

1809797

by Lourens Brits

A WELL WRITTEN REPORT WITH APPROPRIATE RESEARCH
AND CORRECT CITATIONS. CRITICAL KNOWLEDGE AND
ANALYSIS WAS DEMONSTRATED THROUGHOUT.

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Good Structure

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1. Executive summary

A summary should be no more than 300 words, this is excessive

Research conducted enabled a thorough understanding of induction motor drive and control systems, how they are incorporated in an industrial setting as well as the advantages and disadvantages of the various technologies. Conclusions were made that modern variable frequency drives are very efficient through the use of insulated-gate bipolar transistors, which switch at much higher frequencies in comparison with older relay systems. Although this high efficiency and switching frequency does come at a higher cost, savings can be made due to better dynamic response, wider speed control ranges, better power factors and lower starting torque.

Power distribution systems were investigated and the importance of transformers and transmission lines were highlighted as well as the importance of efficiency therein. Resistive and corona losses weren't covered but do play a part in transmission line efficiency. It was confirmed that higher voltages are used in transmission lines to reduce the current-flow, which in turn reduces losses, whilst ensuring the end-user had a reliable power supply.

The transformer practical investigation concluded that the equivalent circuit analysis is a very powerful tool to utilise in the design and implementation stages of transformers, which enables every aspect of a transformer to be mathematically modelled and simulated. Practical tests and measurements were carried out utilising a NanoVip LCR meter which enabled power factor and power measurement, as well as voltage and current.

The open and short circuit tests enabled the measurement of the iron and copper losses respectively, which were used to calculate the equivalent circuit values. The short circuit test involved shorting the secondary winding and safely, as well as gradually increasing the voltage to 8.98v to the primary. The open circuit test was conducted by leaving the secondary winding open circuit and applying full voltage to the primary.

Once the equivalent circuit values were calculated, the circuit was constructed on Multisim to enable simulation of the transformer approximate equivalent circuit. Once again, the importance of the equivalent circuit was apparent as this allowed for voltage regulation tests to be carried out. The voltage regulation tests consisted of simulating various loads on the transformer in the form of a resistor, resistor/inductor and resistor/capacitor load in series on the secondary winding. The values of these loads were pre-determined to be; (R) 33 Ω , (R/L) 36.5 Ω / 93mH and (R/C) 28.3 Ω / 48 μ F.

Predicted voltage regulation figures were obtained from these tests as well as efficiency values. Analysis of the test results concluded that as the load increases, the primary and secondary currents decrease and that the power improves as the load increases.

Finally, practical, simulated and calculated results were illustrated in table form, which allowed analyses and conclusions to be made. Some results did not match exactly as expected but these discrepancies were mostly due to measurement inaccuracies, which could have been avoided by using more modern and UKAS calibrated equipment.

Furthermore, three phase induction motor tests and simulations were carried out to enable, in a similar manner to transformers, equivalent circuit values to be calculated and simulated. These tests included performing a stator resistance, no-load and blocked-rotor test. The motor torque and slip values were plotted on a graph and it was found that the researched theory matches the practical results. During the motoring phase the slip was between 1 and 0, whereas the generating phase exhibited slip of between 0 and -1. Finally the graph also showed the braking effect when the slip was above 1.

Further tests were carried out as part of the practical, which involved speed and slip analysis which was achieved by driving the motor at and above synchronous speed, but due to work circumstances these are not included in this assignment.

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2. Research

Induction Machine speed control

A.C. induction motors are rugged, brushless and asynchronous machines that operate using AC voltage. The basic construction, example shown in figure 1, gives these motors their low maintenance and efficient characteristics that make them very suitable for industrial purposes.

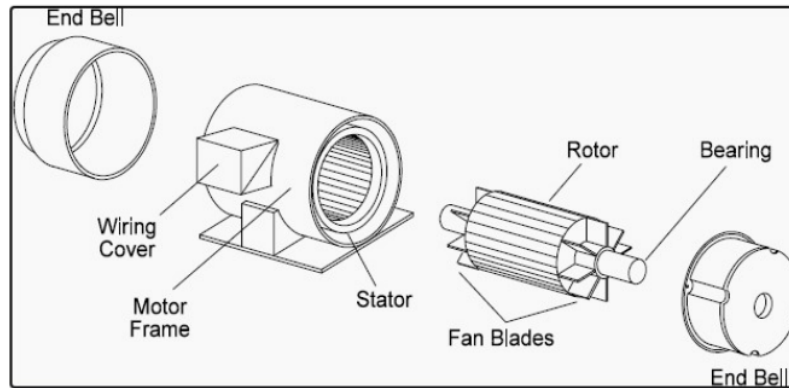


Figure 1 - AC Induction Motor Construction (Csanyi, 2011)

Correctly cited

AC induction motor operates by converting electrical energy into mechanical energy through electromagnetic induction. The stator creates magnetic flux and current, which is intersected by the rotor. This interaction with the magnetic flux causes the rotor to turn, as well as produces the motor torque by turning slower than the motors' synchronous speed, this is known as slip. In the event that the rotor runs in synchronisation with the magnetic flux, the result will be no torque (Ananheim Automation, 2021).

Advantages and Disadvantages of 3-Phase Induction Motors	
Advantages	Disadvantages
Simple and rugged construction	Speed control is difficult
Cheaper - no brushes or commutators	High in-rush currents
Very low maintenance	Operate with low power factor in light load conditions - Higher copper loss = less efficient
Wide range of applications	
Wide range of operating environments	
High starting torque	

Table 1 - Advantages and Disadvantages of induction motors (Wildi, 1997)

Figure 2 shows the relationship of torque and speed. It is clear to see that the motor will produce no torque if synchronous speed is achieved. This image highlights the need for effective and efficient speed control.

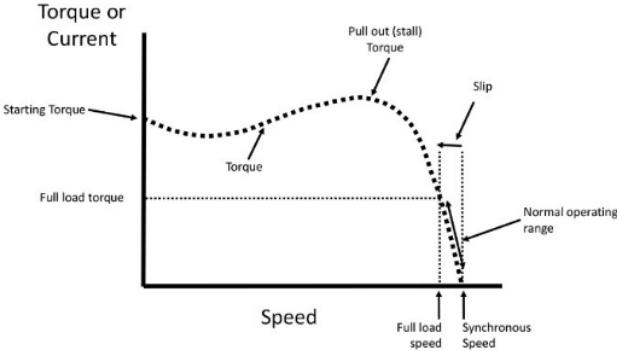


Figure 2 - Torque / Speed relationship (Invertek Drives, 2021)

Table 2 below show five different speed control methods.

Types of AC drives		
Static frequency changers	Convert incoming line frequency directly into load frequency	
Static voltage controllers	Varies AC voltage - used for soft starts	
Rectifier inverter system - Line commutation	Converts incoming AC to DC, which is then converted to AC again - matches the motor frequency (line commutated). Can be voltage or current source from control unit to rectifier	
Rectifier inverter system - Self commutation	Converts incoming AC to DC, which is then converted to AC again - generates own frequency (self commutated). Can be voltage or current source from control unit to rectifier	
Pulse-Width modulation (PWM)	Utilises IGBT's in the rectifier circuit for AC to DC conversion, inverter fed by DC voltage. Voltage and frequency det in inverter buy control unit	

Table 2 - Types of AC speed controllers (Wildi, 1997)

The basic make-up of a rectifier / inverter control system consists of a rectifier, which converts the AC input to direct current (DC) and an inverter that switches the DC to a variable frequency AC output voltage. The rectifier and inverter are controlled by a dedicated controller that will match the generated AC voltage and frequency to the motor at any time. An AC controller is therefore known as a variable frequency drive or VFD (ABB, 2011). Correctly cited

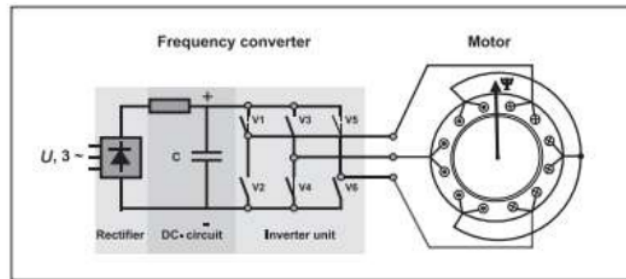


Figure 3 - 3 Phase input frequency converter (ABB, 2011)

Figure 3 shows the basic construction of a VFD; 3-phase AC supplies the rectifier which is coupled to an inverter through a DC circuit. Once the AC voltage has been converted to DC, the DC circuit will filter the pulses in the voltage, thereafter the inverter unit will connect the individual motor phases to either the positive or negative DC output. The position of the switches, marked v1 – v6 will govern which way the magnetic flux rotates, which in turn governs the direction of the motor (ABB, 2011).

Figure 4 shows an example of the operation of the first element of the VFD, the rectifier. Through the use of rectifier diodes (6 for three phase AC) and a capacitor which acts as a DC link. A relatively smooth DC voltage is produced ready to be fed to the inverter through the DC link.

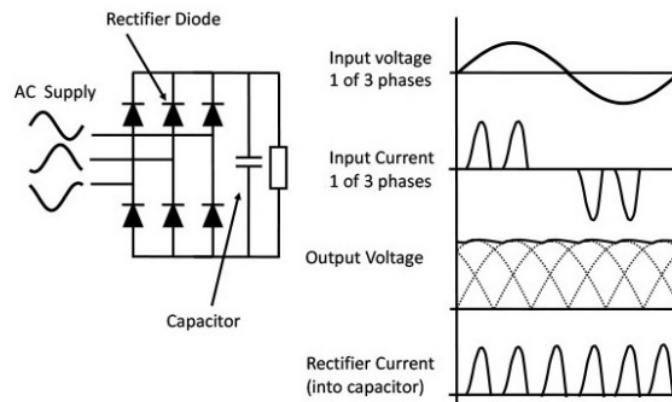


Figure 4 - Rectifier Operation (Invertek Drives, 2021)

In figure 5 the inverter is now coupled to the rectifier through the DC link. By using insulated-gate bipolar transistors (IGBT) as power switches and appropriately coupled parallel diodes, a sinewave of any frequency can be generated through sequence switching. The IGBT

switching process is controlled by a micro-controller, which not only controls the sequence but also varies the on/off time of the switching to control the current (Invertek Drives, 2021).

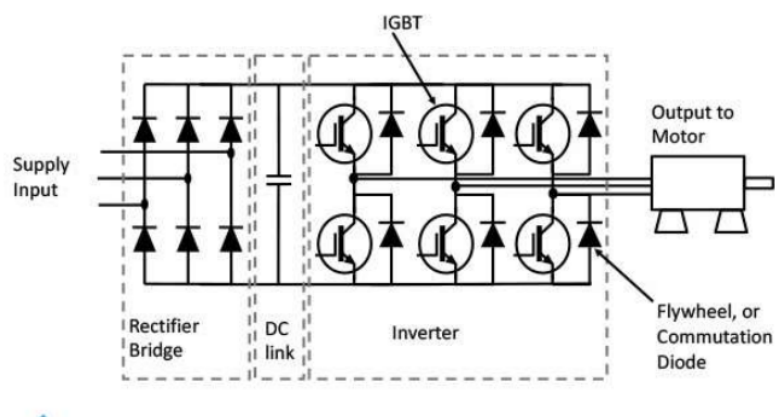


Figure 5 - Inverter section of a VFD (Invertek Drives, 2021)

The time variation in switching the IGBT's on and off is known as Pulse Width Modulation (PWM), which is used to vary the current in the sine wave (Invertek Drives, 2021).

The VFD controller utilises the rapid switching of the IGBT's to vary the voltage applied to motor and thereby controlling the speed. The amount of switch pulses per second is known as the carrier frequency, the carrier frequency can be adjusted. Care should be taken with adjusting the f_c due to excessive heat that could be produced, shortening its lifespan, although a higher f_c will reduce VFD acoustic noise. In the event that the f_c is set too low the result will be less heat produced, with the trade-off of more motor & VFD noise (Inman, 2020).

The basic construction and operation of a VFD has now been explained, for a more detailed illustration of a modern VFD, see Appendix image 1

Advantages and Disadvantages of VFD's	
Advantages	Disadvantages
Energy Efficient - 92-95%	High cost
Good dynamic response - better control	Harmonic currents generated
Better control through wide range of speed, torque and power outputs	
Lower starting currents	
Increased power factor	

Table 3 - Advantages and Disadvantages of VFD's

Industrial Applications of induction machines

Induction motors have been a reliable, cost effective and maintenance friendly building block for a plethora of industrial processes for many years. The simple, robust design, that is easy and relatively cheap to construct, in comparison with DC motors, need very little maintenance and exhibits very good efficiency.

Industrial system design parameters will govern which motor to use. An industrial process design engineer will, amongst other sources, utilise IEC 60034 (NEMA in North America), which is the standard for rotating electrical machines. This standard will cover application, duty, rating, input and output parameters, thermal performance and many other guidelines to identify which motor is best suited for the intended use.

Induction motors are classed according to the intended environment and cooling methods and electrical and mechanical properties.

Within the environmental and cooling methods classification there are several classes, as shown in table 1;

Classification according to environmental and cooling methods	
Class	Environmental and cooling method
Drip proof	Protects against liquid drops and solid particles which falls from any angle between 0-15° from vertical to horizontal.
Splash proof	Protects against liquid drops and solid particles which falls from any angle between 0-100° vertical to horizontal.
Sealed non-ventilated	For use in wet and dusty locations - restricted kW due to lack of ventilation
Sealed ventilated	Medium to high power motors with direct coupled fan for cooling -very commonly used in industrial applications.
Explosion proof	For use in highly flammable or explosive areas, the frames are built to withstand internal explosions. Flanges on end bells are longer to aid in cooling of gas escaping the motor in the event of an explosion

Table 4 - Motor Environmental and cooling classification (Wildi, 1997)

Power systems required to deliver a 3-phase 415AC supply

Power generation in the UK are making positive steps toward a more carbon neutral and sustainable future. Currently the National Grid, which is the UK's power distribution network, has a diverse generating capacity, as shown in figure 6.

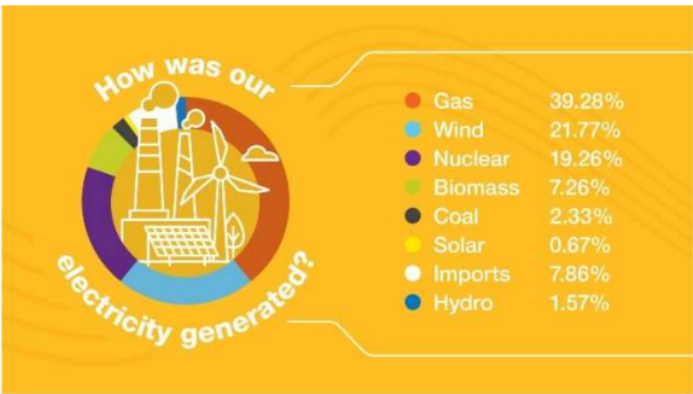


Figure 6 - UK Power Generation Breakdown (National Grid, 2021)

Regardless of the generation method or source, the generated power needs to be conditioned to enable domestic and industrial use. To further evaluate power delivery to a typical industrial factory, a traditional power station and associated conditioning, transmission and distribution system will be used.

Figure 7 shows a typical illustration of a generation, conditioning and distribution network.

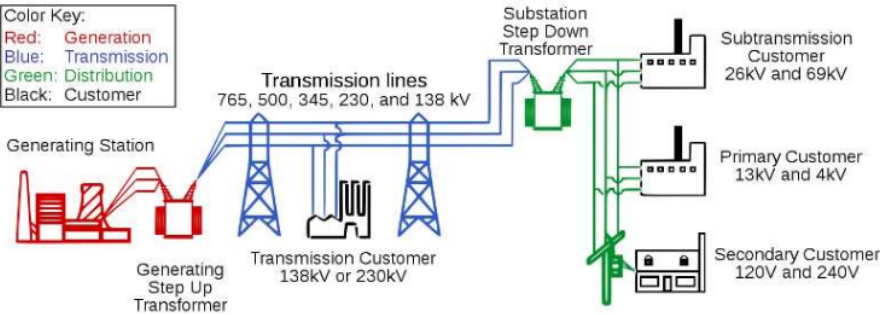


Figure 7 - Generation, Conditioning and Distribution Network (Engineering World Channel, 2020)

Power stations are categorised into three main types;

- Base power - Continually generates at maximum output, i.e. nuclear & coal
- Intermediate power - Adapts to increased demand relatively quickly i.e. hydro.
- Peak generating - Adapts within minutes for brief intervals i.e. diesel, gas turbine or pumped storage.

Liquefied natural gas power stations, for example, will generate power by mixing LNG with air; this combustion takes place in a gas turbine, which drives generator. Most modern LNG plants are combined cycle, meaning that the hot gas turbine exhaust gasses are passed through a heat recovery steam generator which produces high pressure steam that drives a steam turbine for additional generation (GE power, 2021).

Step-up transformers are utilised to increase the generated 3-phase AC power voltage supplied to the National grid from 25 000v to either 275 000v or 400 000v, which in turn reduces the current in the transmission lines. The reduction in transmission current reduces losses through heat, reduces the size of the transmission cables needed and is therefore more efficient, whilst still delivering the needed power to the consumer (Copper Alliance, 2018).

Grid supply points are regional substations that use step-down transformers to reduce this high voltage to 132Kv for distribution to more local substations where it will be stepped-down to 33Kv and then further to 11Kv. A further step-down transformer will be used to reduce the 11kV supply to 415 V for use in an industrial setting (Western Power Distribution, 2021).

Transmission lines account for a percentage of power loss. In the same manner motors and transformers are modelled and evaluated through equivalent circuits, transmission lines can be represented in this manner as well, depending on the line length, as shown in figure 8.

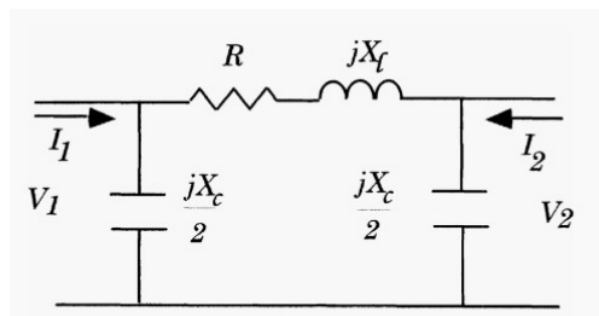


Figure 8 - Medium / Long Transmission Line Equivalent Circuit (One Phase) (Csanyi, 2011)

Referring to figure 8, the transmission line possesses a combined resistance R , total inductive reactance X_L , and the sum of individual capacitive reactance's X_C (connected in parallel), where these impedances are uniformly distributed throughout the line (Wildi, 1997).

Finally, at a location close to an industrial consumer, like a factory, the 11Kv voltage is stepped down to 415v using either three single phase transformers or a single 3-phase transformer, the latter being the more economic option, which will be researched for this part.

The construction of a 3-phase transformer allows for a smaller footprint with the same result as three single phase transformers, as stated by Theodore Wildi in *Electrical Machines, Drives and Power Systems*; *"The magnetic core of such a transformer has three legs that carry the primary and secondary windings of each phase. The windings are connected internally, either in wye or in delta, with the result that only six terminals have to be brought outside the bank. For as given total capacity, a 3-phase transformer is always smaller and cheaper than three single phase transformers"* (Wildi, 1997). Improper Citation

The manner in which the cores are connected, delta – delta, wye-wye, delta-wye, wye-delta or open delta, will depend on the load requirements. (Note; open delta is used to enable transformer maintenance on a three single phase transformer system, where the transformer load capacity will be reduced)

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3. Transformer Investigation

To enable the open and short circuit test as well as the voltage regulation to be carried out and evaluated, the system values had to be measured in safe manner. Measurements were carried out on the CM7501 230v – 110v transformer (see appendix image 2) using a NanoVip LCR meter. The transformer primary was supplied by a variable voltage supply that had overload safety trips installed.

Open Circuit Test

The NanoVip is not an LCR meter

With a voltage applied to the primary winding and the secondary winding left open circuit, core losses (Iron losses) can be measured. R_c is responsible for core losses, I_c is the current that flows into the primary and supplies the core losses, I_m is the magnetising current and X_m is the core reactance converted to mH.

Short Circuit Test

A short circuit test was carried out through the application of a small voltage to the primary whilst shorting the secondary. Safety note; during this experiment, due care was taken whilst increasing the voltage on the primary to 8.98v.

Both circuits were constructed in Multisim as a visual aide. See appendix image 3.

Table 1 - Measured results for open and short circuit tests.

Iron losses - O/Circuit Test		
	Primary	Secondary
Voltage (V)	230 v	113 v
Current (A)	527 mA	0
Power (W)	31.5 w	0
Power Factor (P.F)	0.26	0
Copper losses - S/Circuit Test		
	Primary	Secondary
Voltage (V)	8.98 v	0
Current (A)	1.72 A	3.47
Power (W)	8.08 w	0
Power Factor (P.F)	0.52	0

Table 5 - Open and Short Circuit measured values

Table 2 - Calculated equivalent circuit values can be seen in appendix section 7.2.1

Iron Loss Component Values	
Rc	1679.4 Ω
Xm	451.87 Ω (1.44H)
Ic	137 mA
Im	509 mA
V1	230 v
I1	527 mA
Copper Loss Component Values	
ZIE	5.221 Ω
RIE	2.731 Ω
XIE	4.45 Ω (14.2 mH)
Z2E	1.194 Ω
R2E	0.625 Ω
X2E	1.018 Ω (3.24 mH)
I2	3.596 A

Table 6 - Open and Short Circuit Equivalent Circuit calculated values

The approximate equivalent circuit parameters of the transformer can now be illustrated by combining the results from the practical open and short circuit tests carried out.

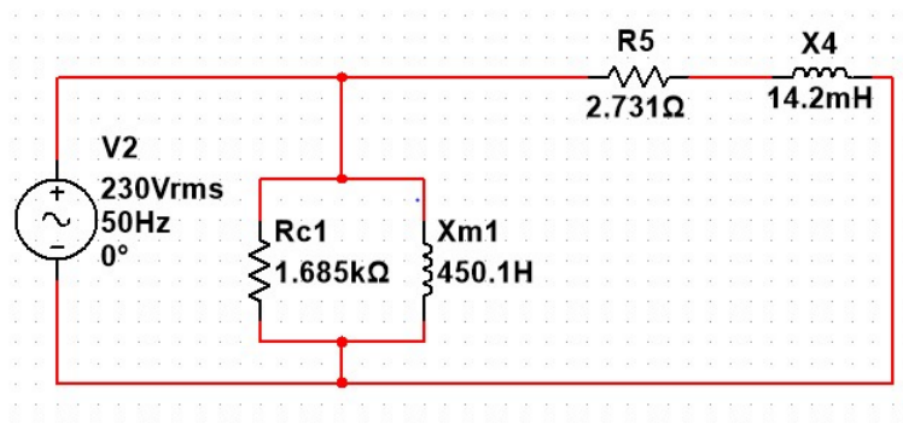


Figure 1 – Open and Short Circuit Approximate Equivalent Circuit

The transformer voltage regulation and efficiency was ascertained by performing the following load tests. Each test aims to replicate various loads on the transformer, where resistance test

simulates lower than full load, inductor test simulates full load and capacitor test simulates over load.

The predicted values of % Regulation calculations are show in appendix section 7.2.3

Transformer Efficiency calculated to be 83.13% Calculations can be seen in Appendix section 7.4.1

$$\% \eta = \frac{\text{output VA} \times \text{p.f} \times 100}{\text{output VA} \times \text{p.f} \times \text{iron loss} \times \text{copper loss}} = \frac{375 \times 0.52 \times 100}{375 \times 0.52 + 31.5 + 8.08} = 83.13\%$$

Tables 11, 12 and 13 show the efficiency results calculated for the following three practical tests.

Resistance test

The resistive load test is performed by adding a 33 Ω resistor in series to the secondary winding.

Predicted value: 110.06v

Inductor / Resistor Test

The inductor load test is performed by adding a 36.5 Ω resistor and 93mH inductor in series to the secondary winding.

Predicted value: 110.31v

Capacitor / Resistor Test

The capacitance load test is performed by adding a 28.3 Ω resistor and 48 μ F capacitor in series to the secondary winding.

Predicted value: 114.76v

These Multisim circuit simulations are shown in Appendix images 4, 5 & 6.

Table 3 shows the measured results.

	Resistance Test		R/L test		R/C Test	
Windings	Primary	Secondary	Primary	Secondary	Primary	Secondary
Voltage (V)	230 v	110 v	230 v	110 v	230 v	114 v
Current (A)	1.78 A	3.23 A	1.55 A	2.26 A	469 mA	1.58 A
Power (W)	388 W	366 W	208 W	177 W	86.3 W	68.8 W
Power Factor (P.F)	0.95	1	0.58	0.72	-0.8	-0.38

Table 7 - Voltage Regulation Measured Results

From the data illustrated in table 3 it is clear to see the following;

During the resistance test the transformer shows a high power factor, with the voltage drop as expected.

During the resistor / Inductor test a large drop in P.F is apparent, confirmed with a reduction of power. More inductance in the circuit causes more lag.

The resistor / Capacitor test shows a rise in voltage and a better power factor, this is due to the output voltage being larger than the rated output for the transformer.

Expectation vs reality:

- As the load increases, the primary and secondary currents decrease
- The power decreases as the load increases,
- The power factor decrease between the resistance test and full load test, but falls to a negative value at over load condition.

Table 4 shows the calculated circuit component values.

V. Regulation Component Values	
E2	113 v
V2	108 v
R2E	0.625 Ω
X2E	1.018 Ω (3.24 mH)
I2	3.596 A
ZL	33 Ω

Table 8 - Voltage Regulation Circuit Calculated Values

To enable further analysis, comparison and evaluation, the aforementioned tests can be simulated using Multisim. These simulated and practical datasets will be compared to the datasheet values.

Appendix figures 7 and 8 show circuit simulation and analysis. The simulation results are shown in tables 5 and 6.

Iron Losses	Datasheet		Simulated		Practical	
	Primary	Secondary	Primary	Secondary	Primary	Secondary
Voltage (V)	230 v	113.8 v	230 v	114.99 v	230 v	113 v
Current (A)	n/a	0	524.958mA	231 nA (0)	527 mA	0
Power (W)	20.16	0	31.507 W	52.953 uW (0)	31.5 W	0
Power Factor (P.F)	n/a	0	0.261	1	0.26	0

Table 9 - Iron Loss Equivalent Circuit analysis

The practical results do match the simulated and data sheet values. There are no datasheet primary current values to compare; therefore a comparison is made between simulated and practical values. The 2.042 mA delta is insignificant and can be due to slight test and measurement inaccuracies. There is an 11.4 W increase in power output recorded between the practical and simulated results vs. datasheet results. The datasheet does not provide power factor data, therefore the comparison of 0.261 simulated and 0.26 practical can be confirmed to match, as expected.

Copper Losses	Datasheet		Simulated		Practical	
	Primary	Secondary	Primary	Secondary	Primary	Secondary
Voltage (V)	n/a	0	8.98 v	8.98 v	8.98 v	0
Current (A)	n/a	n/a	20.496 mA	3.464 A	1.72A	3.47
Power (W)	9.05	0	48.029 mW	80.721 nA (0)	8.08 W	0
Power Factor (P.F)	n/a	0	0.518	1	0.52	0

Table 10 - Copper Loss Circuit analysis

The transformer datasheet has limited information on copper losses, only the primary power figure is published at 9.05 W. Voltage outputs match as expected, as do the simulated and practical values for secondary current. There is a discrepancy to note for simulated primary power, which is significantly lower than the practical results, which can be attributed to a small simulation measurement error; the expected value would be much closer to the practical results. Simulated and practical power factors match as expected.

Further simulation tests carried out on the voltage regulation circuits will enable simulated results to be compared to the values obtained during the practical.

Appendix figures 9, 10 & 11 show the resistance, inductor and capacitance test circuits simulated in Multisim. Measured results are collated in the tables below.

V.Reg. Resistor	Calculated		Simulated		Practical	
Windings	Primary	Secondary	Primary	Secondary	Primary	Secondary
Voltage (V)	n/a	110.06 v	230 v	110.848 v	230 v	110 v
Current (A)	n/a	n/a	3.443 A	3.359 A	1.78 A	3.23 A
Power (W)	n/a	n/a	n/a	372.345 W	388 W	366 W
Power Factor (P.F)	n/a	n/a	n/a	1	0.95	1
Efficiency	n/a		n/a		33.22%	

Table 11 - Resistor Test Result Comparison

V.Reg. R/L	Calculated		Simulated		Practical	
Windings	Primary	Secondary	Primary	Secondary	Primary	Secondary
Voltage (V)	n/a	110.31 v	230 v	110.34 v	230 v	110 v
Current (A)	n/a	n/a	2.571 A	2.357 A	1.55 A	2.26 A
Power (W)	n/a	n/a	n/a	202.788 W	208 W	177 W
Power Factor (P.F)	n/a	n/a	n/a	0.779	0.58	0.72
Efficiency			n/a		41.22%	

Table 12 - Resistor / Inductor Test Result Comparison

V.Reg. R/C	Calculated		Simulated		Practical	
Windings	Primary	Secondary	Primary	Secondary	Primary	Secondary
Voltage (V)	n/a	114.76 v	230 v	114.088 v	230 v	114 v
Current (A)	n/a	n/a	1.396 A	1.587 A	469 mA	1.58 A
Power (W)	n/a	n/a	n/a	71.245 W	86.3 W	68.8 W
Power Factor (P.F)	n/a	n/a	n/a	0.394	-0.8	-0.38
Efficiency	n/a		n/a		76.94%	

Table 13 - Resistor / Capacitor Test Result Comparison

The efficiency calculations can be seen in appendix section 7.4.1. The expectation for transformer efficiency is that maximum efficiency will be achieved when the copper losses are equal to the iron losses.

From the results in tables 11, 12 and 13, the following evaluations can be made;

Voltage Regulation - Resistor Circuit		
	Expectation	Reality
Voltage	Voltage on the primary to be 230v and on the secondary to be 110v	This was found to be true when comparing calculated, simulated and practical results
Current	Primary current to be slightly less than secondary, due to the lower voltage and a resistor in the circuit	Simulated primary current was higher than secondary. Practical primary current nearly half of secondary current
Power	Primary power to be higher than secondary	Simulated primary power not measured, but the expectation was met with the practical results.
P.F	Higher P.F on the secondary	The practical secondary P.F was the same as the simulated secondary P.F
Efficiency	Maximum efficiency will be obtained when the copper losses are equal to the iron losses - Power delta = 22 - therefore lower efficiency	The efficiency is lower than expected - This can be attributed to the higher currents flowing in the transformer as well as a high power outputs to achieve the secondary voltage.

Table 14 - Resistor circuit Expectations vs Findings

Voltage Regulation - Resistor / Inductor Circuit		
	Expectation	Reality
Voltage	Voltage on the primary to be 230v and on the secondary to be 110v with slight variations.	This was found to be true when comparing calculated, simulated and practical results
Current	Primary current to be slightly less than secondary, due to the lower voltage and a resistor in the circuit	Simulated primary current was slightly higher than secondary. Overall less current in the circuit thanks to the added inductor.
Power	Primary power to be higher than secondary	Simulated primary power not measured, but the expectation was met with the practical results where the secondary voltage was achieved using less power.
P.F	Higher P.F on the secondary	The primary P.F was slightly lower than the secondary
Efficiency	Maximum efficiency will be obtained when the copper losses are equal to the iron losses - Power delta = 31 - therefore lower efficiency	41.22% efficiency is due to the lower secondary currents

Table 15 - R/L Circuit Expectations vs Findings

Voltage Regulation - Resistor / Capacitor Circuit		
	Expectation	Reality
Voltage	Voltage on the primary to be 230v and on the secondary to be more than 110v	This was found to be true when comparing calculated, simulated and practical results
Current	Primary current to be slightly less than secondary, due to the lower voltage and a resistor in the circuit	Simulated primary current was lower than secondary. Practical primary current significantly lower than secondary.
Power	Primary power to be higher than secondary	Simulated primary power not measured, but the expectation was met with the practical results - less power needed as the transformer is overloaded.
P.F	Better power factor, with lower P/F on the primary	The simulated secondary P.F was slightly higher than the practical secondary - the transformer is experiencing less losses to achieve the voltage regulation to 110v and is actually producing 114v, hence the excellent P.F
Efficiency	Highest efficiency	Higher efficiency due to less current in transformer as well as less losses.

Table 16 - R/C Circuit Expectations vs Findings

Tables 14, 15 and 16 give a comparison between expected and simulated / practical results. There were some discrepancies noted, but these could be explained with test equipment inaccuracies.

The lagging power factor noted in the resistor and R/L circuit is due to the transformer being loaded, whereas with the R/C circuit the transformer has a leading power factor, confirmed by the higher secondary voltage.

4. Three-phase Induction Motor Investigation

A practical investigation will be carried out into a three-phase induction motor performance. A stator resistance, no-load and blocked rotor test will be carried out to achieve this. Figure 9 illustrates a brief description of each test method.

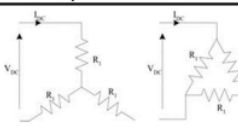
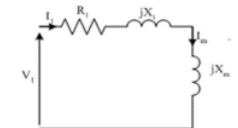
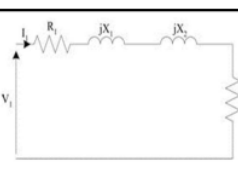
Induction motor analysis				
Test	Method	Equivalent Circuit	Slip	Transformer Equivalent
Stator Resistance	DC voltage applied to stator, reducing per-phase circuit to stator winding resistance. Impedance depends on star delta or wye connection		n/a	n/a
No-load	By applying no load to motor, the magnetising reactance and core loss reactance can be ascertained		Very small	Open Circuit test
Blocked rotor	Lock rotor, increase supply gradually until rated current is reached. Enables rotor resistance and leakage reactance to be ascertained through measuring stator power, current and reactive power.		1	Short Circuit test

Table 17- Induction Motor Testing (Wildi, 1997)

Table 17 shows the similarities between the induction motor tests and transformer tests.

Practical results were obtained from the motor in a safe manner, using suitable test equipment and are illustrated in table 18 – Stator Resistance, 19 – No Load & 20 - Locked Rotor.

Stator Resistance			
	Line 1	Line 2	Line 3
Voltage	11.8v	11.8v	11.8v
Current	330mA	330mA	330mA

Table 18 - Stator Resistance Practical Results

No Load			
	Line 1	Line 2	Line 3
Voltage	214v	214v	214v
Current	529mA	529mA	529mA
Power	61.2W	61.2W	61.2W
P.F	0.31	0.31	0.31

Table 19 - No-Load Practical Results

Blocked Rotor			
	Line 1	Line 2	Line 3
Voltage	25.7v	25.7v	25.7v
Current	489mA	489mA	489mA
Power	19.2W	19.2W	19.2W
P.F	0.88	0.88	0.88

Table 20 - Blocked Rotor Practical Results

The equivalent circuit values calculated (Table 21) using the practical measured results. Calculations can be seen in appendix sections 7.5.1, 7.5.2 and 7.5.3.

Equivalent Circuit Calculated values	
V1	214v
I1	529mA
R1	35.75Ω
Rc	2246Ω
Xm	737.5Ω (2.35H)
I0	305.4mA
R2'	44.73Ω
(X1+X2)'	42.16Ω (136.1mH)
Is	282mA

Table 21 - Induction Motor Equivalent CCT Calculated Values

An equivalent circuit simulation using Multisim can be seen in appendix section 7.5.5

An attempt was made to simulate the induction motor on [Excel Spreadsheet](#) or [Simulink](#), which was partially successful in confirming the calculated results' validity, see appendix section 7.5.6 for simulation screen shots. Unfortunately this was not completed due to current work commitments.

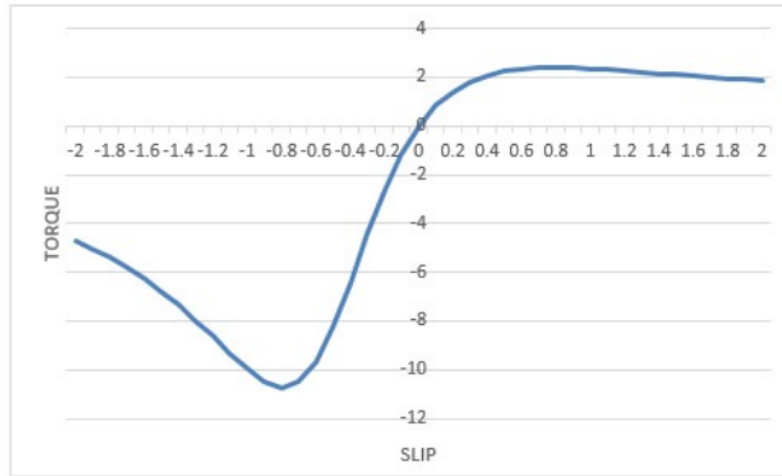
Below is the induction motor torque equation:

$$TG = \frac{3 VI^2 R2'}{\omega s S \left(\left(R1 + \frac{R2'}{S} \right)^2 + (X1 + X2')^2 \right)}$$

Figure 9 - Induction Motor Torque Equation

where is the actual
data generated by the
spreadsheet

There are three states an induction motor can be in when energised, these are motoring, generating and braking; these are briefly discussed in table 22.



Graph 1 - Torque / Slip Graph

	Description	Slip Value
Motoring	The motor is producing positive torque and the motor is turning in the forwards direction.	Between $S=1$ & $S=0$
Generating	The motor is driven in the same direction at a speed that is faster than the synchronous speed.	Between $S=0$ & $S=-1$
Braking	Torque is positive in the reverse direction causing a braking effect.	>1

Table 22 – Motoring / Generating / Braking

The motor torque calculation (appendix 7.5.4) is used to calculate various torque values, using pre-determined slip values. As seen in graph 1, the motor performs as expected in comparison with the motoring, generating and braking descriptions in table 22.

When the slip is below zero the motor will be generating, between zero and one it is motoring and once above 1 the speed drops down and the braking effect takes place.

5. Conclusions and Recommendations and Team Working

5.1 Conclusion and Recommendations

5.1.2 Research

Good conclusions

From the research conducted the following conclusions can be made with regards to induction machine speed control using power electronic converters; IGBT's have greatly improved the switching frequency and efficiency of speed controllers, This, as well as the simple design and low maintenance required for operating induction motors have given way for broad integration into many industries.

The delivery of a 415V AC supply to these industrial motors is only achievable through the use of well-established methods, which would not be able to function without step up and step-down transformers as well as transmission lines. All of which can be accurately simulated and performance predictions ascertained by calculating the equivalent circuit parameters.

5.1.2 Transformer Investigation

The transformer practical highlighted the effectiveness of utilising an equivalent circuit to predict the transformer performance and efficiency. The practical, simulated and predicted values did match, with only a few small discrepancies, which were established to be measurement equipment inaccuracies and simulation errors. These errors can be overcome or reduced by using better test equipment and critically analysing simulation values and meter settings. The open and short circuit tests are industry standard for establishing the internal losses of the transformer and proved to be a valuable tool to predict performance.

Good conclusions

5.1.3 Induction Motor Investigation

The induction motor investigation enabled a thorough understanding of the speed, torque and slip relationship, as well as the motoring, generating and braking stages of the motor. The practical results that were obtained did match predicted and simulated results, albeit a part5 of the practical is not covered in this assignment. The speed and torque relationship would have given a better insight into the motor performance, which would have been achieved by driving the motor faster than synchronous speed with a VFD.

5.2 Team Working

This task was carried out as a team, where the objectives and execution were discussed beforehand to ensure each member understood the objectives and participated in the measurement and validation of practical results. By taking turns to carry out safe measurement of the transformer and induction motor parameters, a thorough understanding could be achieved, as well as confirming competence in standard industrial measurement techniques. Practical results were standardised between the team to ensure continuity in results. All calculations and simulation evaluations were carried out individually.

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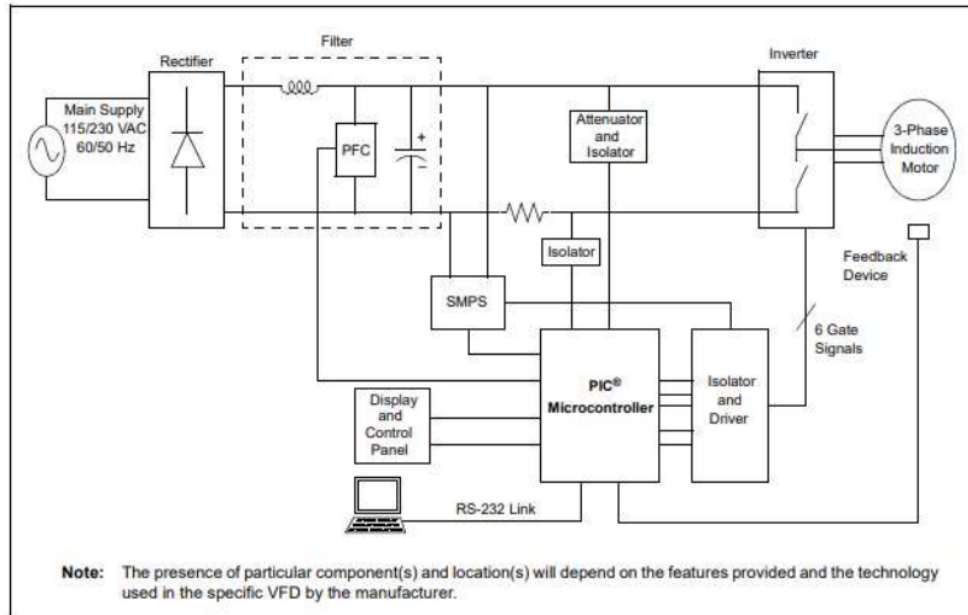
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7. Appendix

7.1 Research

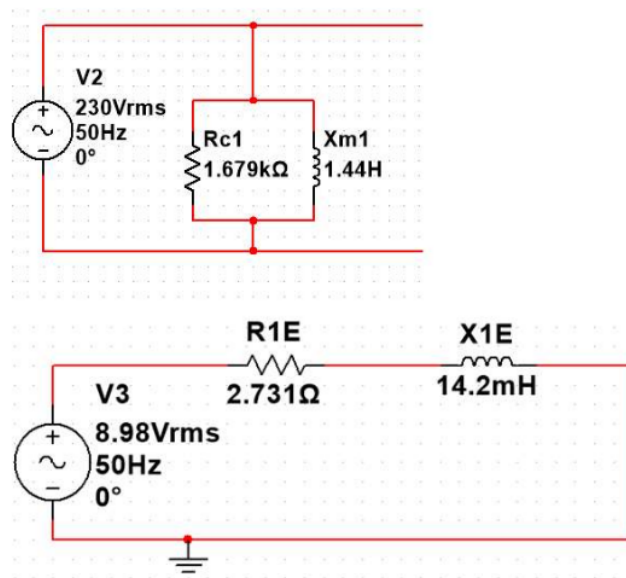


Appendix Image 1 - Typical VFD (Parekh, 2003)

7.2 Transformer practical



Appendix Image 2 - 240v-110v Transformer



Appendix Image 3 - Iron and Copper Loss Equivalent Circuits

7.2.1 Open Circuit (Iron Losses) Calculations

Frequent incorrect use of an equals sign, they can't all be equal!

$$P_{in} = \frac{V_1^2}{RC} = RC = \frac{V_1^2}{P_{in}} = \frac{230^2}{31.5} = 1679.4\Omega$$

$$I_c = \frac{V_1}{RC} = \frac{230}{1679.4} = 0.137A \text{ or } 137mA$$

$$I_o = I_c^2 + I_m^2 = I_o^2 = I_c^2 + I_m^2 = I_m^2 = I_o^2 - I_c^2$$

$$= ((527 \times 10^{-3})^2 - (137 \times 10^{-3})^2) = 0.25896 = \sqrt{0.25896} = 0.509A \text{ or } 509mA$$

$$X_m = \frac{V_1}{I_m} = \frac{230}{0.509} = 451.87\Omega$$

$$X_m = 2\pi f L = L_m = \frac{X_m}{2\pi f} = \frac{451.87}{2\pi \times 50} = 1.44H$$

7.2.2 Short Circuit (Copper Losses) Calculations

You are saying that $P = I$???

$$P = I \times V = I = \frac{P}{V} = \frac{375}{110} = 3.41A$$

$$Z_{1E} = \frac{V_1}{I_1} = \frac{8.98}{1.72} = 5.221\Omega$$

$$R_{1E} = \frac{P_{in}}{I_1^2} = \frac{8.08}{1.72^2} = 2.731\Omega$$

$$X_{1E} = \sqrt{Z_{1E}^2 - R_{1E}^2} = \sqrt{5.221^2 - 2.731^2} = 4.45\Omega$$

$$Z_{2E} = \left(\frac{N_2}{N_1}\right)^2 \times Z_{1E} = \left(\frac{110}{230}\right)^2 \times 5.221 = 1.194\Omega$$

$$R_{2E} = \left(\frac{N_2}{N_1}\right)^2 \times R_{1E} = \left(\frac{110}{230}\right)^2 \times 2.731 = 0.625\Omega$$

$$X_{2E} = \left(\frac{N_2}{N_1}\right)^2 \times X_{1E} = \left(\frac{110}{230}\right)^2 \times 4.45 = 1.018\Omega$$

$$I_2 = \left(\frac{N_2}{N_1}\right)^2 \times I_1 = \left(\frac{110}{230}\right)^2 \times 1.72 = 3.596A$$

$$X_{1E} = 2\pi fL = L_{1E} = \frac{X_{1E}}{2\pi f} = \frac{4.45}{2\pi \times 50} = 0.0142H \text{ or } 14.2mH$$

$$X_{2E} = 2\pi fL = L_{2E} = \frac{X_{2E}}{2\pi f} = \frac{1.018}{2\pi \times 50} = 0.00324 H \text{ or } 3.24mH$$

7.2.3 Voltage Regulation Calculations

Resistor load

$$\phi = \cos^{-1}(0.95) = 18.20^\circ = \sin(18.20) = 0.3123$$

How can they all be equal

$$\% \text{ Regulation} = \frac{I_2 (R_{2E} \times \cos\phi + X_{2E} \sin\phi)}{V_2} \times 100$$

$$= V_2 = E_2 - I_2(R_{2E} \times \cos\phi + X_{2E} \sin\phi)$$

$$V_2 = 113 - 3.23 (0.625 \times 0.95 + 1.018 \times 0.3123) = 110.06v$$

Inductor Load

$$\phi = \cos^{-1}(0.58) = 54.55^\circ = \sin(54.55) = 0.815$$

$$\% \text{ Regulation} = \frac{I_2 (R_{2E} \times \cos\phi + X_{2E} \sin\phi)}{V_2} \times 100$$

$$= V_2 = E_2 - I_2(R_{2E} \times \cos\phi + X_{2E} \sin\phi)$$

$$V_2 = 113 - 2.26 (0.625 \times 0.58 + 1.018 \times 0.815) = 110.31v$$

Capacitance Load

$$\phi = \cos^{-1}(-0.8) = 143.13^\circ = \sin(143.13) = 0.600$$

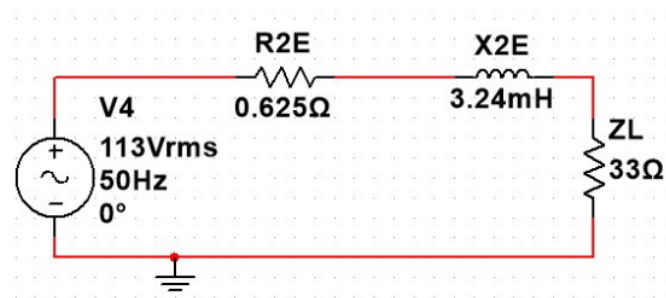
$$\% \text{ Regulation} = \frac{I_2 (R_{2E} \times \cos\phi + X_{2E} \sin\phi)}{V_2} \times 100$$

$$= V_2 = E_2 - I_2(R_{2E} \times \cos\phi + X_{2E} \sin\phi)$$

$$V_2 = 113 - 1.58 (0.625 \times -0.8 + 1.018 \times 0.600) = 114.76v$$

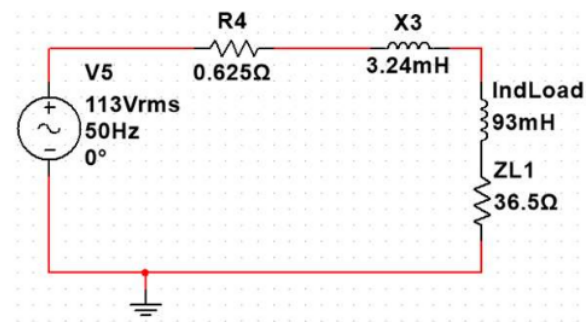
7.2.4 Voltage Regulation Circuits

Resistive load



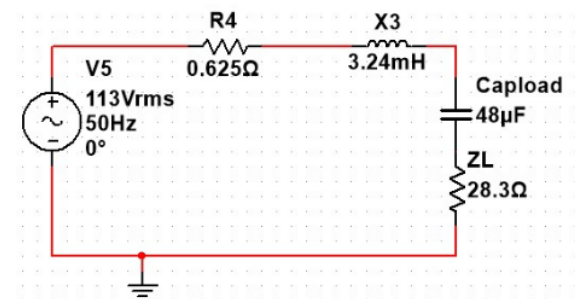
Appendix Image 4 - Resistive Load Equivalent Circuit

R/L Load



Appendix Image 5 - Resistor / Inductor Load Equivalent Circuit

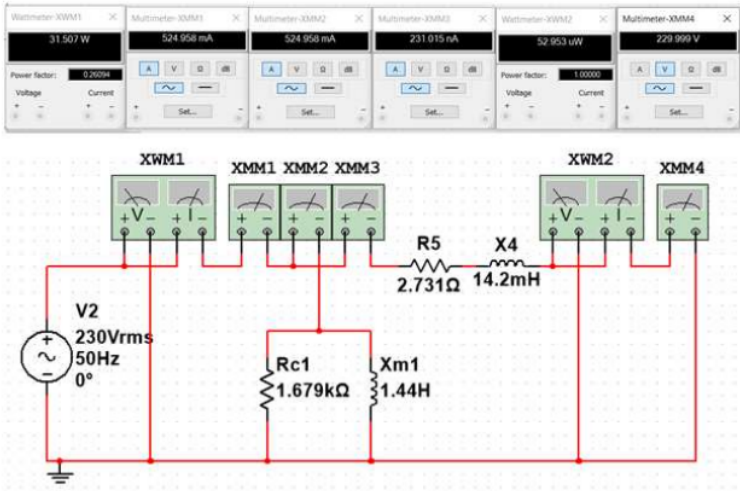
R/C Load



Appendix Image 6 - Resistor / Capacitor Load Equivalent Circuit

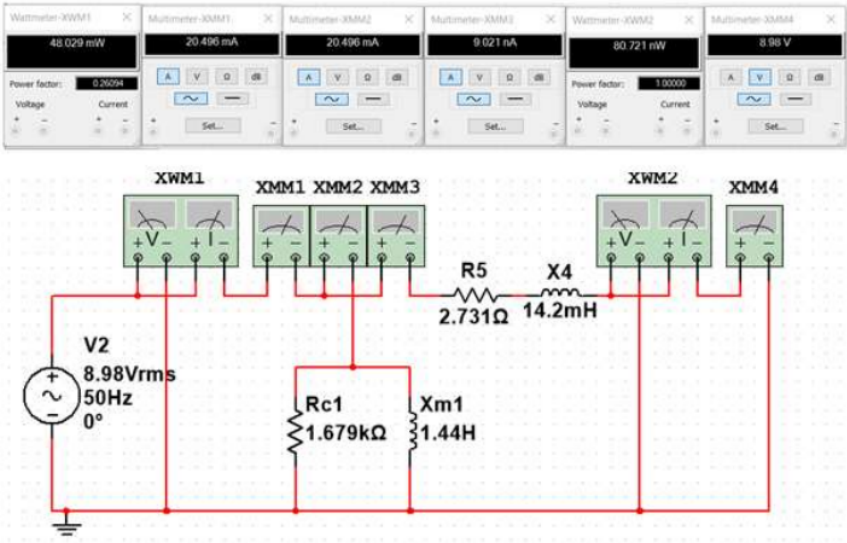
7.3 Equivalent circuit simulation and analysis

Iron Losses Equivalent circuit.



Appendix Image 7 - Iron Losses Equivalent Circuit

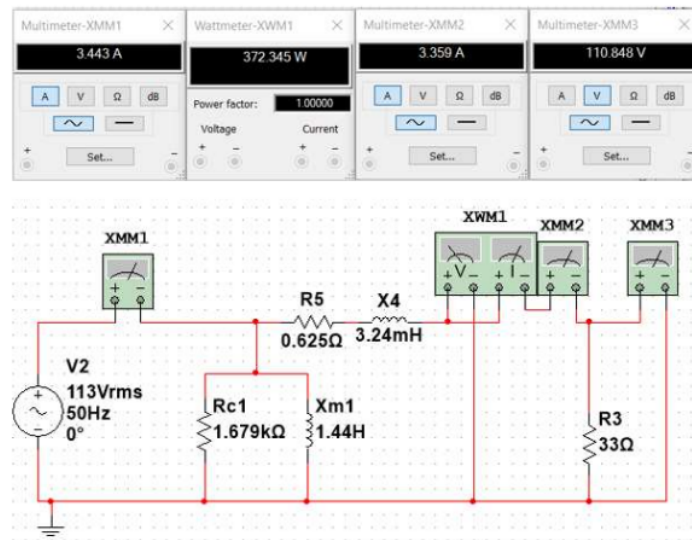
Copper Losses Equivalent Circuit.



Appendix Image 8 - Copper Losses Equivalent Circuit

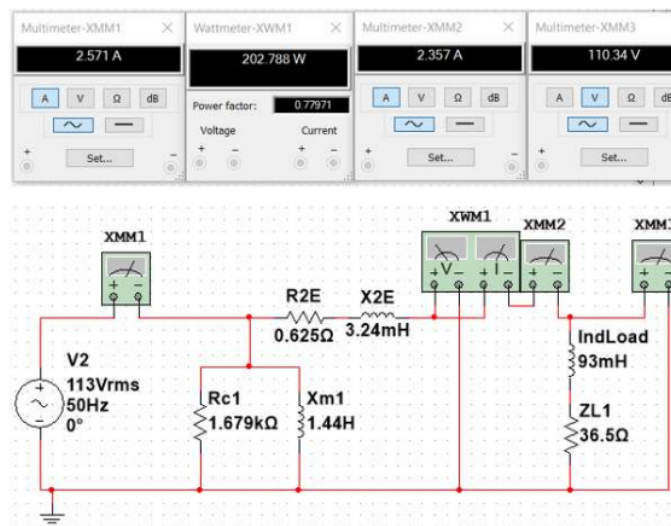
7.4 Voltage Regulation Simulated Circuits

Resistance Test.



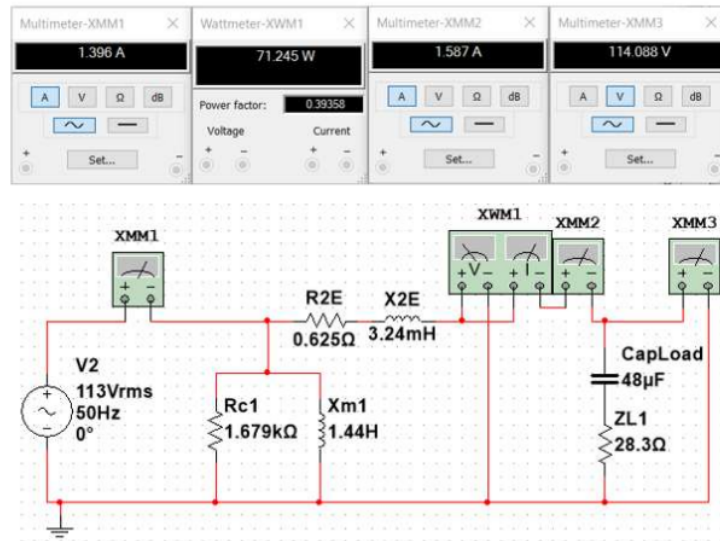
Appendix Image 9 - Resistance Test Simulation

Inductor / Resistor load



Appendix Image 10 - Resistor / Inductor Simulation

Capacitor / Resistor Load



Appendix Image 11 - Resistor / Capacitor Simulation

7.4.1 Voltage Regulation test efficiency calculations

Voltage Regulation test efficiency calculations;

$$\frac{375 \times 1 \times 100}{(375 \times 1) + 388 + 366} = 33.215 \%$$

$$\frac{375 \times 0.72 \times 100}{(375 \times 0.72) + 208 + 177} = 41.22 \%$$

$$\frac{375 \times 1.38 \times 100}{(375 \times 1.38) + 86.3 + 68.8} = 76.94 \%$$

7.5 Inductor Motor Testing

7.5.1 Stator Resistance Test

$$R_1 = V = I \times R = R = \frac{V}{I} = \frac{11.8}{330 \times 10^{-3}} = 35.75 \Omega$$

7.5.2 – No-Load Test

$$I_0 = \frac{I_L}{\sqrt{3}} = \frac{529 \times 10^{-3}}{\sqrt{3}} = 305.4 \text{ mA}$$

$$P_0 = \frac{1}{3} \times P_{NL} = \frac{1}{3} \times 61.2 = 20.4 \text{ W}$$

$$P.F = \cos \phi = \frac{P_0}{V_0 \times I_0} = \frac{20.4}{214 \times 305.4 \times 10^{-3}} = 0.312$$

$$\text{Phase angle} = \phi_0 = \cos^{-1}(0.312) = 71.82^\circ$$

$$\text{Sine of phase angle} = \sin \phi (71.82) = 0.950$$

$$R_c = \frac{V_0}{I_0 \times \cos \phi} = \frac{214}{305 \times 10^{-3} \times 0.312} = 2245.9 \Omega$$

$$X_M = \frac{V_0}{I_0 \times \cos \phi} = \frac{214}{305 \times 10^{-3} \times 0.950} = 738.56 \Omega$$

$$X_M (\text{Henry}) = 2\pi f L = L_m = \frac{X_M}{2\pi f} = \frac{737.5}{2\pi 50} = 2.34 \text{ H}$$

7.5.3 Locked Rotor Test

$$I_{sc} = \frac{I_{br}}{\sqrt{3}} = \frac{489 \times 10^{-3}}{\sqrt{3}} = 282 \text{ mA}$$

$$P_{sc} = \frac{1}{3} \times P_{br} = \frac{1}{3} \times 19.2 = 6.4 \text{ W}$$

$$\cos \phi_{sc} = P_{sc} / (V_{sc} \times I_{sc}) = \frac{26.4}{25.7 \times 282 \times 10^{-3}} = 0.8831$$

$$\phi_{sc} = \cos^{-1}(0.8831) = 27.98^\circ$$

$$\sin \phi_{sc} = \sin(27.98) = 0.4692$$

$$Z_{sc} = \frac{V_{sc}}{I_{sc}} = \frac{25.7}{282 \times 10^{-3}} = 91.13 \Omega$$

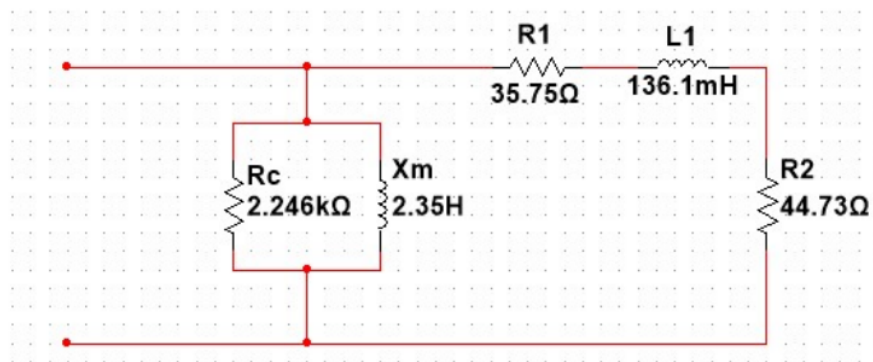
$$R_1 + R_2' = Z_{sc} \times \cos \phi_{sc} = 91.13 \times 0.8831 = 80.48 \Omega$$

$$R_2' = (R_1 + R_2') - R_1 = 80.48 - 35.75 = 44.73 \Omega$$

$$X_1 + X_2' = Z_{sc} \times \sin \phi_{sc} = 91.13 \times 0.4692 = 42.76 \Omega$$

$$X_1 + X_2' = 2\pi f L = L_m = \frac{X_1 + X_2'}{2\pi f} = \frac{42.76}{2\pi 50} = 136.1 \text{ mH}$$

7.5.4 Induction Motor Equivalent Circuit Simulation



7.5.5 Induction motor total torque equation

$$TG = \frac{3 VI^2 R_2'}{\omega_s S \left(\left(R_1 + \frac{R_2'}{S} \right)^2 + (X_1 + X_2')^2 \right)}$$

7.5.6 Simulink Induction Motor Modelling

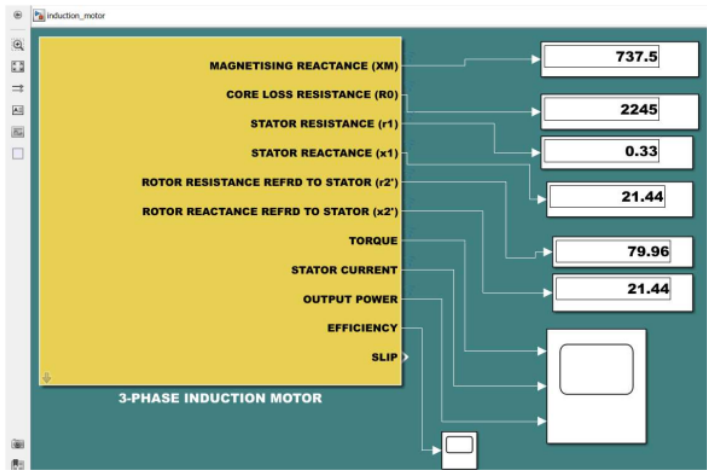


Figure 10 - Simulink Induction Motor Equivalent Circuit Simulation

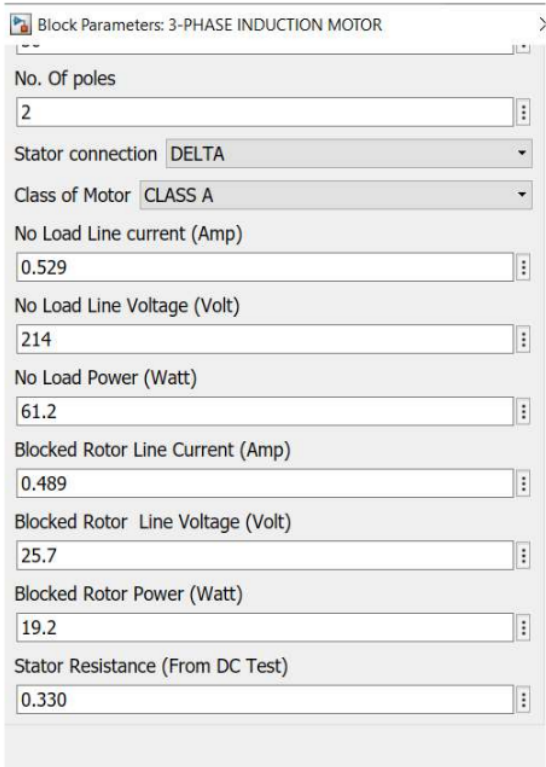


Figure 11 - Simulink Induction Motor Equivalent Circuit Simulation values

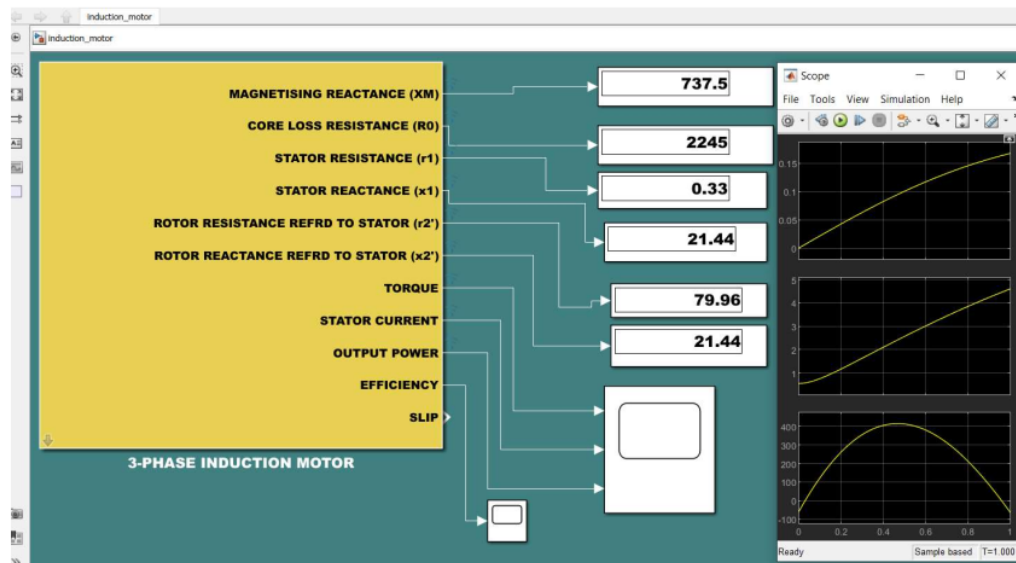


Figure 12 - Simulink Induction Motor Equivalent Circuit Simulation - Torque / Stator Current & Power

1809797

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

61 / 100

PAGE 1

PAGE 2

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Good Structure

Report is structured exactly as stated in the assignment brief.

PAGE 3

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Text Comment. A summary should be no more than 300 words, this is excessive

PAGE 5

PAGE 6

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Correctly cited

Citation method conforms to Harvard standard, well done.

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PAGE 8

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Correctly cited

Citation method conforms to Harvard standard, well done.

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Improper Citation

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PAGE 15

Text Comment. The NanoVip is not an LCR meter

PAGE 16

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Text Comment. Excel Spreadsheet

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QM

Good conclusions

You have shown understanding here from these observations and deductions

QM

Good conclusions

You have shown understanding here from these observations and deductions



Wide Range of Sources

You have shown good evidence of reading from a wide range of sources.



Correct method of listing.

You have listed your sources correctly according to the Harvard method.

Text Comment. Frequent incorrect use of an equals sign, they can't all be equal!

Text Comment. You are saying that $P = I$???

Text Comment. How can they all be equal ??????????????????????????????

LOURENS BRITS**61****1. ENGAGEMENT WITH LITERATURE**

Engagement with a wide range of literature, including sources retrieved independently. Selection of relevant and credible sources. Very good use of referencing, with no/very few inaccuracies or inconsistencies. (13/20)

13**2. KNOWLEDGE AND UNDERSTANDING**

Knowledge is reasonably extensive. Exhibits very competent critical understanding of the well-established concepts and principles of the subject and the main methods of enquiry. Breadth and depth of knowledge. (13/20)

13**3. COGNITIVE AND INTELLECTUAL**

Some critical evaluation and analysis of concepts and principles, though descriptive in parts. An emerging awareness the limits of their knowledge and ability to use evidence to support the argument though with some tendency to assert/state opinion rather than argue on the basis of reason and evidence. Mostly valid arguments

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and logical judgements. Not all results have been analysed. (10/20)

4. PRACTICAL APPLICATION



A good and appropriate application of established methods, materials, tools and/or techniques. Clear appreciation of the context of the application. Mainly consistent, accurate and logical application of theory to practice, making appropriate links between the two. Can identify problems and propose mostly appropriate solutions outside the context in which they were first studied. Not all results have been presented. (10/20)

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5. TRANSFERABLE SKILLS



Can communicate professionally confidently and consistently in a suitable medium for the audience. Work is coherent, very fluent and is presented proficiently. Can work autonomously with initiative. Where relevant can work professionally within a team, showing leadership skills as appropriate, and meeting obligations. Demonstrates excellent skills for employment requiring the exercise of personal responsibility and decision-making and an appetite for further development. (15/20)

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