end rings and cage conductors connecting the rings. The stator e.m.f induces a current into these conductors.

The other type of rotor design is the wound rotor. Hughes (Hughes, 2006) also states that a wound rotor consists of *"a set of identical coils wound in slots on the rotor, known as the armature."* Current is fed to the rotor terminals, which supply slip rings that then supply a current to these rotor coils. This current then generates the stator e.m.f.

1.2 Analysis of an Approximate Per Three-Phase Wound-Rotor Induction Motor Circuit and Derivative Equations

The best way to observe a circuit drawing of a three (per) phase induction motor is by interpreting it as an equivalent circuit. This can be done treating the circuit as a “rotating transformer” (Hughes, 2006) with a primary and secondary side, like a regular transformer. The primary will represent the stator and the secondary will represent the rotor. This circuit can be seen in figure 2:

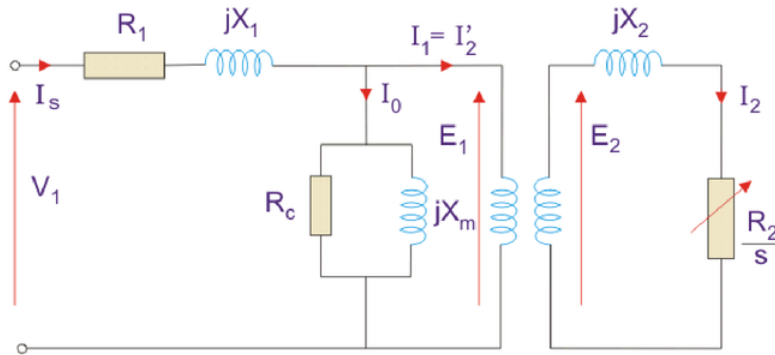


Figure 2 - Three Phase Induction Motor Equivalent Circuit (electrical4u)

The upper rail of the diagram represent the resistance and leakage reactance of both sides, with R_1 and X_1 representing the stator resistance and leakage reactance on the primary side, and R_2 and sX_2 representing the rotor resistance and leakage reactance on the secondary side. R_c and X_m then represent the laminations of the stator on the primary side. The e.m.f of the circuit is then represented by the two coils with E_1 being the primary and sE_2 being the secondary. The stator rotor winding ratio is also shown by N_1 and N_2 . (Amin, 2001)

Research has been carried out into how this equivalent circuit would look if the stator winding impedance and stator core were neglected. The new evaluated circuit can be seen in figure 3:

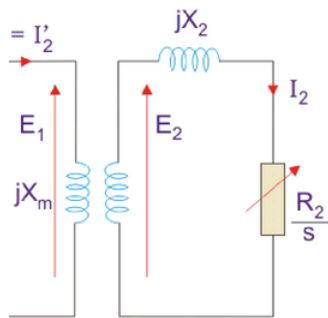


Figure 3 - Neglected Stator Side Equivalent Circuit (electrical4u)

This shows that the primary stator side of the circuit now only has values for the e.m.f and the rotor windings ratio, using E_1 and N_1 respectively. On the secondary rotor side the resistance is now divided by s showing R_2/s . This is because the ideal transformer needs a ratio of E_1/E_2 . I_2 is used as the balancing current that supplies the rotor. (Amin, 2001)

This equivalent circuit can then be used to derive a formula for the rotor impedance by the following calculations:

$$Z_2 = \text{Rotor Impedance}$$

$$\text{If } E_1 = V_1$$

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

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

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

(Amin, 2001)

The rotor current equation can then be derived from this equation:

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

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

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

(Amin, 2001)

This rotor current equation will be used in task 2 for the simulation. Power lost in the rotor can be derived from this equation, as stated by Bakshi (M.V.Bakshi, 2009) by use of:

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

$$P_{loss} = \frac{s^2 |E_2|^2 R_2}{(R_2^2 + s^2 X_2^2)}$$

(M.V.Bakshi, 2009)

Heat losses from the rotor specifically can be expressed in the form:

$$\text{Heat loss} = 2\pi s n_s T$$

(M.V.Bakshi, 2009)

The T in this equation represents torque in the circuit

Bakshi (M.V.Bakshi, 2009) states that this equation can be used with the original power loss equation, to derive the torque equation for the motor. This can be seen below:

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

1.3 Speed Control and Braking Methods in Industrial applications

Austin Hughes states that “there are typically two basic methods of braking a motor; injection and plug braking” (Hughes, 2006), and this is true. These are the two industrial standardised ways of braking a motor when it is running, to it coming to a full stop.

Plug braking is similar to the method of phase reversal. This is when two of the phases on a motor circuit are swapped with one another, switching the rotation of the field. This is usually done by methods of having external 3 phase contactors for the circuit, where one would be used for forward rotation and the other used for reverse rotation. For example while a motor is running in forward, if the reverse function was to be activated, swapping over two phases, this would cause negative torque to the motor due to the switched rotation of the field, causing instant deceleration of the motor until 0. The motor will then slowly accelerate back up in the opposite direction. The braking method comes into play at 0. When the motor decelerates to 0 the supply would need to be disconnected. Thus the motor has slowed down to a halt. (Hughes, 2006)

Mechanical braking is another more widely used method of braking an induction motor to a stop. The operation of this brake is simple, as explained by Parr (E.A.Parr, 1998)(P. 351) “When the supply is applied to the motor, the brake lifts allowing rotation. When the supply is removed the brake comes on stopping the motor.” They also go on to state that the brake can act as a fail-safe to stop the driven motor from running away. This is a purely mechanical method of braking.

A third method of braking used across the industry is DC injection braking. This is when a DC current is supplied to the motor coils causing a braking force within the motor. Usually utilising a rectifier, the DC current is supplied using a transformer of low voltage and high amperage. This can only be done for a few seconds otherwise the motor temperature will increase and overheat. This type of braking system cannot be used as a “handbrake” type device to prevent the motor from driving like the mechanical brake can. (E.A.Parr, 1998)

2. Simulation

Using the formulae found in task 1, simulated data needed to be generated in order to plot two graphs against fractional slip between -1 to 2. The two equations used were the torque equation and the rotor current equation. Data values for the equations were given in the assignment brief and were as follows:

- Open circuit EMF between slip-rings = 161.6V
- Rotor Resistance = 4.8 Ω
- Locked rotor Reactance = 39.6 Ω
- Supply Frequency = 50Hz
- Motor poles = 2

The equations derived in task 1 and used for the simulation are as follows:

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

$$\text{Example of data used for -1 fractional slip: } \frac{3}{(2\pi \times 50)} \times \frac{-1 \times 161.6^2 \times 4.8}{(4.8^2 + (-1)^2 \times 39.6^2)} = -0.75$$

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

$$\text{Example of data used for -0.5 fractional slip: } \frac{-0.5 \times 161.6}{\sqrt{4.8^2 + (-0.5)^2 \times 39.6^2}} = -3.97 \text{ A}$$

The data derived from these equations was then compiled into a table that can be seen in figure 7. A graph was also derived from this data and can be seen in figure 4.

The graph shows that when generating and/or motoring the current always steadily, but quickly increases to a plateau of 4 Amps. This shows that the motor has a very high start current and is shown by the orange line plotted on the graph in figure 4.

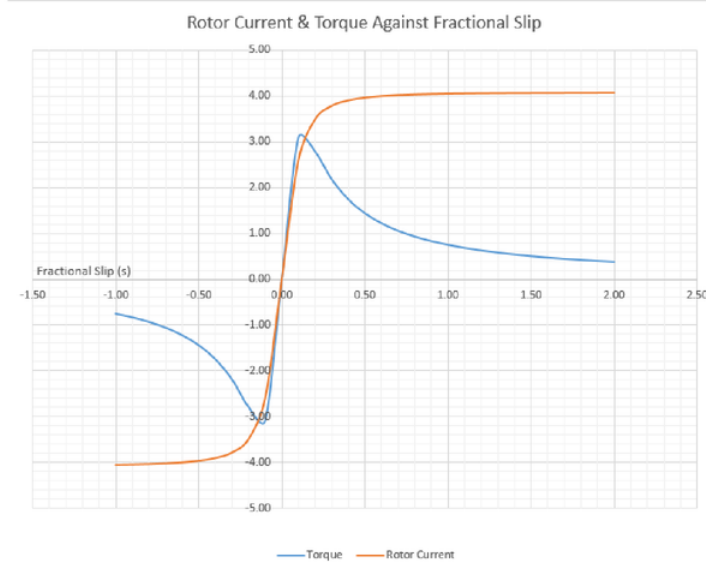


Figure 4 - Rotor Current & Torque against Fractional Slip Graph

When referring to the plotted points for torque, the graph shows the three working stages of a motor; braking, motoring and generating. All these stages are plotted in blue. For the set of data used the generating stage is found on the negative axis of x and y. This is due to 's' being negative when the motor is generating as the motor is being driven faster than synchronous speed by an external load. There is also a constant braking force from the stator field.

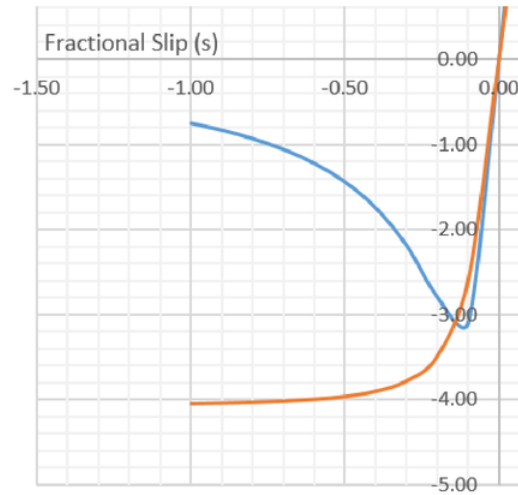


Figure 5 - Generating Stage

The motoring stage is found between 0 and 1 on the x axis. At this stage $N_r = 0$ is the cross over between generating and motoring. 1 on the x axis is the point at which the braking stage occurs. The stage between 0 and 1 on the x axis depicts the development of positive torque due to the rotor rotating at a slower speed than the stator field, or slower than synchronous speed. This also shows that $N_r = N_s$ with N_s being fractional slip. Braking occurs when N_r becomes negative as the motor has a force acting upon it that is the opposite direction of the stator field's rotation.

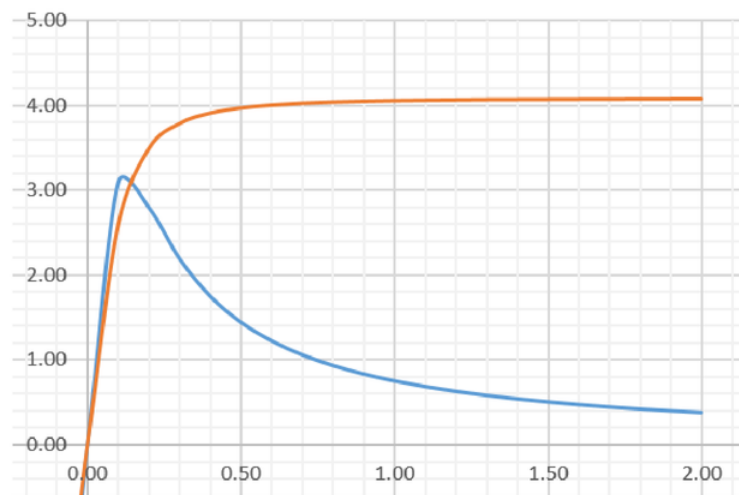


Figure 6 - Motoring & Braking Stages

Figure 7 shows the table of results found in the simulation process by using the equations derived in task one. The first column shows the fractional slip values from -1 increasing to 2. The rotor speed column used a calculation to determine the rotor speed at each increment of fractional slip. At synchronous speed at 50 Hz, the 2 pole motor would be running at 3000 rpm with 0 fractional slip. The equation used to determine the other increments of rotor speed can be seen below. The value of 60 used is for the number of seconds over 1 minute.

$$\text{Rotor Speed} = \frac{n_s \times 60 \times (1-s)}{\text{Motor Poles}/2}$$

The torque and rotor current equations were then used to determine the other values for the last two columns.

Fractional Slip (s)	Rotor Speed	Torque	Rotor Current	Open CCT EMF (v)[E2]	161.6
-1.00	6000.00	-0.75	-4.05	Rotor Resistance (Ω)[R2]	4.8
-0.90	5700.00	-0.83	-4.04	Locked Rotor Reactance (Ω)[X2]	39.6
-0.80	5400.00	-0.93	-4.03	Supply Frequency (Hz)	50
-0.70	5100.00	-1.06	-4.02	Motor Poles	2
-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	Ns (Freq/Pole pairs)	50
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		

Figure 7 - Table of Simulated Results

3. Practical Investigation

The third task for this report was to carry out a practical investigation into a three-phase wound rotor induction motor. For this experiment the motor needed to be wired in delta with a manual starter and a brake used to simulate load. A VSD motor needed to also be connected for the generating part of the experiment. An instrument was then used to measure torque, speed, input power, line current, line voltage and power factor.

The first test performed was simulating the motor running under load. This began at 0 (no load) and incremented up to 1 Nm. The increments varied slightly due to the brake being difficult to tighten at a consistent rate, however we attempted to increment it in 0.2 Nm as best as possible. Fractional Slip was calculated as $s = (N_s - N_r) / N_s$ with N_s being the synchronous speed of 3000, and N_r being the stator speed. It is evident that there is a consistent pattern in the way fractional slip increments up as the load increases. It is also evident that as the load increases the stator speed slows from the original 2950 rpm to 2500 rpm at 1 Nm of load. The current also increase as the load increases as the motor is having to work harder drawing a larger current. The watt output increases four fold from 110 watts at no load to 407 watts at 1 Nm load. The power factor shows an inductive load as the power factor is below 1 for this first experiment. This is also known as lagging (current lags voltage). The power factor does increase as a greater load is applied and the stator speed slows, as more of the energy is being consumed by the load. The VAR (volt-ampere reactive) originally begins decreasing from 178 at 0 Nm, to 170 at 0.4 Nm. After this point it begins to increase again eventually going beyond the original 178 value and reaching 189 at 1 Nm load. This illustrates the fluctuation of the reactive power in the circuit due to the current and voltage moving while not in phase. VA (volt-ampere) represents the apparent power in the circuit.

Motoring Under Load								
Fractional Slip (s)	Load	Voltage (V)	Stator Speed (r)	Stator Current (A)	Watts	Power Factor (Cos Ø)	VAR	VA
0.0167	0	214	2950	0.568	110	0.53	178	209
0.0333	0.05	213	2900	0.621	148	0.64	175	230
0.05	0.1	213	2850	0.628	152	0.66	174	233
0.067	0.2	213	2800	0.705	195	0.75	172	259
0.083	0.4	213	2750	0.779	213	0.81	170	289
0.1	0.5	213	2700	0.883	278	0.85	171	326
0.1167	0.7	211	2650	0.99	314	0.87	174	359
0.1333	0.8	211	2600	1.04	325	0.88	175	364
0.15	0.9	211	2550	1.13	371	0.9	183	425
0.1667	1	211	2500	1.23	407	0.91	189	451

Figure 8 - Practical Motoring Table of Results

Figure 9 shows the recorded load plotted on a graph against fractional slip. Load is plotted against the Y axis with fractional slip being on the X axis. There is the obvious trend that as the load increases, fractional slip increases at a steady rate. While there are some curves in the plotted points, the line of best fit shows that the average trend is increasing.

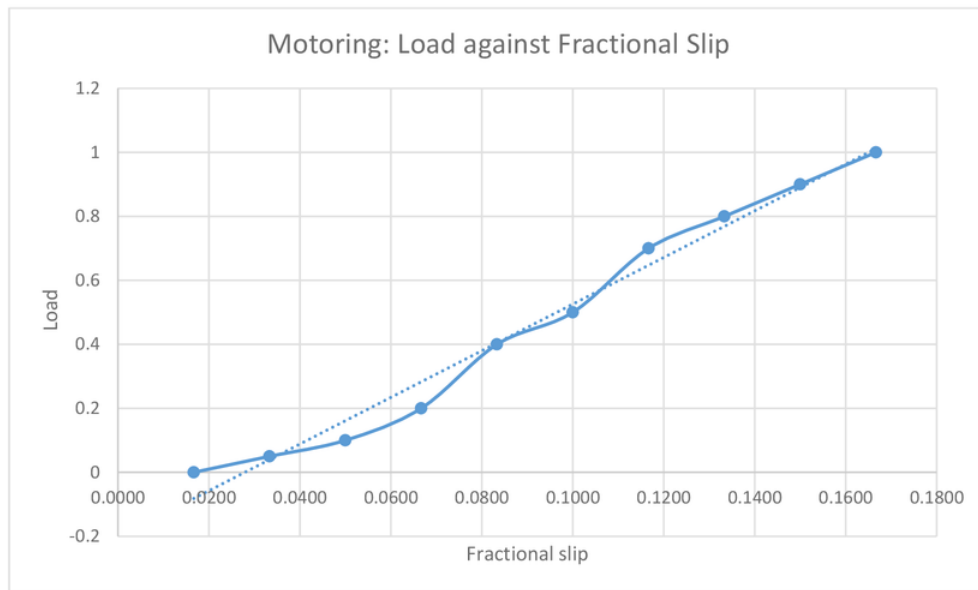


Figure 9 - Motoring Load against Fractional Slip Graph

The second part of the experiment involved connecting and running the VSD. This would in theory simulate the motor generating, as it would be running above synchronous speed. The VSD was increased in speed so that the stator speed would increment in values of 50rpm. As the motor was now generating fractional slip would be negative as we were driving faster than synchronous speed. The same equation was used to determine fractional slip and it shows that once again it increments at a steady and equal rate. The voltage slightly increases over the course of the experiment due to the motor now generating. The stator current also increases from 0.536 A at synchronous speed, to 1.12 A at 300 rpm above synchronous speed. The wattage drastically increases from 40.6 to 294, due to the motor running faster than synchronous speed. The power factor also became negative as expected as the motor was in the generating stage as did VAR. VA increased from 200 at synchronous speed, to 423 at 300 rpm above synchronous speed. The calculated power shows the generated power from driving the rotor above synchronous speed (speed of the emf). The equation used was:

$$\text{Calc Power} = \sqrt{3} \times V_l \times I_l \times \cos\phi$$

Generating									
Fractional Slip (s)	Load	Voltage (V)	Stator Speed (r)	Stator Current (A)	Watts	Power Factor (Cos Ø)	VAR	VA	Calc Power
0	0	214	3000	0.536	40.6	0.2	196	200	39.73463117
-0.0167	0	216	3050	0.577	42.1	-0.21	-213	218	-45.33248081
-0.0333	0	217	3100	0.657	91.2	-0.36	-231	248	-88.89723057
-0.05	0	218	3150	0.732	128	-0.47	-244	275	-129.9050576
-0.067	0	218	3200	0.885	200	-0.6	-268	334	-200.4987374
-0.083	0	219	3250	0.998	248	-0.65	-286	379	-246.0643176
-0.1	0	219	3300	1.12	294	-0.67	-306	423	-284.6410728

Figure 10 - Practical Generating Table of Results

Figure 11 shows the measured line voltage (Y axis) plotted against fractional slip (X axis). This graph is plotted decrementing on the negative x axis due to the motor generating. Although the plotted points are not entirely consistent, the line of best fit shows that as the line voltage increased, fractional slip also increased.

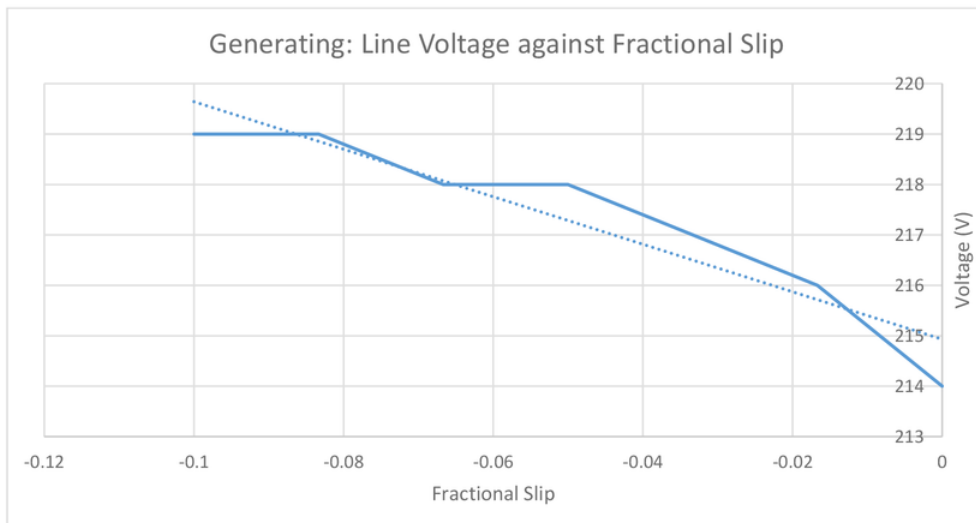


Figure 11 - Generating Line Voltage against Fractional Slip Graph

Figure 12 shows the measured stator current (Y axis) plotted against fractional slip (X axis). Once again the X axis on this graph is negative due to the generating stage of the motor. The plotted data is steady and consistent as it matches up very closely with the line of best fit. This graph shows that as the current increases, so to does fractional slip, as expected.

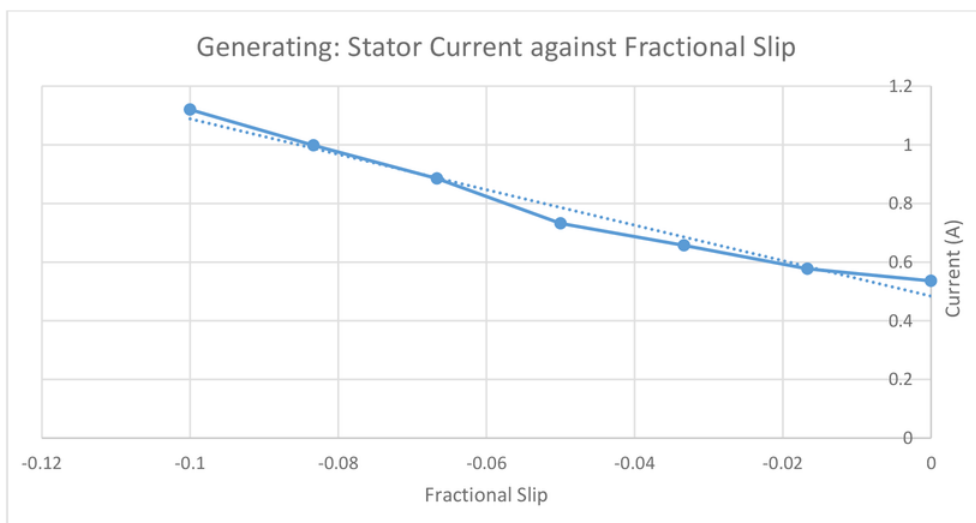


Figure 12 - Generating Stator Current against Fractional Slip Graph

Figure 13 shows the measured power factor (Y axis) plotted against fractional slip (X axis). The graph shows both fractional and power factor dropping into the negative region of the graph due to the generating state of the motor and the VSD driving the stator above synchronous speed. The graph shows a gentle curve plotted as power factor decreases and gets closer to -1, fractional slip also decreases.

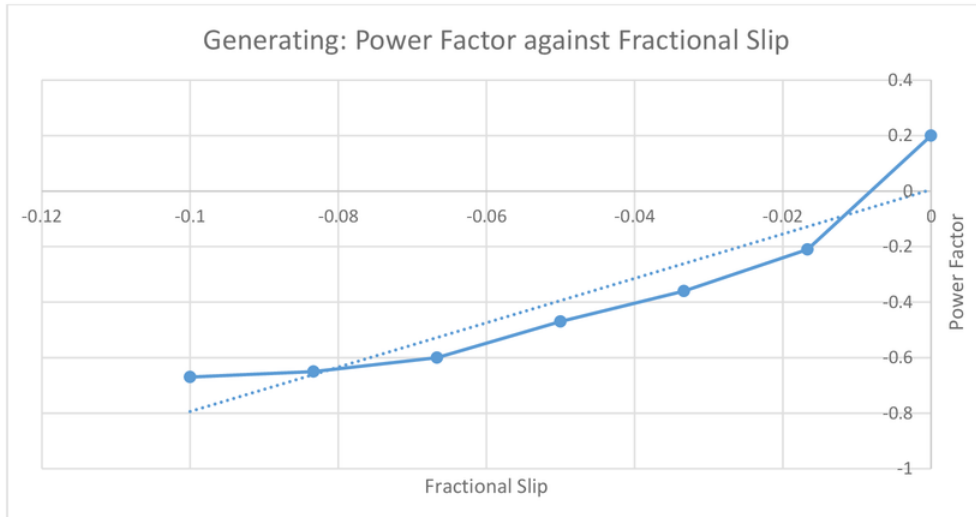


Figure 13 - Generating Power Factor against Fractional Slip Graph

Figure 14 shows the calculated power (Y axis) plotted against fractional slip (X axis). This is once again plotted in the negative axis of the graph as the motor is generating. The plotted points line up closely with the line of best fit showing a consistency between the degradation of power and fractional slip.

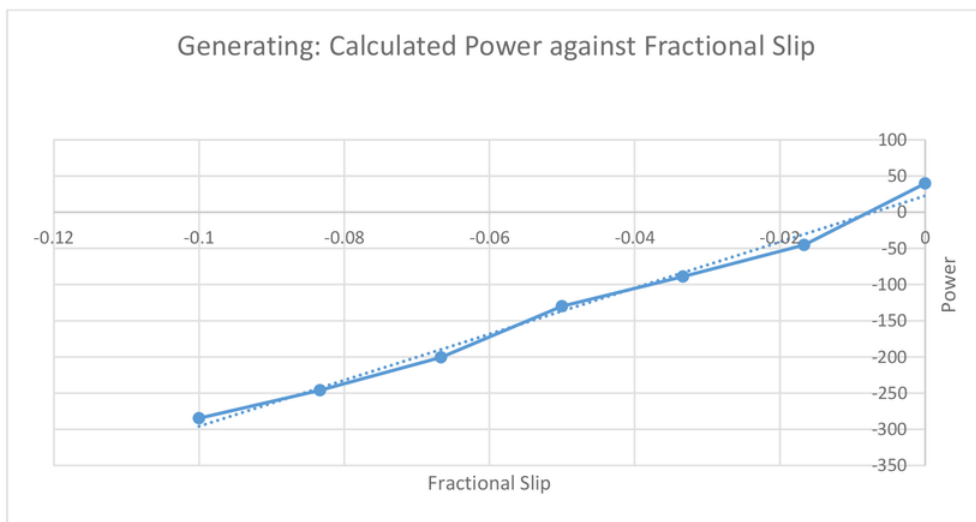


Figure 14 - Generating Calculated Power against Fractional Slip Graph

4. Conclusions & Recommendations

The purpose of this assignment was to carry out three main tasks; research a key topic, use that research to simulate an experiment, then follow that up with a practical experiment relating back to the research.

The research topic for this assignment was to describe the basic construction of two types of three phase induction motors, assess equivalent circuits for these motors, derive equations to be used in the other two tasks, and describe various methods of motor braking. All of these points were fulfilled with the equations derived, that being rotor current and torque equations, were very useful in the simulation task and following practical task.

The second task involved using the equations found in the research to perform basic calculations relating to the task of induction motors, and apply the found criteria to plot a graph detailing motor current and torque against fractional slip. This was completed and equations were written out using the Microsoft Excel format and used to plot a graph using Excel. This graph was then assessed thoroughly. The simulation displayed results that would have been expected of a typical torque and rotor current graph for a three phase induction motor against fractional slip.

The third and final task involved a practical investigation into an induction motor configured in delta configuration, and used in two motor stages; motoring and generating. This practical investigation was a success as the data taken from the investigation for both stages was used to plot five graphs against fractional slip, all involving load, line voltage, stator current, power factor and calculated power. An equation was also derived in order to get values of calculated power. All of these graphs displayed results that were expected.

5. Works Cited

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6. Appendices

Scott Dedoncker Ass 1 Power & Machines Final Submission

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

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GRADING FORM: CSG-RUBIC

SCOTT DEDONCKER

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RESEARCH-INFORMED LITERATURE

 Section 1: Your research - Good evidence of reading. However, not all aspects of research have been included. (13/25) Section 5: Your use of Harvard referencing for citing and listing - Small range of source listed but not quite done correctly according to Harvard. This also applies to your citation method. (2/5) **15**

KNOWLEDGE AND UNDERSTANDING

 Section 2 - Explanation of simulation - A good explanation has been provided of how simulation was carried out with relevant equation from theory and research. However the table of results should come before the graphs. (7/10) Section 3 - Explanation of practical investigation - Good explanation given but it would have helped if you had supplied a schematic diagram of the setup together with a photo of the system. (6/10) **13**

ANALYSIS

 Section 2: Analysis of simulation - Results have been analysed to some extent but it leaves your reader unclear. Further marks were available for some conclusions and comments on the regions of operation of the machine. (4/10) Section 3: Analysis of practical experimental results - Analysis is mainly descriptive and could have been enhanced with more references to the theory and simulation results. (6/10) Section 4: Overall conclusions and recommendations - Assignment tasks were reviewed **15**

but technical facts have not been summarised and no recommendations have been made. (5/10)

PRACTICAL APPLICATION AND DEP.



Section 2: Presentation of simulation results - Results are well presented in table and graph format. (5/5) Section 3: Presentation of practical results - Results are well presented in table and graph format. (5/5)

10

SKILLS FOR PROFESSIONAL PRAC.



All sections - Report is well presented with a good structure and clear figures which have also been listed. Report is also generally well written. (9/10)

9