

Assignment_1

by Emyr Dyer

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HND Electrical & Electronic Engineering

Investigation into Three Phase Induction Motors

PSDE5027 – Power and Machines

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1 RESEARCH

1.1 CONSTRUCTION & OPERATION COMMON TO WOUND & CAGE INDUCTION MOTORS

The stator of both the Wound and Cage Induction motor surrounds the rotor, and has steel laminations that are insulated through oxide coating or varnish (which reduces eddy currents) that makes up the core, into which the insulated copper windings are placed in a clockwise and anti-clockwise pattern to provide opposing electromagnetic poles with a spacing of 120° between the three-phase windings to create the rotating magnetic field when a Three-Phase AC supply is applied to the Stator Windings (Wilkinson, 1965). The windings' leads are led out into the terminal box on the motor's frame and configured into either star or delta configuration. The rotor is held in the frame, supported by bearings which allow the rotor to turn and at the end of the Rotor, there will be a fan to provide cooling as the rotor turns. The frame itself would have suitable mounting points to secure the motor to a stable surface, and a nameplate to identify the motor specifications. A typical layout of a Wound Induction Motor is shown in Figure 1.2, and the layout of a Cage Induction Motor would be similar, minus the differences identified in Section 1.2.

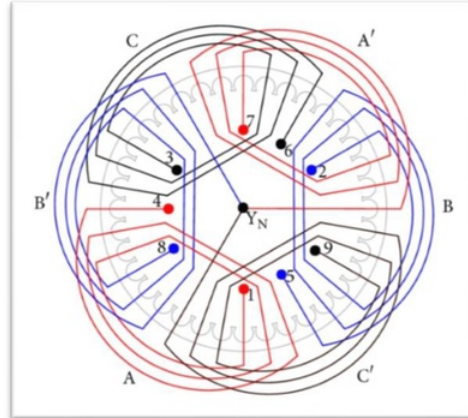


Figure 1.1: Typical Induction Motor Stator winding configuration

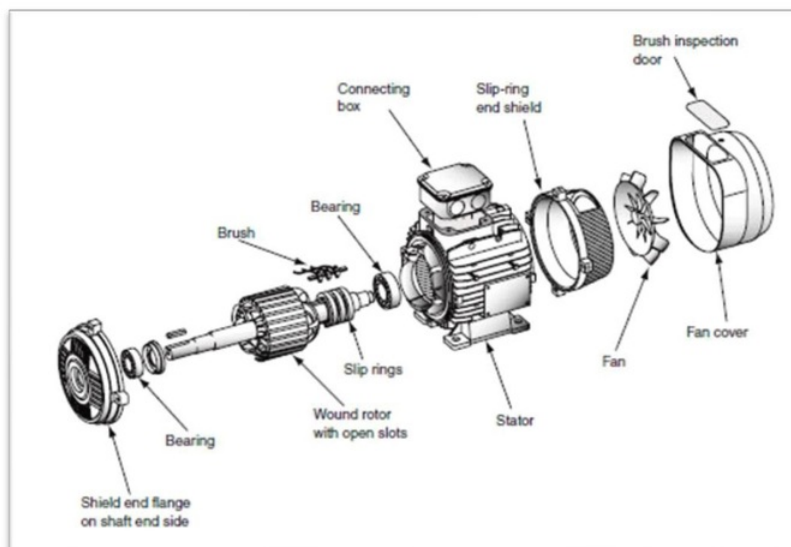


Figure 1.2: Exploded diagram of a Wound Induction Motor

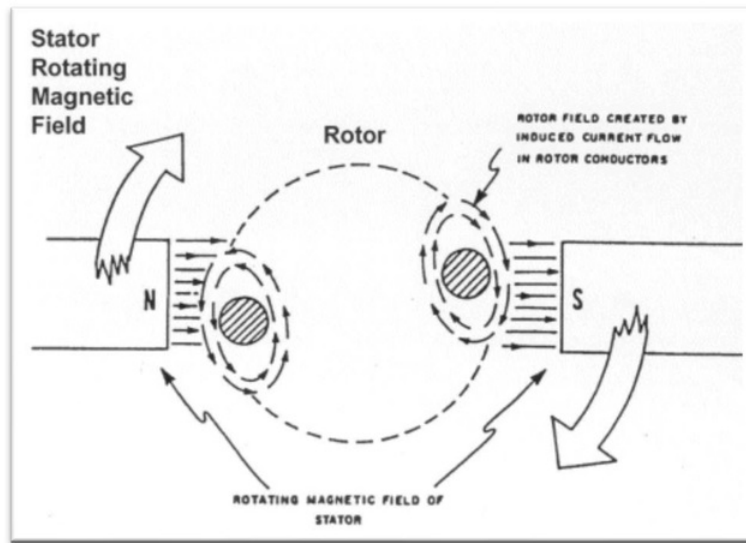


Figure 1.3: Current induced in Rotor

The rotating magnetic field in the stator will induce EMF in the Rotor Bars or Windings as the field passes through and results in current flow in the rotor. The poles created in the rotor will then chase the stator's rotating magnetic field. It should be stated that there should be a difference in speed (slip) in the rotor's field and the stator's field provided there is a load, as if the speed of both were to equal, there would be no EMF, so no current flow, and so no torque.

Both a Wound and Cage Induction Motor can be configured in the terminal box, (located on the frame) in either Star (Wye) or Delta configuration. The Star configuration can be either three or four wire, the four wire connection in particular is essential in unbalanced connections as the fourth wire is used for return current, so that in the event that there is a failure in one of the other three wires, the return current can compensate for the extra current.

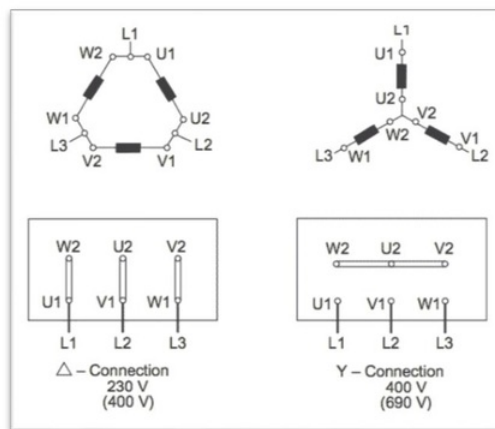


Figure 1.4: Star & Delta configuration with Terminal Box configurations

In Figure 1.5, the effect of rotating poles is shown according to the changing sine waves from the Three-Phase supply.

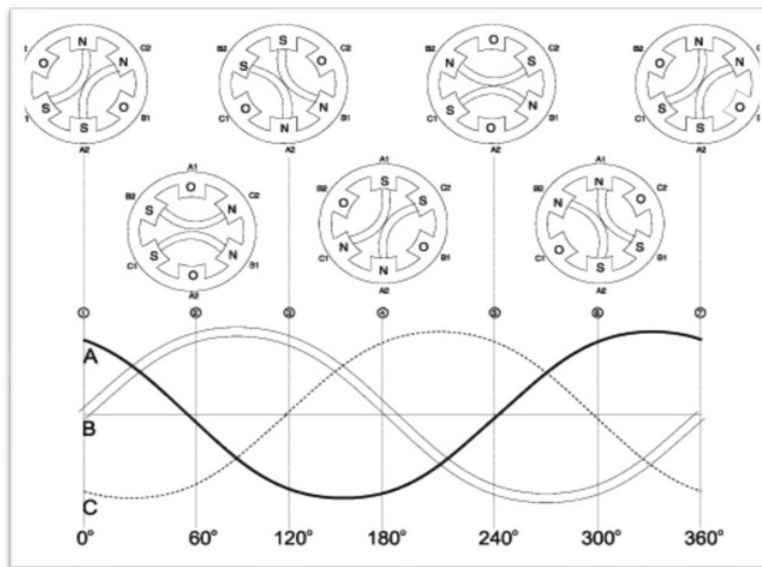


Figure 1.5: Rotating Magnetic Field Produced by Three-Phase Supply

1.2 CAGE INDUCTION MOTOR CONSTRUCTION AND OPERATION

Also called a squirrel cage rotor, the cage induction rotor is constructed of a shaft with steel laminations around it which provide high resistance against electrical currents, but allow magnetic fields to permeate through. The laminations have slots to accommodate the skewed conductor bars from which the motor gets its name. The bars may either be Aluminium which in small rotors would be cast into the slots or Copper where they are welded or bolted to rings at opposite ends of the rotor cylinder, and as a result provide a desired short circuit. Regarding the skewing of the conductor bars, there are several advantages, such as the reduction of magnetic hum, increased slip, and avoided rotor locking as bars will not be perfectly locked to the magnetic field of the stator (due to skewing) (Amin, 2001).

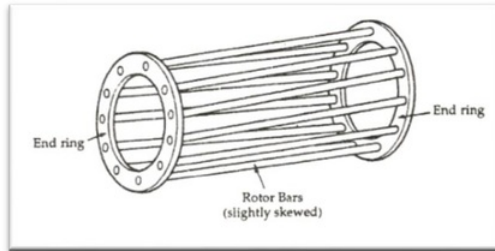


Figure 1.6: Cage Rotor Bars and Rings



Figure 1.7: Complete Cage Rotor

Speed control of a cage induction motor is achieved by adjusting the number of poles or the frequency as is shown by the following equation.

$$N_s = 120 \times f/p$$

A preferable method of speed control is achieved through altering the frequency of the supply to the stator as the rotor is physically isolated in terms of connection. To control the frequency, a Variable Frequency Drive is employed to ramp up and down the supply frequency. The core components that make up a VFD include a Six Diode Bridge converter which turns the Three-Phase AC supply into DC, A capacitor and filter that takes away the ripple left over from the AC, and the Inverter which turns the DC back into AC. The Inverter mirrors the Converter in terms of layout, however instead of Diodes, quick responding switches are used to change the DC into varying width square waveform pulses of constant magnitude, this method of representing a Sine Wave is referred to as Pulse Width Modulation. By increasing the frequency, the revolutions is increased, however torque is lost, due to the increase in inductive reactance in the motor's coils with increasing signal frequency, which can be compensated for by adapting the Voltage to the Frequency when accelerating or decelerating (Carrow, 2000).



Figure 1.8: Variable Frequency Drive

There are six distinct classes of cage induction motor that as shown in Table 1.1. Different classes are better suited for certain tasks like pumping or fans e.g. Classes A and B.

	Starting Torque	Starting Current	Slip	Feature
<i>Class A</i>	Normal	Normal	Normal	Low resistance and reactance.
<i>Class B</i>	Normal	Low	Normal	Can start at full-load.
<i>Class C</i>	High	Low	Normal	Double cage rotors.
<i>Class D</i>	High	Low	High	Thin rotor bars which reduce flux leakage.
<i>Class E</i>	Low	Normal	Low	Reduced slip at load rated.
<i>Class F</i>	Low	Low	Normal	Start with high reactance. Start at high voltage.

Table 1.1: Cage Induction Motor Classes

1.3 WOUND ROTOR MOTOR CONSTRUCTION AND OPERATION

The wound rotor motor like the previously discussed motor has a rotor and a stator, however the rotor is constructed very differently. The rotor's slotted steel laminations around the shaft are fitted with copper windings and linked to three brass slip-rings that are mounted on one end of the shaft to complete the circuit (Lab-Volt (Québec) Ltd, 2003).

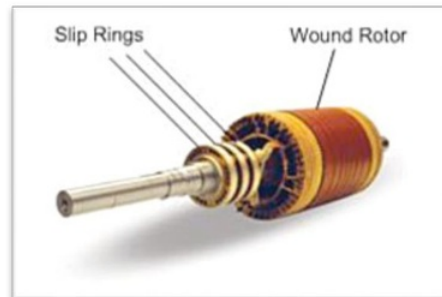


Figure 1.9: Wound Rotor

The slip rings are connected to by a brush gear, that has carbon brushes which contact the slip rings and allows the rotor to turn and still provide a circuit connection. Naturally over time, the carbon brushes will wear down result in carbon fouling within the casing of the motor and would need to be replaced to continue operation. From the brush gear, connections are made to adjustable resistor banks (Smith & Herman, 2004).

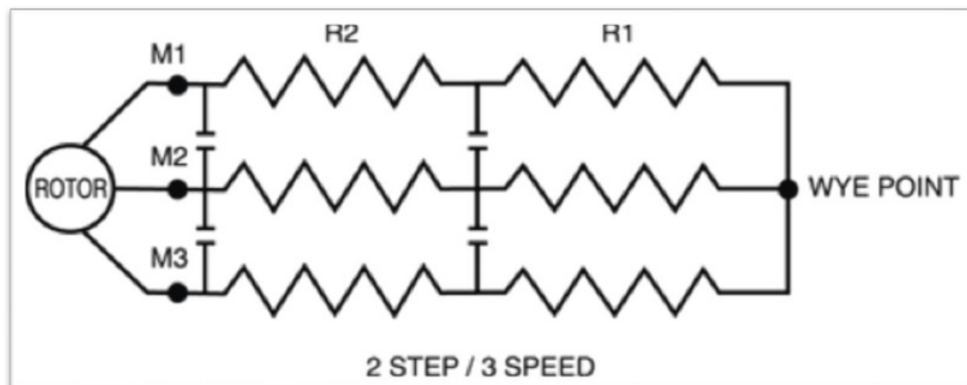


Figure 1.10: Resistor Bank Schematic

During start-up, high resistance is presented to the stator which reduces current and speed, but increases torque. Once the physical resistances to movement on the load are overcome, torque can be reduced, and speed increased through removing resistance by shorting the higher resistance banks out. When increasing the speed, the resistance is then removed which reduces torque. High current in the rotor is not as much of an issue in small motor applications, however it is greatly problematic in larger motors.

The Wound Rotor Motor has similar characteristics to a three-phase transformer with the windings in the rotor and stator being like the primary and secondary windings of a three-phase transformer.

1.4 EQUIVALENT CIRCUIT FOR A THREE-PHASE WOUND INDUCTION MOTOR

To determine the characteristics of the Wound Induction Motor, it is possible to calculate using an equivalent circuit due to the similarity stated earlier to that of a transformer. An equivalent circuit is shown in Figure 1.11, which shows the iron and copper losses in the Rotor and Stator.

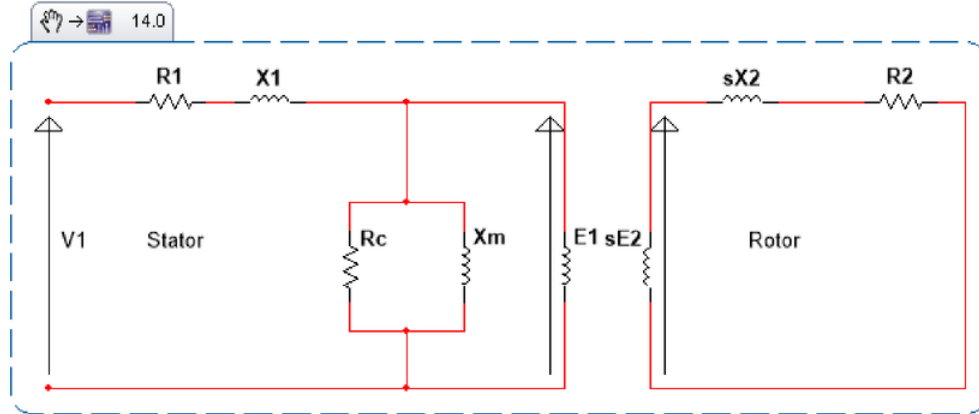


Figure 1.11: Equivalent Circuit

The factors in the Equivalent Circuit above, are explained below:

R_1 = Primary Winding Resistance, R_c = Primary Core Losses, X_1 = Primary Winding Inductance, X_M = Magnetising Winding Reactance, V_1 = Primary Phase Voltage, E_1 = Primary EMF

Secondary

R_2 = Secondary Winding Resistance, sX_2 = Secondary Leakage Reactance, E_2 = Secondary EMF

Both

N_1/N_2 = Transformer Winding Ratio

Taking the above assumptions, the following is true:

$$E_2 = \left(\frac{N_2}{N_1} \right) \times E_1 \text{ and } f_p = S f_s.$$

As the rotor's speed is increased, the value of S would go down, which in turn F_p would also drop.

X_2 and E_2 are effectively dependent on frequency.

The previous equivalent circuit is redrawn to include the currents expected.

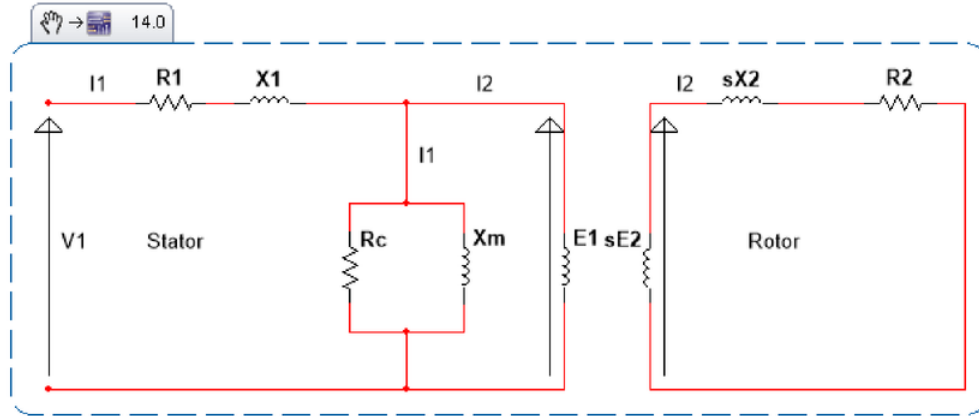
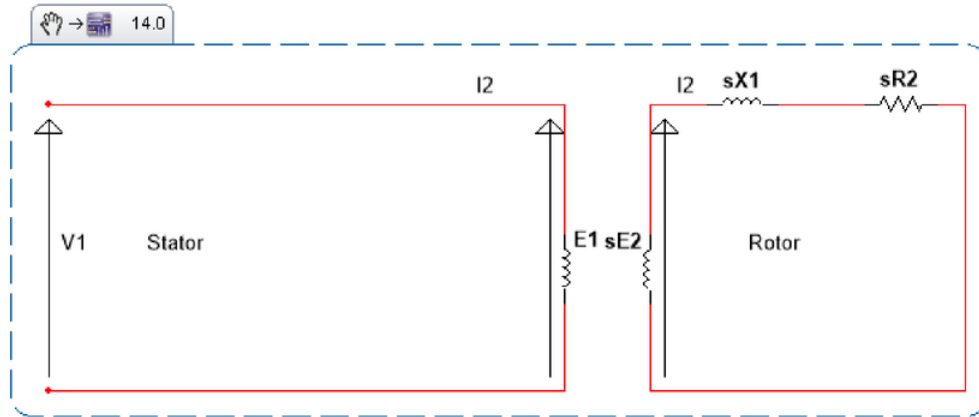


Figure 1.12: Equivalent Circuit with Currents Added

There is a balancing current in the Rotor and Stator shown as I_2 . With this in mind the equivalent circuit can be simplified further.



Using this equivalent circuit, the following is determined.

$$|E_2| = \frac{N_2}{N_1} \times |E_1| \text{ and since } E_1 = V_1, \text{ this would mean, } |E_2| = \frac{N_2}{N_1} \times |V_1|.$$

$$\text{The rotor impedance can then be calculated using, } |Z_2| = \sqrt{\left(\frac{R_2^2}{s}\right) + X_2^2}$$

$$\text{And the rotor current is found with } |I_2| = \frac{|E_2|}{|Z_2|} \times \frac{|E_2|}{\sqrt{\frac{R_2^2}{s^2} + X_2^2}} \rightarrow \frac{S|E_2|}{\sqrt{\frac{R_2^2}{s^2} + S^2 X_2^2}} \rightarrow \frac{|E_2|}{\frac{1}{s} \sqrt{R_2^2 + S^2 X_2^2}} \rightarrow \frac{S|E_2|}{\sqrt{R_2^2 + S^2 X_2^2}}$$

$$\text{So the Power Lost can be found with, } P_{Loss} = |E_2|^2 \times R_2 = \frac{S^2 |E_2|^2 R_2}{(R_2^2 + S^2 X_2^2)}$$

A Torque equation is found as, $P_S = T \omega_R = 2\pi n_R T$ and $P_P = T \omega_R = 2\pi n_R T$ because $\omega = 2\pi n$.

By putting $n_s = (1 - S)n_p$ into the above to find the power of the rotor, $P_R = 2\pi(1 - S)n_s T \rightarrow P_R = 2\pi n_s T - 2\pi S n_s T \rightarrow P_R = P_S - sP_S$ and sP_S is the energy or copper losses in the rotor.

Torque can then be found using $P_{Loss} = 2\pi S n_s T$, so referring back to the original equivalent circuit,

$$2\pi S n_s T = \frac{s^2 |E_2|^2 R_2}{(R_2^2 + s^2 X_2^2)} \therefore T = \frac{1}{2\pi n_s} \times \frac{s |E_2|^2 R_2}{(R_2^2 + s^2 X_2^2)} \therefore T_{Max} = \frac{|E_2|^2}{4\pi n_s X_2}$$

2 SIMULATION

Using suitable formulae to produce equations in a Microsoft Excel Spreadsheet, two graphs were produced using the equations $T = \frac{1}{2\pi n_s} \times \frac{s|E_2|^2 R_2}{(R_2^2 + s^2 X_2^2)}$ and $|I_2| = \frac{s|E_2|}{\sqrt{R_2^2 + s^2 X_2^2}}$.

To simulate the two characteristics of the Three-Phase Wound Induction Motor, the following information was given;

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

Fractional Slip	Rotor Speed	Torque	Rotor Current
-1.00	6000	-0.75	-4.05
-0.90	5700	-0.83	-4.04
-0.80	5400	-0.93	-4.03
-0.70	5100	-1.06	-4.02
-0.60	4800	-1.22	-4.00
-0.50	4500	-1.44	-3.97
-0.40	4200	-1.75	-3.91
-0.30	3900	-2.19	-3.78
-0.20	3600	-2.79	-3.49
-0.10	3300	-3.09	-2.60
0.00	3000	0.00	0.00
0.10	2700	3.09	2.60
0.20	2400	2.79	3.49
0.30	2100	2.19	3.78
0.40	1800	1.75	3.91
0.50	1500	1.44	3.97
0.60	1200	1.22	4.00
0.70	900	1.06	4.02
0.80	600	0.93	4.03
0.90	300	0.83	4.04
1.00	0	0.75	4.05
1.10	-300	0.69	4.06
1.20	-600	0.63	4.06
1.30	-900	0.58	4.06
1.40	-1200	0.54	4.07
1.50	-1500	0.51	4.07
1.60	-1800	0.47	4.07
1.70	-2100	0.45	4.07
1.80	-2400	0.42	4.07
1.90	-2700	0.40	4.07
2.00	-3000	0.38	4.07

Table 2.1: Calculated Simulation Figures

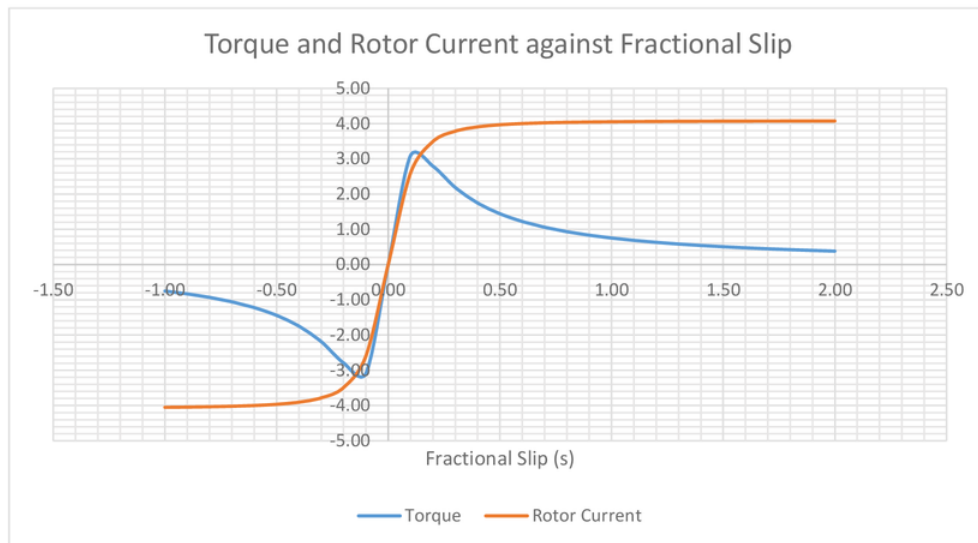


Figure 2.1

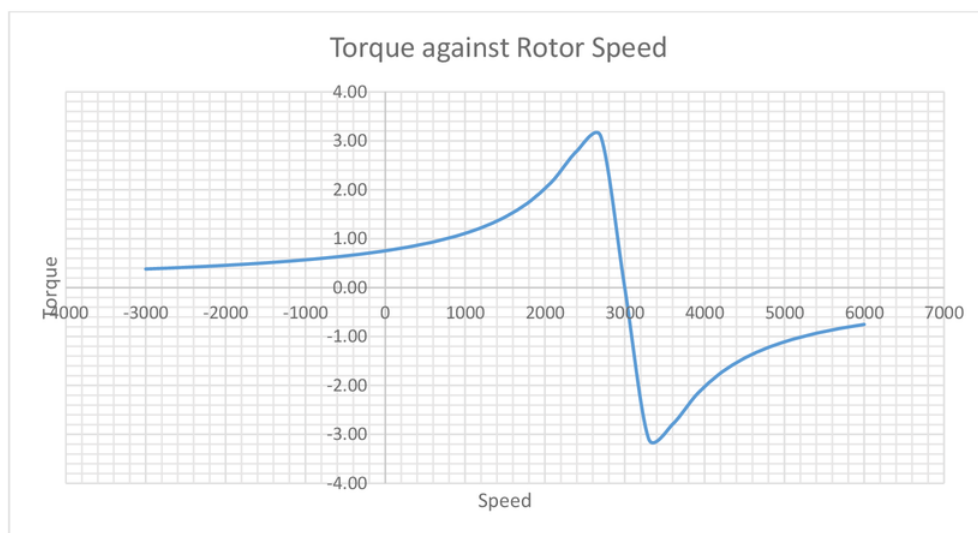


Figure 2.2

What can be seen in Figure 2.2 is that the peak Torque value is at a speed of 2700 or in Figure 2.1 when there is a slip of 0.1, whereas slip increases, or speed of the rotor reduces, Torque drops off. As the slip increases, the Torque drops further as the rotor is lagging further behind the Stator field. As the speed of the Rotor is sped up over 3000, there is negative Torque present as the Rotor is now turning faster than the Stator field, likely because there is an external driving force or prime mover on the Rotor. I should also be noted that at a higher Rotor speed or negative slip, the Current in the Rotor is reversed. The negative Torque is observed as a braking effect on the load.

From the above observations, the following equation is derived showing that there is generation:

$$n_R = 2N_s, \text{ so } S = \frac{n_s - 2n_s}{n_s} = \frac{-n_s}{n_s} = -1, \text{ and to show the increase in slip, where } n_R = -n_s,$$

$$S = \frac{n_s - (-n_s)}{n_s} = \frac{2n_s}{n_s} = 2, \text{ showing the breaking effect experienced by the load, as the rotor is now opposing the Rotating Magnetic Field.}$$

3 PRACTICAL INVESTIGATION

3.1 MEASURED RESULTS

From the experiment, where an adjustable Load was put on an Induction Motor, the following results in Table 3.1 and Table 3.2 were recorded where Slip was calculated, and then Graphs produced.

Torque [Nm]	Speed [RPM]	Line Current [A]	Line Voltage [V]	Power Factor	Apparent Input Power [VA]	Real Input Power [VAr]	Output Power [W]	Angular Velocity [rad/s]	% Slip
0	2950	0.57	214	0.53	209.00	177.00	110.00	308.92	0.02
0.05	2900	0.62	213	0.64	230.00	175.00	148.00	303.69	0.03
0.1	2850	0.64	213	0.67	233.00	174.00	152.00	298.45	0.05
0.2	2800	0.71	213	0.75	259.00	172.00	195.00	293.22	0.07
0.4	2750	0.78	213	0.81	289.00	170.00	230.00	287.98	0.08
0.5	2700	0.88	213	0.85	326.00	171.00	278.00	282.74	0.10
0.7	2650	0.99	213	0.87	359.00	174.00	314.00	277.51	0.12
0.8	2600	1.04	213	0.88	364.00	175.00	325.00	272.27	0.13
0.9	2550	1.13	213	0.9	425.00	183.00	371.00	267.04	0.15
1	2500	1.23	213	0.91	451	189	407	261.80	0.17

Table 3.1: Motoring Readings and Calculated Values

Speed [RPM]	Line Current [A]	Line Voltage [V]	Power Factor	Apparent Input Power [VA]	Real Input Power [VAr]	Output Power [W]	Angular Velocity [rad/s]	% Slip
3000	0.536	213	0.2	200.00	196	40.6	314.16	0.00
3050	0.577	213	-0.21	218.00	-213	42.1	319.40	-0.02
3100	0.657	213	-0.36	248.00	-231	91.2	324.63	-0.03
3150	0.732	213	-0.47	275.00	-244	128	329.87	-0.05
3200	0.885	213	-0.6	334.00	-268	200	335.10	-0.07
3250	0.998	213	-0.65	379.00	-286	248	340.34	-0.08
3300	1.12	213	-0.67	423.00	-306	294	345.58	-0.10

Table 3.2: Generating Readings and Calculated Values

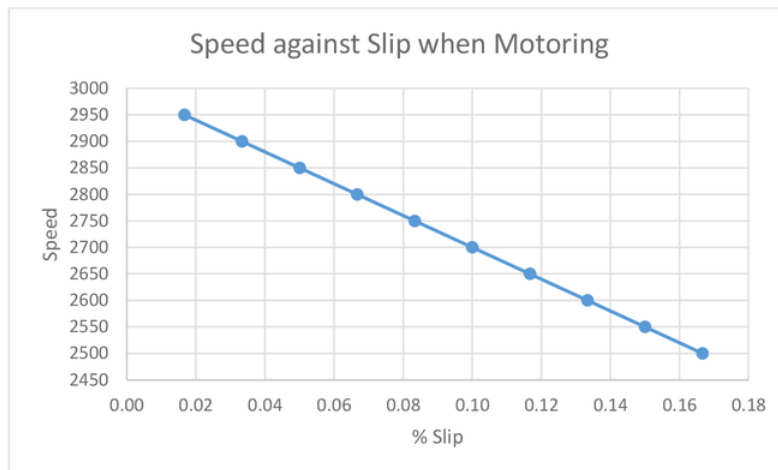


Figure 3.1

It is shown in Figure 3.1, that which should be expected is that there is a linear relationship between Speed and Slip. At roughly 0 slip, the speed of the rotor matches the stator field, but as slip increases, the speed difference also increases.

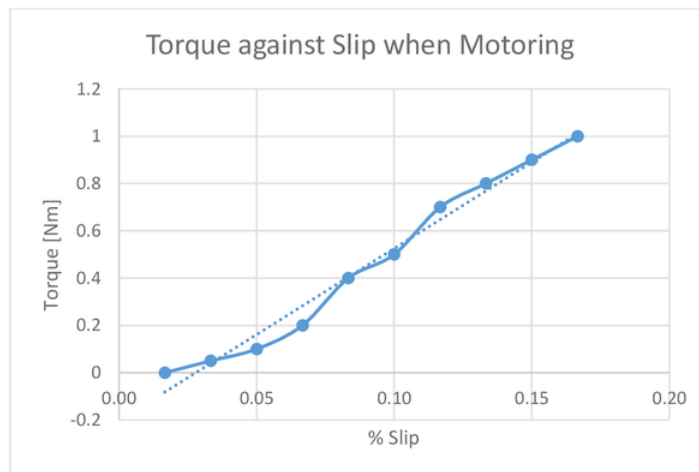


Figure 3.2

In Figure 3.2, as the Load increases on the Rotor, the Slip increases as well as the Torque in an almost perfect linear fashion.

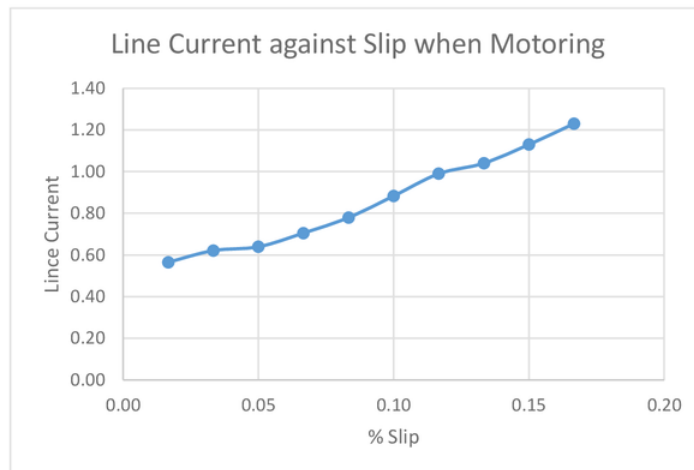


Figure 3.3

Continuing the linear characteristic is the Line current, so as Load is increased, the Current draw increases also to compensate.

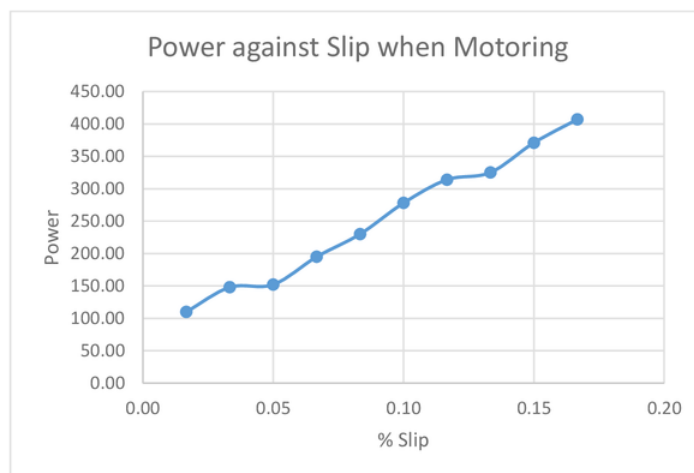


Figure 3.4

Power also increases linearly, as the Load is increased on the Rotor.

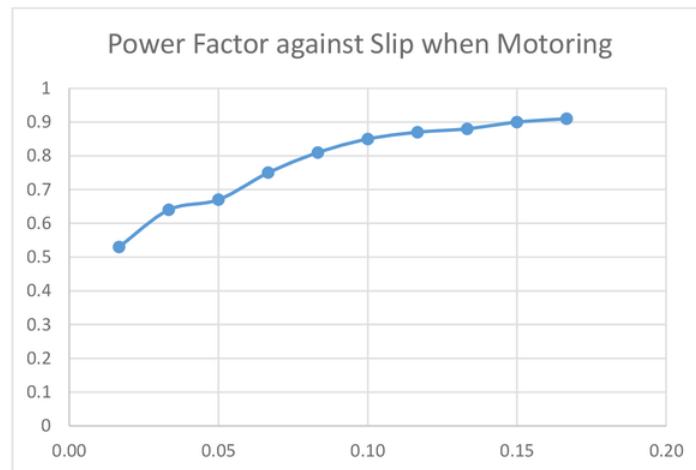


Figure 3.5

In Figure 3.5, there is a gradual curve showing a sharp increase in Power Factor which then slowly increases as Slip increases. The Power Factor settles at 0.9 and increases no further.

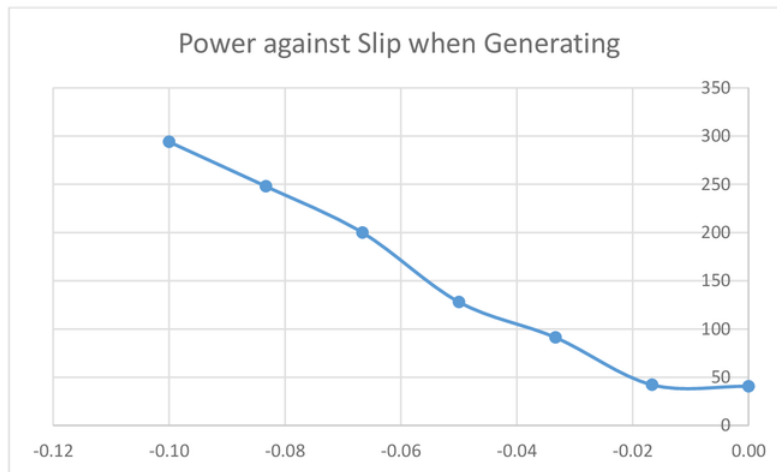


Figure 3.6

Figure 3.6 shows that measured Power increases, as the Rotor turns the other way, showing a generating effect.

4 CONCLUSIONS AND RECOMMENDATIONS

Induction Motors are very useful machines due to their simplicity in terms of physical construction i.e. Cage Induction Motor's isolated rotor and Wound Induction Motor's easy to replace brushes, and are effective enough in applications from hoists to pumps. One type of Induction Motor may have one advantage over the other in specific applications, however between the two, most solutions in moving load can be addressed.

When simulating a Motor through calculations, the three characteristics of generating, breaking and motoring could be observed on the curves according to slip.

The practical observation of an Induction motor in motoring and generating proved to be rather successful, as the expected characteristics were observed after charts were produced. To produce a better result, more data samples at more increments could have been recorded to produce a more accurate chart as well as a more controllable braking method. Regarding braking, the other alternative braking methods could have been employed to show performance and accuracy.

5 WORKS CITED

- Amin, B. (2001). In *Induction Motors: Analysis and Torque Control*. Springer Science & Business Media.
- Carrow, R. S. (2000). AC-Induction-Motor Theory and Variable-Frequency Drive Basics. In *Electrician's Technical Reference: Variable Frequency Drives* (p. 51). Cengage Learning.
- Lab-Volt (Québec) Ltd. (2003). In *The Wound-rotor Induction Motor and Applications. Student Manual*. Lab-Volt.
- Smith, R. L., & Herman, S. L. (2004). In *Electrical Wiring Industrial: Based on the 2005 National Electric Code*. Cengage Learning.
- Wilkinson, K. (1965). In *Rewinding Small Motors* (1st ed., p. 10). London: Newnes.

6 IMAGE SOURCES

Figure 1.1: Typical Induction Motor Stator winding configuration	https://www.researchgate.net/profile/Ricardo_Alvarez-Salas/publication/299523366/figure/fig9/AS:349741994004480@1460396397058/Three-phase-induction-motor-stator-winding-structure.png
Figure 1.2: Exploded diagram of a Wound Induction Motor	https://talk.electricianforum.co.uk/uploads/monthly_2017_07/01.jpg.69a46ee66c7fa7d2df7a5e28f7f4626a.jpg
Figure 1.3: Current induced in Rotor	http://www.joliettech.com/images/operating_principles_of_induction_motor.gif
Error! Reference source not found.	https://qph.ec.quoracdn.net/main-qimg-ab8bc2de0786149f63b1e36b500aefad
Figure 1.5: Rotating Magnetic Field Produced by Three-Phase Supply	http://www.galco.com/images/ac_motor_fig12.gif
Figure 1.6: Cage Rotor Bars and Rings	https://circuitglobe.com/wp-content/uploads/2016/01/construction-of-an-induction-motor-fig-3.png
Figure 1.7: Complete Cage Rotor	http://www.machinedesign.com/sites/machinedesign.com/files/uploads/2015/03/Wirnik_by_Zureks.gif
Figure 1.8: Variable Frequency Drive	https://media.rs-online.com/t_large/R621119-01.jpg
Figure 1.9: Wound Rotor	https://www.tmeic.com/sites/default/files/assets/images/element/1292531834_energy_wound_rotor_induction.jpg
Figure 1.10: Resistor Bank Schematic	http://www.meisterintl.com/images/AC-Wound-Rotor-Induction-Motor-Resistor.png

7 APPENDICES

Assignment_1

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

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GRADING FORM: CSG-RUBIC

EMYR DYER**63****RESEARCH-INFORMED LITERATURE**

Good evidence of research and background reading. Further marks were available for a fuller discussion of speed control and methods of braking. (16/25)
Small range of sources listed and cited correctly. (2/5)

18**KNOWLEDGE AND UNDERSTANDING**

A brief explanation is given with relevant equations from theory. (6/10) Brief explanation given but further marks were available for a schematic diagram of the setup together with a photo to support. (5/10)

11**ANALYSIS**

A brief analysis is provided. Further marks were available for relating results to theory, identifying regions of operation and optimum performance. (4/10) Evidence provided of analysis is good, attempts made to interpret results in the light of theory but there are some errors in the table. (6/10)

15

Some helpful conclusions drawn but further marks were available for a more in-depth comparison between theory, simulation and practical results. (5/10)

PRACTICAL APPLICATION AND DEP.



Results are well presented in table and graphic form. (5/5) Good presentation of results but output power has been wrongly calculated. (4/5)

9

SKILLS FOR PROFESSIONAL PRAC.



A well presented and structured report, generally well written with good images - listed and labelled correctly. (10/10)

10