

1809799

by Thomas Grennan

AN EXCELLENT REPORT WITH EXCELLENT RESEARCH AND
CONSISTENT CITATIONS. EXCELLENT KNOWLEDGE AND
CRITICAL ANALYSIS WAS DEMONSTRATED THROUGHOUT.
PRESENTATION WAS EXCELLENT.

MARK AGREED.



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Contents

Good Structure

Table of Figures	3
Tables of Results.....	3
1. Executive summary	4
2. Research.....	6
3. Transformer Investigation.....	12
4. Three-phase Induction Motor Investigation	21
5. Conclusions and Recommendations	26
6. Citation List.....	28
7. Appendix	30
Appendix 7.1 – Transformer Data Sheet.....	30
Appendix 7.2 – Open Circuit Test	31
Appendix 7.3 – Transformer Open Circuit Calculations.....	31
Appendix 7.4 – Short Circuit Test	32
Appendix 7.5 – Transformer Short Circuit Calculations.....	33
Appendix 7.6 – Regulation Test Explanation and Equivalent Circuits	34
Appendix 7.7 – Voltage Regulation Calculations.....	36
Appendix 7.8 – Load Testing and Analysis.....	38
Appendix 7.9 – Stator Resistance Test and Calculations.....	42
Appendix 7.10 – No Load Test and Calculations	43
Appendix 7.11 – Blocked Rotor Test and Calculations.....	44
Appendix 7.12 – Three Phase Motor Equivalent Circuit	45
Appendix 7.13 – Torque vs Slip Test Results.....	46
Appendix 7.14 - Induction Motor Synchronous Speed Test Results	47
Appendix 7.15 – Induction Motor Slip Test Results	47

Table of Figures

Figure 1 - Three Phase VSI	6
Figure 2 – PWM Output from an Inverter	7
Figure 3 – Comparison of the classification of motors	8
Figure 4 – Diagram of the National Grid power station	10
Figure 5 – Circuit diagram of Three-phase supply voltage	11
Figure 6 – Open Circuit Equivalent Circuit.....	12
Figure 7 – Short Circuit Equivalent Circuit.....	13
Figure 8 – Transformer equivalent circuit referred to the primary	14
Figure 9 - Transformer equivalent circuit referred to the secondary	15
Figure 10 – Transformer Open Circuit Equivalent Circuit under Analysis	17
Figure 11 - Transformer Short Circuit Equivalent Circuit under Analysis	18
Figure 12 – Induction Motor Calculated Torque vs Slip Comparison Graph	23
Figure 13 - Induction Motor Practical Torque vs Slip Comparison Graph.....	24
Figure 14 – Synchronous Speed vs Power Factor Graph.....	25
Figure 15 – Transformer Datasheet	30
Figure 16 – Regulation Equivalent Circuit: Full Load	34
Figure 17 - Regulation Equivalent Circuit: Overload	34
Figure 18 - Regulation Equivalent Circuit: Complex RC Load	35
Figure 19 - Regulation Equivalent Circuit: Complex RC Load	35
Figure 20 – Transformer Full Load Testing and Analysis	38
Figure 21 - Transformer Overload Testing and Analysis	39
Figure 22 - Transformer RL Load Testing and Analysis	40
Figure 23 - Transformer RC Load Testing and Analysis	41
Figure 24 – Three-Phase Motor Equivalent Circuit	45

Tables of Results

Table 1 – Open Circuit Practical Results	12
Table 2 – Open Circuit Component Values	12
Table 3 – Short Circuit Practical Results	13
Table 4 – Short Circuit Component Values	13
Table 5 – Voltage Regulation Practical Results: Full Load	16
Table 6 - Voltage Regulation Practical Results: Overload	16
Table 7 - Voltage Regulation Practical Results: Complex RL Load.....	16
Table 8 - Voltage Regulation Practical Results: RC Load	16
Table 9 – Transformer Open Circuit Comparison Results	17
Table 10 - Transformer Short Circuit Comparison Results	18
Table 11 - Transformer Regulation Comparison Results	19
Table 12 - Transformer Efficiency Comparison Results	20
Table 13 – Induction Motor Stator Resistance Test Results	21
Table 14 – Induction Motor No Load Test Results	21
Table 15 – Induction Motor Blocked Rotor Test Results	21
Table 16 – Induction Motor Equivalent Circuit Values	22
Table 17 - Transformer Full Load Testing Comparison Table	38
Table 18 - Transformer Overload Testing Comparison Table.....	39
Table 19 - Transformer RL Load Testing Comparison Table	40
Table 20 - Transformer RC Load Testing Comparison Table.....	41
Table 21 – Torque Vs Slip Calculation Results	46
Table 22 - Induction Motor Synchronous Speed Tests Results.....	47
Table 23 - Induction Motor Synchronous Slip Test Results	47

1. Executive summary

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This report consists of 4 significant sections. Section 1 outlines the research undertaken; this research set a basis for the assignment. The research undertaken was focused on Transformers and Induction Motors, specifically on methods of speed control of an induction motor through the use of power electronic converters, typical applications where induction machines are used in industry and finally the power systems that are required in order to supply industrial facilities with three-phase power.

Section 2 focused on the single-phase transformer, specifically undertaking various experimental procedures in order to find out key information about the transformer's performance, in terms of Copper losses, Iron Losses, Efficiency and Regulation. Open Circuit and Short Circuit tests were undertaken in order to obtain readings of Voltage, Current, Power and Power factor, all tests were undertaken in a safe manner using a Nanovip analyser. Calculations were derived from the results obtained as seen in the appendix, from these calculations the equivalent circuit component values were found. An equivalent circuit referred to the primary was the constructed within the Multisim package using the calculated component values, this equivalent circuit was tested using measuring equipment in order to find the same values obtained in the practical test, the simulated and practical values were then tabulated along with the manufacturers datasheet and analysis and comparisons were made.

Further tests were undertaken in section 2, The transformers output was 'loaded' with different loads, these being Resistive, RL, RC and Overload. The results obtained were tabulated ready for analysis and comparison. Suitable calculations were made to predict how the transformer is expected to perform, the transformer was modelled within Multisim, this time referred to the secondary. The output of the transformer was connected to the same loads undertaken in the experiment, various test equipment such as Voltmeters, Ammeters and Wattmeter's were connected to the transformer and these values were also tabulated, Suitable comparisons and analysis were then made. From these tests undertaken, suitable data was obtained in order to analyse the efficiency and regulation of the transformer under these various loads.

The 3rd section of the report is focused on the testing and analysis of a three-phase induction motor. Three primary tests were undertaken on the motor, these being the 'No Load', 'Blocked Rotor' and 'Stator Resistance' tests. Results were obtained by the Nanovip analyser, these results were then inserted into equations in order to derive the induction motors equivalent circuit values. Further testing was undertaken, the motor was externally driven in order for it to reach above synchronous speed to ensure it entered a generating state, values for RPM and power factor were taken, a graph was then plotted showing the relationship between these values. The motor was then driven and various values of torque were applied and values for slip were recorded. From these tests the equivalent motor circuit parameters were entered as variables into a spreadsheet equation in order to derive a graph representing a Torque vs Slip response, this was then compared with graph obtained from the practical and suitable comparisons were made.

Section 4 entails the conclusions and recommendations of the report and experiments from an overall point of view.

2. Research

2.1 Induction machine speed control methods using power electronic converters

An induction motor, also known as an 'asynchronous' motor is most widely used motor in industrial applications, depending on its design they are operated from single or three phase supplies. In many industrial applications the speed of the motor is often needed to be controlled, the speed of the induction motor is either controlled by the frequency of the supply voltage which sets up the speed of the field, and the voltage applied to the stator (Weidauer, 2014). Correctly cited

In order to control the speed of the motor 'Power Electronics Converters' (PECs) are utilised in control systems and power processors for various industrial applications, the defined purpose of a PEC is to perform power-conditioning in order to suit the specified applications requirements by changing one form of electrical energy to another by supplying current and voltage of different frequencies and magnitudes. PECs use semi-conductor electronic devices such as SCRs and IGBTs which can operate from less than line frequencies of 50Hz to radio frequencies of 100s of MHz, Power conversion has many forms, DC-AC PECs are used by inverters providing a constant variable AC voltage, AC-AC PECs are used by many Variable Frequency Drives (VFD), Also known as AC Drives, in order to change the voltage or frequency of an AC source, this application is primarily utilised for induction motor control. (Blaabjerg, 2018). The speed of a motor can be controlled by using a phase-angle controller, this device varies the phase-angle and in turn varies the RMS voltage supplied to the stator controlling the motors speed, these devices are typically used in soft-starts and Cycloconverters which are compact ways of controlling speed, however they are not very efficient. (OrientalMotor, 2018).

Within industrial applications in processing plants a more efficient method of speed control utilises the 'Variable Frequency Drive', or VFD. A VFD controls the motor speed by varying the frequency supplied to the motor, these devices consist of a rectifier circuit, a dc link and an inverter. A diagram of a three-phase voltage source inverter is seen in figure 1 (Canada, 2015). Correctly cited

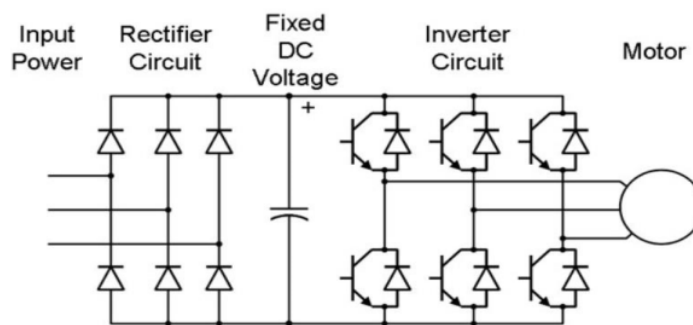


Figure 1 - Three Phase VSI (VFDS.org, 2019)

An AC Voltage at Line Frequency of 50Hz is applied to the VFD input terminals, this three-phase alternating current flows through the rectifier circuit which is an arrangement of diodes converting the AC input into DC. The DC output from the rectifier will have some distortion in the form of ripple, a reservoir capacitor (also known as a DC Link in VSI Inverters) is used to counteract this, supplying a smooth DC output to the inverter circuit in order to turn the current back to AC. Using semi-conductor devices such as Insulated-gate bipolar transistors (IGBTs) which utilises pulse width modulation, turning the transistors off and on up to 1000 times per second (1000Hz) in order to produce a sinusoidal output replicating AC voltage, the higher the supplied frequency to the motor the faster the motor will operate. An example of PWM output from a VFD is seen in figure 2 (Omron, 2017). By varying frequency and voltage together, the V to F ratio is maintained which gives the maximum flux within the motor and therefore the optimum efficiency. (Daware, 2019).

Correctly cited

Correctly cited

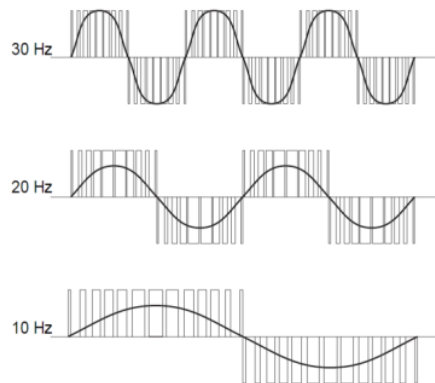


Figure 2 – PWM Output from an Inverter (Glampe, 2017)

Current Source Inverters (CSI) have a similar topology to the VSI; however, they use inductors in their DC link for inductive energy storing to store DC current and in turn regulating the current ripple between the rectifier and inverter. CSIs use gate turn-off thyristors as their semiconductor devices, these thyristors are turned on and off creating a PWM output with regulated frequency (Collins, 2016).

Correctly cited

For applications such as milling machines where quick torque control is needed a flux-vector drive is needed in order for the induction motor to perform quickly and match the performance of a DC motor (ABB, 2017).

Correctly cited

In simple applications the output frequency is often controlled from the operator interface on the VFD control panel, Potentiometers are used to give an analogue input to the drive which gives an analogue signal proportional to the frequency output. More complex applications use PLCs to give analogue outputs to the drive to give speed reference (vfds, 2017).

Correctly cited

2.2 Industrial Applications of Induction Motors

AC Motors such as the squirrel cage induction motor are the most commonly used induction machine in the world. These motors are used in various industrial applications such as Conveyors, Pumps, Lifts, Cranes, Hoists, Industrial fans and also within manufacturing machines such as lathes and milling machines. It is essential that a motor is chosen by matching its specification to the specific application, this could be: Supply Voltage and Frequency, Starting and Control, Enclosure Rating, RPM and Continuous rating (elprocus, 2019).

The National Electrical Manufacturers Association (NEMA) have defined classes of motors based on their application; this is shown in figure 3 (Cavallo, 2018).

- Class A Motors- normal starting torque, high starting current, low slip, high efficiency. Applications include fans, blowers, small pumps, etc.
- Class B Motors- normal starting torque, low starting current, low slip. Applications include voltage starters and Class A applications.
- Class C Motors- high starting torque, low starting current. Applications include compressors, conveyors, reciprocating pumps, crushers, etc.
- Class D Motors – highest starting torque, low starting current, high operating slip, low efficiency. Applications include punch presses, bulldozers, die-stamping machines, high-impact loading, etc.

Figure 3 – Comparison of the classification of motors (Cavallo, 2018)

AC Induction motors are ideal for conveyor systems that continuously operate in one direction, they are often used in order to move components along assembly lines. These motors can be fixed or variable speed (VFD or Potentiometer controlled). Typical applications are 'Belt Conveyors' where two or more pulleys with a continuous loop of material whereby the conveyor belt rotates around them, the motors are typically mounted at the head or pulling end of the conveyor. This application is often used for materials that require a solid surface to move along (Automation, 2020). Correctly cited

Roller conveyors are another typical industrial application utilising AC induction motor, these can be belt or chain driven which are powered by the motor, these conveyors have 'rollers' which are a metal shaft housed within a metallic material depended on the application. These are often used for flat materials such as boxes (Lamb, 2013).

Pumps are used in industrial applications when circulating, removing or supplying liquids such as oil or water, these pumps utilise motors within their operation. Automotive machines such as radiator clenching machines which connect the radiator to the inlet and outlet tanks, huge force is needed to 'clench' these therefore this is done by hydraulic cylinders which are supplied by a hydraulic power pack, whereby a tank with an oil reservoir will have a three-phase motor mounted on top. The pump will then provide the systems valves with the pressurised hydraulic oil needed, when these valves are electrically controlled via a PLC the cylinders will operate and produce extensive pressure to the part (Nachtwey, 2020). Correctly cited

A hoist is a device which is used to lift or lower a load using a lift-wheel or a drum, these are typically used for elevators. These systems need a constant load torque at all times; therefore, an induction motor is ideal for this

application. A Three-Phase induction motor is coupled with a gearbox which turns a drum with a cable which supports the mass (WEG, 2019).

Correctly cited

2.3 Power Systems required to deliver a three-phase, 415VAC supply to a typical factory

The National Grid is one of the world's largest utilities which focuses on the transmission and distribution of electricity in Great Britain. The National Grid is a system of cables and transformers which connects power stations to consumers such as industrial factories (Figure 4) (Grid, 2020). Correctly cited

In the UK coal, uranium, oil, gas, hydro, wind and solar are the main sources of energy used in power generation, the power generated from these substations is typically around 25kV. Electricity is often generated in great distances from end consumers; therefore, the power lines have high resistances due to the length of the lines, due to this resistance a power line will have a loss of $I^2 R$ which will be wasted as heat. (Eirgrid, 2017)

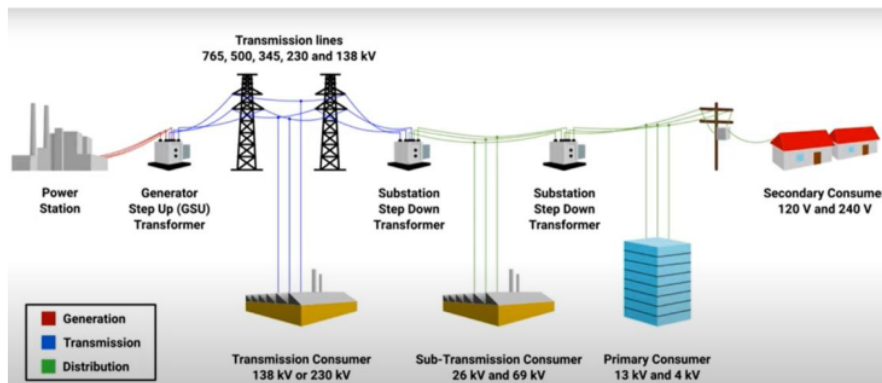


Figure 4 – Diagram of the National Grid power station (Networks, 2019)

To reduce these losses power companies, utilise Generator Step-Up transformers to increase the voltage out of the power station and in-turn reduce the current and power losses along the transmission lines. The voltage from the power station is increased by the step-up transformer to between 132kV to 765kV greatly reducing the current and losses, this increased voltage is sent to a sub-station which then feeds this power into the transmission lines which are held by transmission towers, the voltage will travel long distances to a substation which will have a step-down transformer. Different consumers will require different voltages, large industrial plants might require 33kV, these plants typically have their own substations which will step-down the voltage to the rating required.

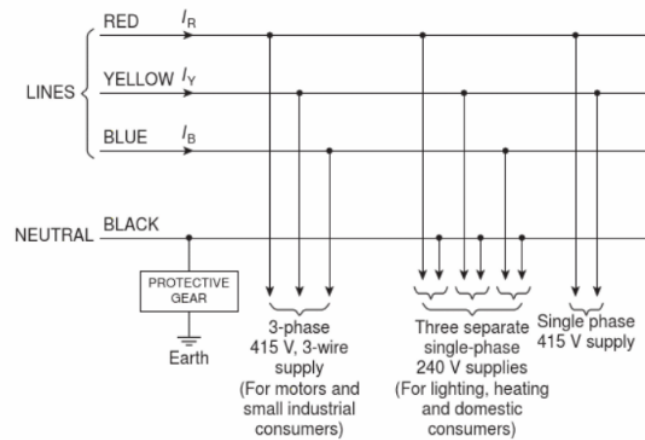


Figure 5 – Circuit diagram of Three-phase supply voltage (Symonds, 1980)

Primary consumers such as large offices and hospitals will require lower voltages of around 13kV and 3.3kV, whereas secondary consumers like small factories will require three-phase 415VAC which will be stepped down via a local transformer. Three-phase double wound transformers are typically used for this, three pairs of single-phase windings are mounted on one core, the primary and secondary windings are mounted on top of each other as concentric cylinders and these windings may be with the primary delta-connected and the secondary star connected, or delta-delta, star-delta or star-star depending on the application. In factories it is most common that the secondary side of the transformer is connected in star, the star point is a reference point for neutral allowing 230VAC to be used between L1, L2 and L3 to neutral. (Electronicstutorials, 2018)

Correctly cited

Excellent research

3. Transformer Investigation

3.1 Open Circuit Test

The first experiment undertaken is the open circuit test to find the transformers iron losses, an explanation is seen in appendix 7.2. The values from the experiment are seen in table 1.

Open Circuit (Iron Losses)		
	Primary	Secondary
Voltage	230V	113V
Current	0.527A	
Power	31.5W	
Power Factor	0.26p.f	

Table 1 – Open Circuit Practical Results

Values obtained from the experiment are substituted into calculations in order to derive component values for the equivalent circuit. These calculations can be seen in appendix 7.3, the component values obtained are seen in table 2.

Open Circuit Component Values	
Rc	1.679K Ω
Xm	451.2 Ω
Ic	0.137A
Im	0.509A
Lm	1.438H
V1	230V
I1	0.527A

Table 2 – Open Circuit Component Values

Using the values obtained from the equations, the equivalent open circuit transformer was designed, this is the first half of the transformer equivalent circuit seen in figure 6.

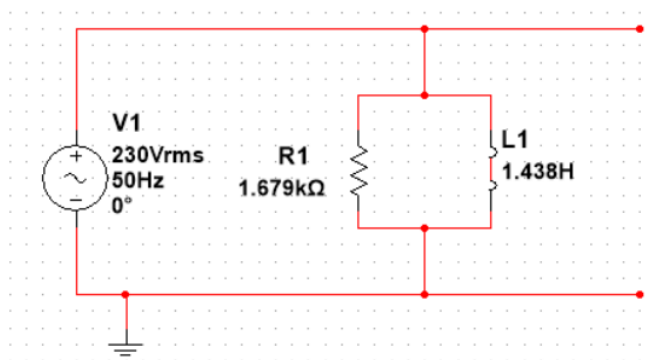


Figure 6 – Open Circuit Equivalent Circuit

3.2 Short Circuit Test

The transformers copper losses are found through the short circuit test, this test is explained in appendix 7.4, and the values obtained from the test are seen in table 3.

Short Circuit (Copper Losses)		
	Primary	Secondary
Voltage (V)	8.98V	
Current (I)	1.72A	3.47A
Power (W)	8.08W	
Power Factor (p.f)	0.52p.f	

Table 3 – Short Circuit Practical Results

Values obtained from the experiment were inserted into the equations seen in appendix 7.5, in order to calculate the component values. The component values obtained are seen in table 4.

Short Circuit Component Values	
Z1E	5.221 Ω
R1E	2.731 Ω
X1E	4.45 Ω
Z2E	1.194 Ω
R2E	0.625 Ω
X2E	1.018 Ω
I2	3.596A
L1E	14.2mH
L2E	3.24mH

Table 4 – Short Circuit Component Values

The equivalent short circuit transformer circuit was designed using the values obtained from the calculations, this is the second half of the transformer equivalent circuit, this will be combined with the open circuit equivalent circuit (Figure 7).

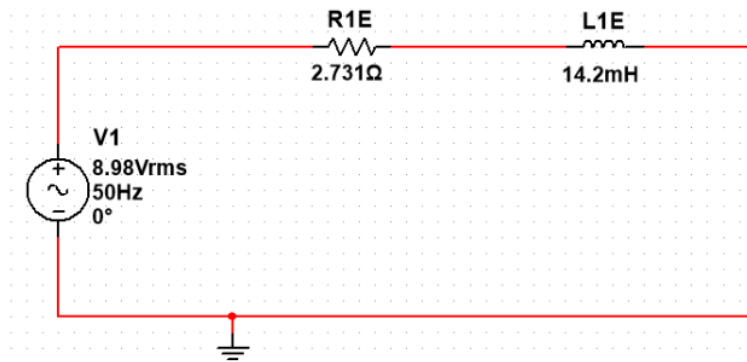


Figure 7 – Short Circuit Equivalent Circuit

3.3 Primary Referred Transformer Equivalent Circuit

The Open and Short circuit equivalent circuits are combined to produce the primary referred transformer equivalent circuit (Figure 8)

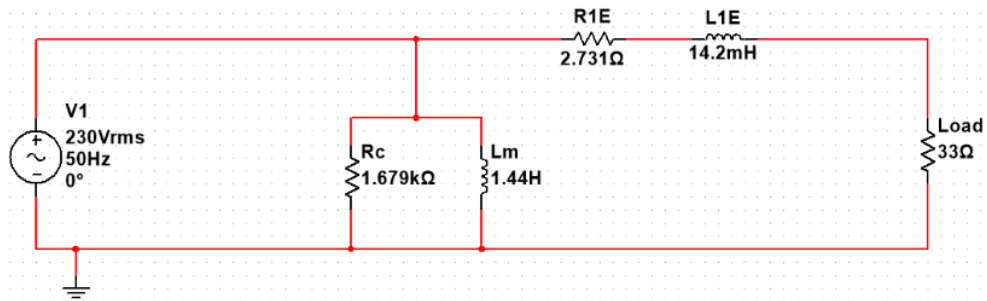


Figure 8 – Transformer equivalent circuit referred to the primary

3.4 Transformer Regulation

When the transformer's secondary is under load, the secondary's terminal voltage V_2 decreases. As the power factor falls, the voltage drop increases. This is the regulation of the transformer, expressed as a percentage by the calculation:

$$Regulation = \left(\frac{E_2 - V_2}{E_2} \right) \times 100$$

The secondary output terminals of the transformer were loaded with various different loads to view the effect that passive components have on the transformer's regulation. These loads are Full Load, Overload and Complex loads of series RL and RC components. For these tests, the equivalent circuit used is referred to the secondary from tables 2 & 4. This circuit with the experimental loads are seen in appendix 7.6.

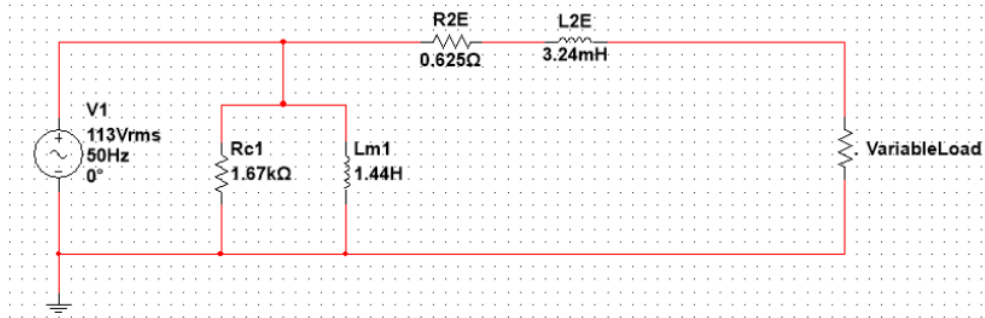


Figure 9 - Transformer equivalent circuit referred to the secondary

The results of the regulation tests are seen in section 3.5.

3.4.1 Transformer Regulation Practical Results

Full Load

Voltage Regulation - Full Load		
	Primary	Secondary
Voltage (V)	230V	110V
Current (I)	1.73A	3A
Power (W)	372W	333W
Power Factor (p.f)	0.93p.f	1

Table 5 – Voltage Regulation Practical Results: Full Load

Over Load

Voltage Regulation - Overload		
	Primary	Secondary
Voltage (V)	230V	108V
Current (I)	2.81A	5.06A
Power (W)	630W	551W
Power Factor (p.f)	0.98p.f	1

Table 6 - Voltage Regulation Practical Results: Overload

Complex RL Load

Voltage Regulation - Complex RL Load		
	Primary	Secondary
Voltage (V)	230V	110V
Current (I)	1.55A	2.26A
Power (W)	208W	177W
Power Factor (p.f)	0.6p.f	0.72p.f

Table 7 - Voltage Regulation Practical Results: Complex RL Load

Complex RC Load

Voltage Regulation - Complex RC Load		
	Primary	Secondary
Voltage (V)	230V	114V
Current (I)	469mA	1.58A
Power (W)	86.3W	69W
Power Factor (p.f)	-0.8p.f	-0.39p.f

Table 8 - Voltage Regulation Practical Results: RC Load

Using the values obtained in the practical experiments, mathematical calculations were derived to predict the voltage regulation of the four loads, these are seen in appendix 7.7. As three different experiments were performed to obtain data, they were compared together for each load type, this is seen in appendix 7.8.

3.5 Transformer Experiment – Testing and Analysis

All of the equivalent transformers were connected to analysis equipment in Multisim in order to test the circuits simulated performance, this can be compared to the experimental results and the results expected from calculations and manufacturer data sheets. For the Open and Short Circuit tests the equivalent circuit is referred to the primary, whereas the load testing is referred to the secondary.

3.5.1 Open Circuit

Figure 10 shows the 'Open Circuit' equivalent circuit with the analysis equipment connected.

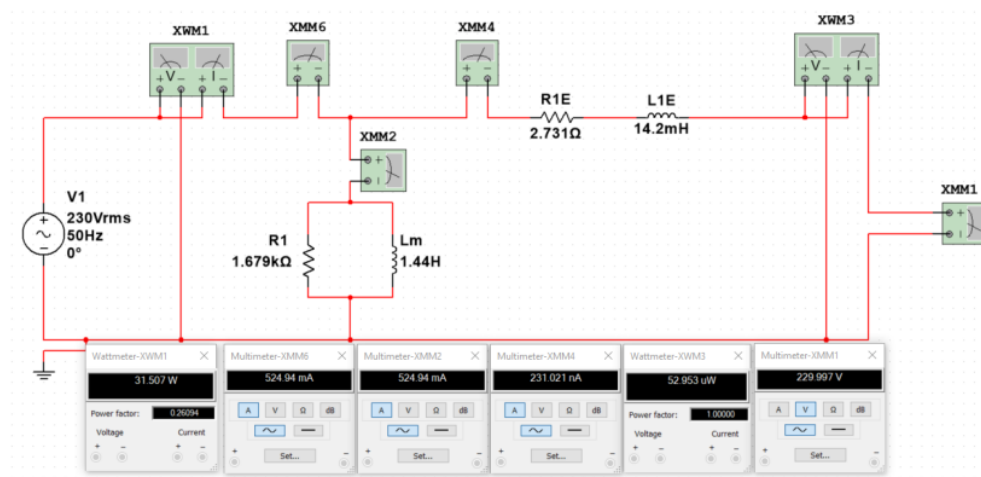


Figure 10 – Transformer Open Circuit Equivalent Circuit under Analysis

As seen in figure 10 and table 9, the experimental, simulated and manufacturers data all coincide with each other with the exception of the datasheets primary power which has a discrepancy of 11.34W, this may be an error on the manufacturers part as both simulation and calculations support each other's results. The only other discrepancy is the Voltage value obtained from the experiment for the secondary Voltage which has an error of 1V to the simulation and 800mV to the datasheet, this is likely due to the Nanovip's accuracy. The datasheet did not supply much information which could be compared, however between the simulation and experiment all values coincide.

Equivalent Circuit - Open Circuit (Iron Losses)						
	Primary			Secondary		
	Experiment	Simulation	Datasheet	Experiment	Simulation	Datasheet
Voltage	230V	230V	230V	113V	114V	113.8V
Current	527mA	525mA				
Power	31.5W	31.5W	20.16W			
Power Factor	0.26p.f	0.261p.f				

Table 9 – Transformer Open Circuit Comparison Results

3.5.2 Short Circuit

Figure 11 shows the ‘Short Circuit’ equivalent circuit with the analysis equipment connected.

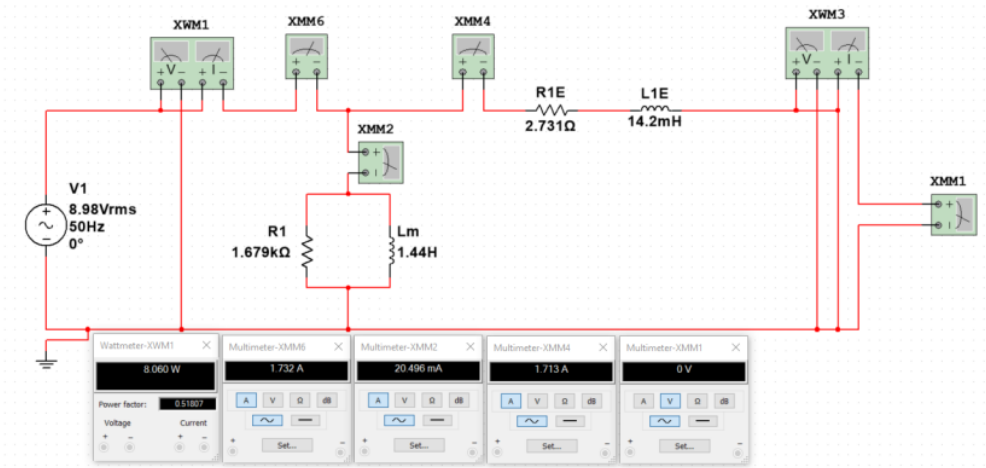


Figure 11 - Transformer Short Circuit Equivalent Circuit under Analysis

Figure 11 and table 10 show that the values obtained are highly accurate with the biggest error between the experiment and simulation being a current discrepancy of 10mA which is negligible, the values obtained for voltage and power factor are highly accurate. Like the open circuit test there is a discrepancy between the datasheets power rating and the experiment and simulation, however for this test is a miniscule discrepancy.

Table 10 - Transformer Short Circuit Comparison Results

Equivalent Circuit - Short Circuit (Copper Losses)						
	Primary			Secondary		
	Experiment	Simulation	Datasheet	Experiment	Simulation	Datasheet
Voltage	8.98V	8.98V				
Current	1.72A	1.73A		3.47A	3.464A	
Power	8.08W	8.06W	9.05W			
Power Factor	0.52p.f	0.518p.f				

3.5.3 Transformer Regulation Comparison

A table was constructed using data obtained from the load testing in appendix 7.8 to calculate the difference each load has on the transformer's regulation. It is known that when the transformer's secondary is loaded, the secondary voltage falls, and as the power factor decreases the volt drop increases, this is typical for Resistive and Resistive-Inductive loads, Capacitive loads have leading power factors, this causes a negative regulation in turn increasing the output voltage of the transformer secondary.

	Regulation Comparison between different loads								
	Practical			Simulation			Calculation		
	E2	V2	%	E2	V2	%	E2	V2	%
Resistive Load	113V	110V	2.66%	113V	110.85V	1.90%	113V	110.06V	2.60%
RL Load	113V	110V	2.66%	113V	110.34V	2.35%	113V	110.31V	2.38%
RC Load	113V	114V	-0.88%	113V	114.1V	-0.97%	113V	114.8V	-1.59%
Overload	113V	109V	3.53%	113V	109.77V	2.89%	113V	108.7	3.81%

Table 11 - Transformer Regulation Comparison Results

The Resistive load performed as expected with the output voltage falling on average by around 2.6% due to the voltage drop across the resistor, this regulation value is typical for small transformers, a discrepancy of 0.7% is seen when comparing the simulation to the practical and calculation, this is likely due to Multisim being highly accurate, whereas errors when rounding calculations and the Nanovip's accuracy cause inaccuracies.

The voltage drop seen for the RL load is expected due to their lagging power factor which causes a voltage drop at the output terminals, along with the volt drop across the resistor. The RL regulation values were generally accurate between the three tests, with the only minor discrepancy being around 0.3% when comparing the practical to the simulation and calculations, the cause of this error is likely due to the reliability of the Nanovip.

The Resistive-Capacitive load produced a negative regulation as expected due to leading power factor of the capacitor, as a result a voltage rise to around 114V is seen at the output. The three test results coincide with each other with small discrepancies, the largest being 0.7% which is minor, this is likely due to errors when rounding calculations, calculating component values in Multisim and the accuracy of the Nanovip.

The overload load caused the biggest regulation out of all the loads as expected, this is due to a greater voltage drop caused by the overload condition drawing more current. Values from the practical and calculation are accurate, however the simulation has a discrepancy of 0.64% to the practical and 0.92% to the calculation, this is likely due to Multisim being highly accurate, whereas the calculated values and practical will have errors due to components and test equipment, and the rounding of calculations.

*Calibration of the
NanoVip*

3.5.4 Transformer Efficiency Comparison

	Efficiency Comparison between different loads					
	Practical			Simulation		
	Pin	Pout	%	Pin	Pout	%
Resistive Load	372W	333W	89.50%	379.4W	372W	98.15%
RL Load	208W	202W	97.12%	206.3W	202.8W	98.31%
RC Load	86.3W	69W	80%	72.8W	71.25W	97.90%
Overload	630W	551W	87.00%	729.7W	696.45W	95.44%

Table 12 - Transformer Efficiency Comparison Results

Using the results obtained for power in and power out from the various load tests, the transformers efficiency under these loads is calculated using the equation:

$$Efficiency = \frac{Power\ Out}{Power\ In} \times 100$$

An ideal transformer has no losses; therefore, an ideal transformer is 100% efficient. However, transformers have load losses and no-load losses which account for this loss of efficiency. Small transformer such as the one used in the experiment can have 97-99% efficiency (Association, 2019). From the results obtained in table 12 it is clearly seen that there are major discrepancies between the practical and simulation this is likely due to the reliability of the Nanovip analyser used in the practical, the largest discrepancy being a 17.9% error between the results from the RC test.

The results obtained from the simulation has produced efficiency results that correspond with the expected results of the transformer used. The resistive and resistive-inductive loads proved to be the most efficient loads as expected, even due to the discrepancies from the practical these loads still produced the best efficiency, the resistive-capacitive load also produced a highly efficient simulated value, only 0.4% less than the RL circuit.

As expected, the Overload load produced the worst efficiency of 95.44%, as the transformer is overloaded it begins to overheat which causes power to be lost in the form of heat, reducing the efficiency. Poor efficiency is expected when overloading a transformer as it is worked above its full load rating, this is seen in table 12 which shows that under overload conditions far greater power was consumed. The overload practical value has a higher efficiency than the RC load which shows displays the unreliability of the Nanovip.

4. Three-phase Induction Motor Investigation

For the three-phase induction motor investigation three tests were undertaken on the motor, these tests were undertaken to obtain values that are substituted into the motor equations in order to derive an equivalent circuit of the motor. These tests are the 'Stator Resistance Test', the 'No-Load Test' and the 'Blocked Rotor Test'.

4.1 Stator Resistance Test

Stator Resistance Test - DC Test			
	L1	L2	L3
Voltage	11.8V	11.8V	11.8V
Current	330mA	330mA	330mA

Table 13 – Induction Motor Stator Resistance Test Results

4.2 No Load Test

No Load Test - Open Circuit			
	L1	L2	L3
Voltage	214V	214V	214V
Current	529mA	529mA	529mA
Power	61.2W	61.2W	61.2W
Power Factor	0.31p.f	0.31p.f	0.31p.f

Table 14 – Induction Motor No Load Test Results

4.3 Blocked Rotor Test

Blocked Rotor - Short Circuit			
	L1	L2	L3
Voltage	25.7	25.7	25.7
Current	489mA	489mA	489mA
Power	19.2W	19.2W	19.2W
Power Factor	0.88p.f	0.88p.f	0.88p.f

Table 15 – Induction Motor Blocked Rotor Test Results

4.4 Three-Phase Induction Motor Equivalent Circuit

From the experiments performed on the induction motor and the calculations undertaken in appendix 7.9-7.11, the component values for the motor equivalent circuit were calculated as seen in table 16, the equivalent circuit is seen in appendix 7.12.

Equivalent Induction Motor Component Values	
Component	Value
V1	214V
I1	529mA
R1	35.75 Ω
Rc	2245.9 Ω
Xm	737.5 Ω / 2.35mH
Io	305.4mA
R2'	44.73 Ω
X1+X2'	42.16 Ω / 136.1mH
Isc	282mA

Table 16 – Induction Motor Equivalent Circuit Values

4.5 Three Phase Induction Motor – Testing and Analysis

4.5.1 Torque vs Slip - Calculated

Using the values obtained in the motor test the total torque value can be calculated with the equation below as a function in excel. The theory states that torque is proportional to slip when the slip is between 0 and 0.1. This test is undertaken to investigate the effects that various values of slip have on the induction motors torque and to prove the validity of this theory.

$$Total Torque = \frac{3 VI^2 R2'}{\omega s \left[\left(R1 + \frac{R2'}{s} \right)^2 + (X1 + X2')^2 \right]}$$

Figure 12 depicts the results of the experiment seen in appendix 7.13. It is clearly seen that value of torque is proportional to the value of slip, Slip is the difference between rotor speed and synchronous speed. When the slip and torque is negative the motor is in its 'Generating Mode' whereby the rotor runs at a faster speed than the magnetic field, therefore the motor creates mechanical power which is then generated into electrical power. When the slip and torque are in their positive quadrant up to a slip value of 1 the motor is in its 'Motoring Mode' where the magnetic field drives the rotor at below synchronous speed, in this mode electrical power is used to produce mechanical power. At a Slip value of over 1 it is seen that the motor enters 'Braking Mode' whereby the polarity reverses causing the motor to rotate in reverse stopping it, this method of braking is known as 'plugging' (Electrical4U, 2020). It can be seen that the torque is directly proportional to slip when the slip value is between 0 and 0.15, this is seen as the curve produced has a linear line between torque and slip at these values, which confirms the theory.

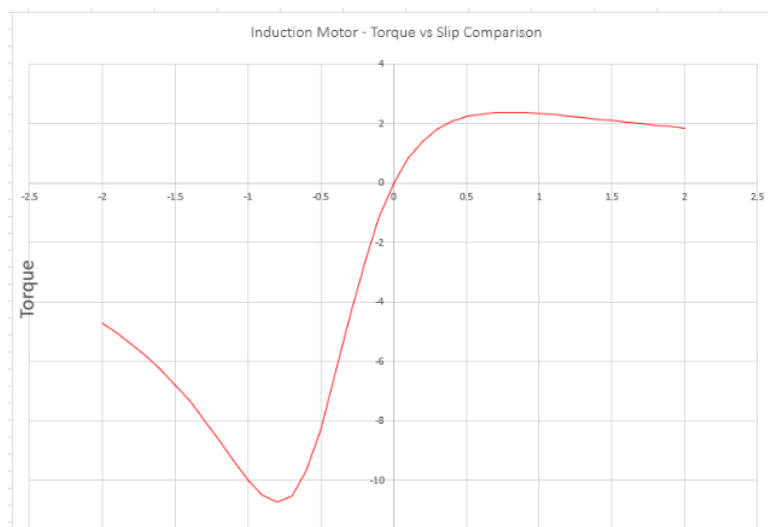


Figure 12 – Induction Motor Calculated Torque vs Slip Comparison Graph

4.5.2 Torque vs Slip - Practical

The theory that the value of Slip and Torque are proportional is further confirmed by the graph plotted using values obtained from the test seen in appendix 7.14. The graph produced from these values in figure 13 clearly shows that Slip is proportional to torque, there is a minor discrepancy between 0 and 0.2Nm, however this is likely due to user error when reading out the results at quick intervals, from 0.2Nm to 0.8Nm it is accurately seen that slip and torque are proportional.

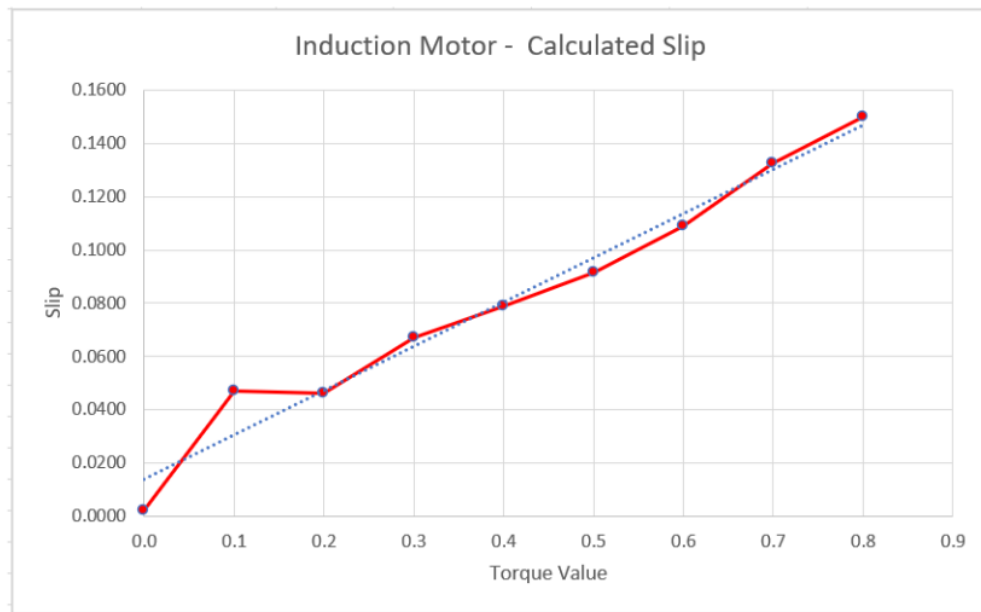


Figure 13 - Induction Motor Practical Torque vs Slip Comparison Graph

4.5.3 – Driving an Induction Motor via an external source

The induction motor was then externally driven in order for it enter 'Generating Mode' by driving at above the rated synchronous speed. The results table from this test is seen in appendix 6.15, the graph from these results is seen in figure 14.

It is seen that when the motor is driven at synchronous speed it has a positive power factor as the machine is not generating, as the motor is driven over synchronous speed and enters its generating mode it produces a negative power factor which is relative to the RPM, this is due to the principle of power factor that when a machine generates its own power which flows back to the source, creating a negative power factor. It is seen in figure 14 that the higher RPM that the motor runs at causes the negative power factor to increase, proving that the motors speed is relative to power factor.

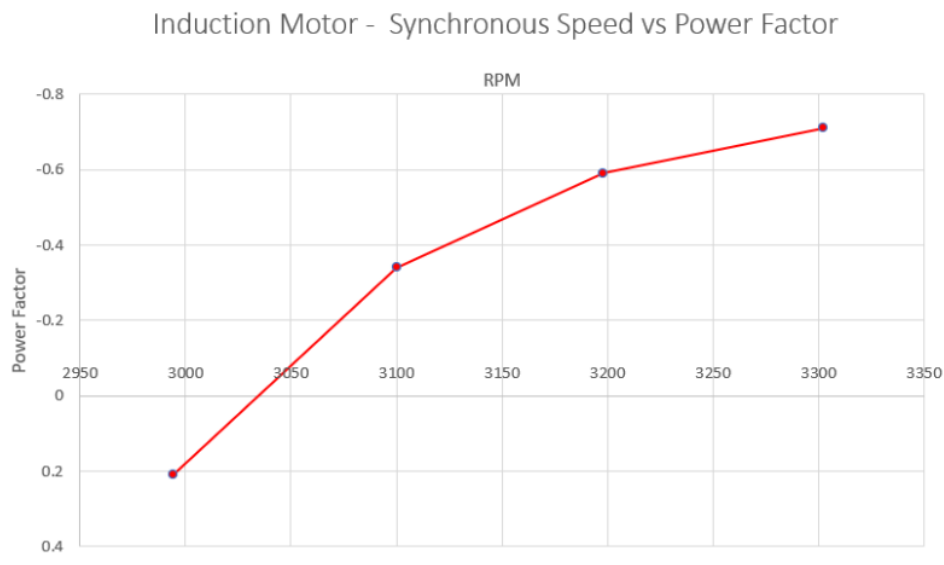


Figure 14 – Synchronous Speed vs Power Factor Graph

5. Conclusions and Recommendations

From an overall point of view in terms of the calculations, results and observations undertaken, this report has proved successful. Comprehensive research was undertaken based around induction machine speed control using PECs, industrial applications of induction machines and the power systems needed to supply three-phase power to industrial factories, this research laid a basis for the tasks undertaken in this report as it presented a background to why the machines investigated are used in industry.

The first experimental task undertaken was the investigation into the Single-Phase Transformer was successful, Important aspects of testing and analysis were undertaken on the transformers. Mathematical skills were developed when deriving the equations in order to construct the equivalent circuit, along with analytical skills when comparing experiments, calculations, predictions, simulations and data sheets. For a large section of the task the results obtained were highly accurate when comparing the short circuit open circuit and load tests between experiments, simulation and calculations. Minor discrepancies are seen when comparing some of these to the manufacturer's datasheet, however it is hard to accurately compare to the datasheet as the parameters under which they tested the transformer are unknown. The tests undertaken for the transformer's regulation was successful, it was predicted that the resistive load would have the highest regulation, this was proven with a value of 2.6%, the RC circuit was predicted to have a negative regulation due to the leading power factor that the capacitor has which power to flow back to the source, causing the output voltage to rise, this was confirmed by the three various tests undertaken which all prove this theory correct. A further prediction that the overload condition would cause the poorest regulation was also proven as seen in table 11. When comparing the transformers efficiency, it was clearly seen that the practical results had large discrepancies when compared to the simulation, this is due to the accuracy of the Nanovip instrument used, when comparing the theory to the simulated results there was an overlap proving the accuracy.

The second experiment undertaken on the three-phase induction motor was highly successful. From the research undertaken key principles about the applications and control methods of induction motors was understood, laying a basis whereby the experiment was built upon. The tests were successfully undertaken, these being the 'No-Load', 'Blocked Rotor' and 'Stator Resistance' tests, from these values the equivalent circuit parameters were successfully calculated. Further tests were undertaken to investigate the relationship between the key properties of the three-phase motor, these being Torque vs Slip and RPM vs Power Factor. From these results undertaken it was seen that torque and slip are directly proportional to each other, from research and the practical experiment analysis of the torque vs slip response was undertaken, from this it was learnt that the motor is in generating mode when the slip and torque are negative due to the rotor running faster than the magnetic field causing the mechanical power produced to generate electrical power. From the research and practical undertaken it was seen that when the values of slip and torque are positive the motor is in its motoring phase whereby the magnetic field is driving the rotor below synchronous speed turning electrical power into a mechanical output power, this phase only happens up to a slip value of 1, when the value of slip increases above 1 the motors polarity reverses causing the motor to rotate in the opposite direction, this is plug braking.

From this report it was also seen that the RPM of the motor and Power Factor are also proportional. From the results obtained from the test undertaken it was seen that when a motor is externally driven passed its synchronous speed it produces a negative power factor as it has entered generating mode.

As a recommendation the transformer experiments could have been repeated with a full calibrated analyser which would have produced a more reliable set of results to compare the predictions, calculations and simulations against in turn strengthening the reliability of the analysis undertaken, However, due to the global pandemic this was not a viable option.

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Good range of sources

7. Appendix

Appendix 7.1 – Transformer Data Sheet

RS Part No		260-4244
Transformer Type		CM7501
Continuous Output Rating (VA)		375
Intermittent, 5 mins on 15 mins off. (VA)		750
Primary Voltage (V)		230
Frequency		50/60Hz
Off-Load Secondary Volts (V)		113.8
Full-Load secondary Volts (V)		109.6
Regulation at Continuous Rating		4%
Efficiency at Continuous Rating		90%
Iron Loss (Watts)		20.16
Copper Loss at Continuous rating	Primary (Watts)	9.05
	Secondary (Watts)	10.74
Insulation Resistance at 2kV for 1 Minute		>200M Ω
Flash Test Voltage for 1 minute		2kV
Primary Winding Resistance at 20 °C		1.79 Ω
Secondary Winding Resistance at 20 °C		0.52 Ω
Winding Temperature Rise	Primary (°C)	96
	Secondary (°C)	89
Primary Thermal Circuit Breaker Rating		3Amp
Dimensions, Width x Depth x Height (mm)		160x210x220
Weight (Kg)		9
Output Sockets		1x16A BS EN 60309

Figure 15 – Transformer Datasheet (Meynell, 2020)

Appendix 7.2 – Open Circuit Test

The open circuit test is used in order to find the “Iron Losses” within the transformer, Iron losses are constant for given values of frequencies and flux density, Iron losses comes under two types: Hysteris loss and Eddy current loss. Hysteresis loss is heat loss within the transformer core due to alternating magnetic flux, eddy current loss is also a loss of heat due to EMF being induced within the core causing circulating current and due to the low resistance of the core a considerable amount of power can be lost.

As the transformer in testing is 230Vac to 110Vac, a 230Vac supply from a variable power supply was connected to the primary side of the transformer whilst the secondary side of the transformer was left as open circuit.

A “Nanovip” analyser is used to measure the Voltage (V), Current (I), Power (W) and Power Factor (P.F). Using a Nanovip analyser was connected to the transformers primary line conductor in order to obtain values for Voltage, Current, Power Factor and Watts, the analyser was clamped around the secondary's line conductor to attain the voltage rating.

Appendix 7.3 – Transformer Open Circuit Calculations

$$R_c = \frac{!V_1!^2}{P_{in}} = \frac{230^2}{31.5} = 1679.37\Omega$$

$$I_c = \frac{!V_1!}{R_c} = \frac{230}{1679.37} = 0.137 \text{ A or } 137\text{mA}$$

$$I_m = \sqrt{I_{O^2} - I_c^2} = \sqrt{0.527^2 - 0.137^2} = 0.509\text{A}$$

$$X_m = \frac{!V_1!}{I_M} = \frac{230}{0.509} = 451.9\Omega$$

$$L_m = \frac{X_M}{2\pi f} = \frac{451.9}{100\pi} = 1.438\text{H}$$

Appendix 7.4 – Short Circuit Test

The short circuit test is also known as the copper losses test, Copper losses are variable and result due to heat energy dissipated due to the heating of the transformers conductors due to their natural resistance, R_1 is the primary resistance and R_2 is the secondary resistance therefore the total copper loss is $I_1^2 \cdot R_1 + R_2$.

For this test the transformers primary was connected to the variable power supply (PSU), The secondary of the transformer was also connected to the PSU, however live and neutral were connected to create a short circuit condition. The maximum current that the secondary can draw was calculated using information from the transformers data sheet in appendix 7.1, $I = \frac{P}{V} = \frac{375}{110} = 3.41A$

Using the “Nanovip” analyser connected to the secondary line wire, using the variable power supply the voltage was adjusted slowly until the secondary was drawing its maximum rated current of 3.41A, Once the analyser was reading the rated current the values for the primary and secondary circuit were obtained.

Appendix 7.5 – Transformer Short Circuit Calculations

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

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

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

$$L_{1E} = \frac{X_{1E}}{2\pi f} = \frac{4.45}{100\pi} = 2.731\Omega$$

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

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

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

$$I_2 = \frac{N_1}{N_2} * I_1 = \frac{230}{110} * 1.72 = 3.596A$$

Inappropriate use of the equals sign, they can't all be

equal

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

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

Appendix 7.6 – Regulation Test Explanation and Equivalent Circuits

Full Load

The full load test is performed to investigate how the transformer performs at its rated full load. A 33Ω resistor is connected across the transformers secondary output terminals as seen in figure 16.

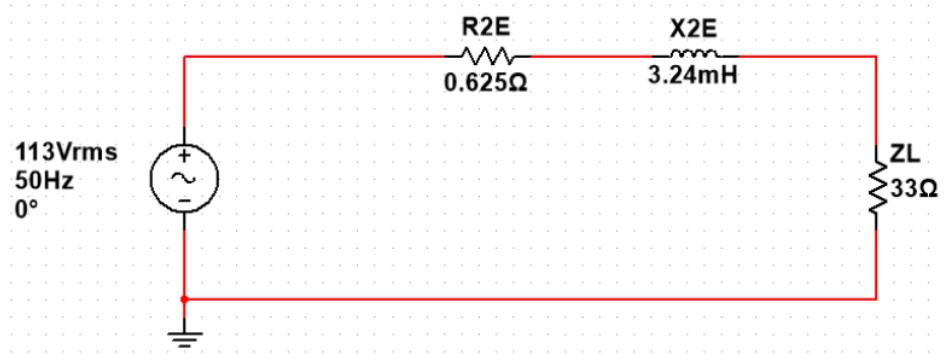


Figure 16 – Regulation Equivalent Circuit: Full Load

Overload

An overload test is also performed to investigate how the transformer performs at a load that is rated higher than its full load specification. In order to perform this test, the load resistor from the full load test is halved in order for the transformer to draw more current than rated, mimicking an overload condition. (Figure 17)

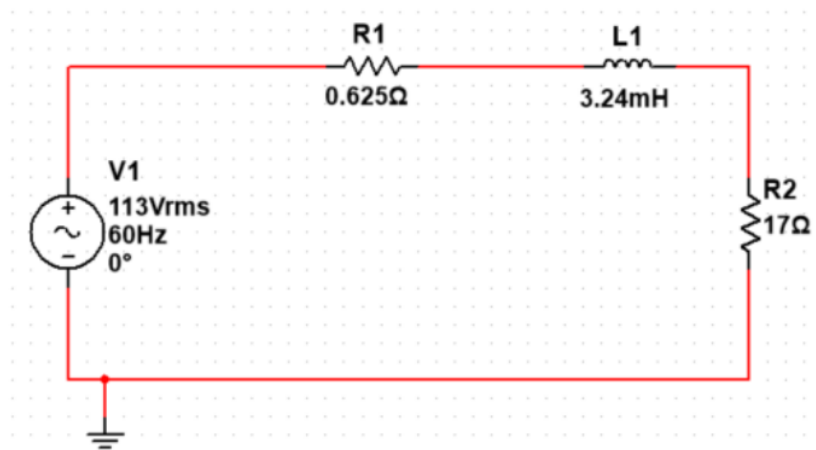


Figure 17 - Regulation Equivalent Circuit: Overload

Complex Load

The load on the secondary of the transformer may not always be purely resistive, tests were undertaken through calculation in order to predict how the transformer will cope under complex loads.

RC Load

The first complex load is the RC circuit, this consists of the regulation equivalent circuit with a 28.3Ω resistor and a $48\mu\text{F}$ capacitor in series across the load. The complex RC equivalent circuit is seen in figure 18.

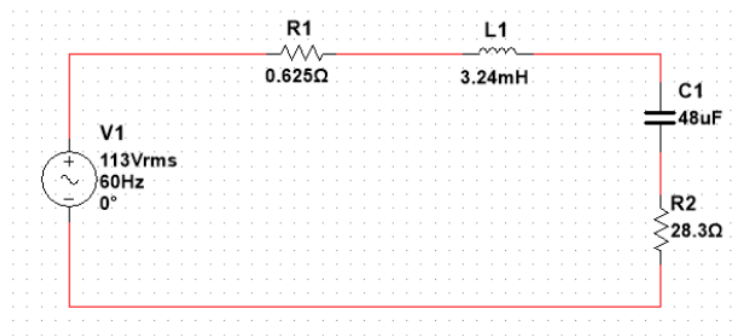


Figure 18 - Regulation Equivalent Circuit: Complex RC Load

RL Load

The second complex load is an RL load, this has a 36.5Ω resistor and a 3.24mH inductor in series across the load. Figure 19 shows the equivalent Multisim of the complex RC circuit.

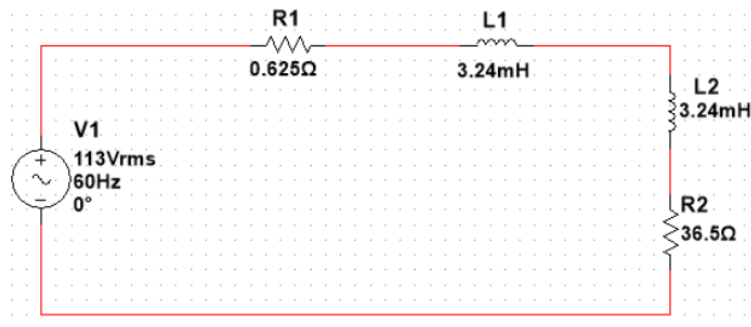


Figure 19 - Regulation Equivalent Circuit: Complex RL Load

Appendix 7.7 – Voltage Regulation Calculations

Full Load

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

$$\begin{aligned}\% \text{ Regulation} &= \frac{I_2 (R_2 E \cos \phi_2 \mp X_2 E \sin \phi)}{V_2} \times 100 = V_2 \\ &= E_2 - I_2 (R_2 E \cos \phi_2 \mp X_2 E \sin \phi)\end{aligned}$$

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

Over Load

$$\phi = \cos^{-1}(0.98) = 11.48^\circ = \sin(11.48) = 0.199$$

$$\begin{aligned}\% \text{ Regulation} &= \frac{I_2 (R_2 E \cos \phi_2 \mp X_2 E \sin \phi)}{V_2} \times 100 = V_2 \\ &= E_2 - I_2 (R_2 E \cos \phi_2 \mp X_2 E \sin \phi)\end{aligned}$$

$$V_2 = 113 - 5.06 (0.625 \times 0.98 + 1.018 \times 0.199) = 108.88V$$

RL Load

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

$$\begin{aligned}\% \text{ Regulation} &= \frac{I_2 (R_2 E \times \cos \phi_2 \mp X_2 E \sin \phi)}{V_2} \times 100 = V_2 \\ &= E_2 - I_2 (R_2 E \times \cos \phi_2 \mp X_2 E \sin \phi)\end{aligned}$$

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

RC Load

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

$$\begin{aligned}\% \text{ Regulation} &= \frac{I_2 (R_2 E \times \cos \phi_2 \mp X_2 E \sin \phi)}{V_2} \times 100 = V_2 \\ &= E_2 - I_2 (R_2 E \times \cos \phi_2 \mp X_2 E \sin \phi)\end{aligned}$$

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

Appendix 7.8 – Load Testing and Analysis

Full Load – Testing and Analysis

Figure 20 shows the 'Full Load' equivalent circuit which is referred to the secondary, with the analysis equipment connected.

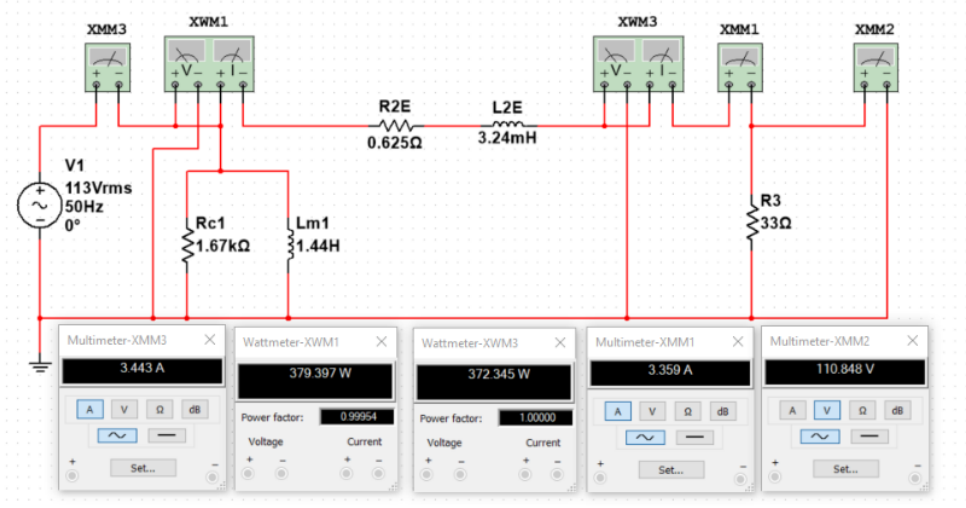


Figure 20 – Transformer Full Load Testing and Analysis

Figure 20 and table 17 show that for the 33Ω load test there are discrepancies between the experimental and simulated values for current and power of 0.36A and 39.35W respectively, data obtained for voltage has a 0.85V error when comparing the simulation to the calculation and experiment. These errors are likely due to errors during the experiment or rounding errors from calculations causing simulation components to have discrepancies.

Voltage Regulation - Resistor Load						
	Primary			Secondary		
	Experiment	Simulation	Calculated	Experiment	Simulation	Calculated
Voltage	230V			110V	110.85V	110V
Current	1.73A			3A	3.36A	
Power	372W			333W	372.345W	
Power Factor	0.93p.f			1p.f	1p.f	

Table 17 - Transformer Full Load Testing Comparison Table

Over Load – Testing and Analysis

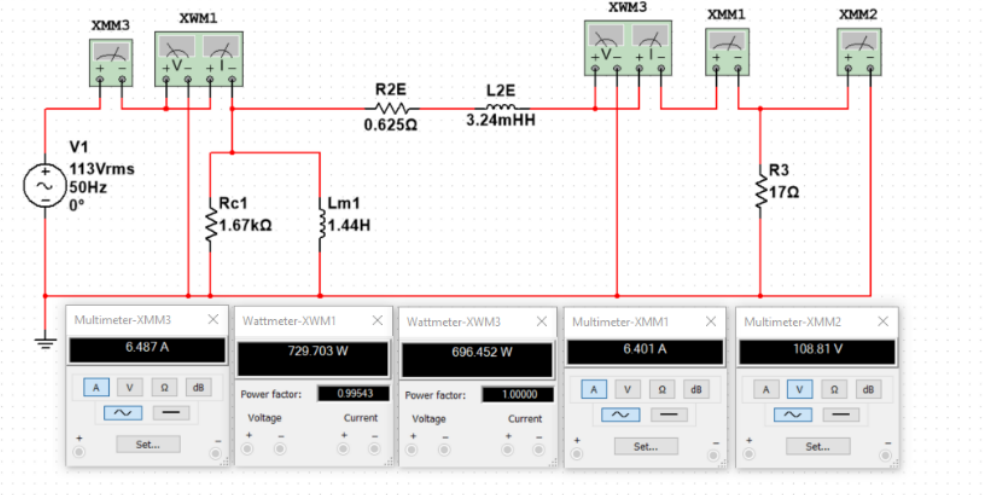


Figure 21 - Transformer Overload Testing and Analysis

Figures 21 and table 18 display the voltage regulation overload test, the values obtained for power factor and voltage are highly accurate between simulations, experiments and calculation. However, there are large errors between the experiment and simulation for current and power with differences of 1.341A and 145.45W respectively, this is likely due to experimental accuracy or calculation errors from rounding to enable simulated components to be slightly wrong. As expected under overload conditions the output voltage has dropped by around 2V to 108V compared to normal loading conditions of 110V.

Voltage Regulation - Overload						
	Primary			Secondary		
	Experiment	Simulation	Calculated	Experiment	Simulation	Calculated
Voltage	230V			108V	108.8V	108.7
Current	2.81A			5.06A	6.401A	
Power	630W			551W	696.45W	
Power Factor	0.98p.f			1	1	

Table 18 - Transformer Overload Testing Comparison Table

RL Load – Testing and Analysis

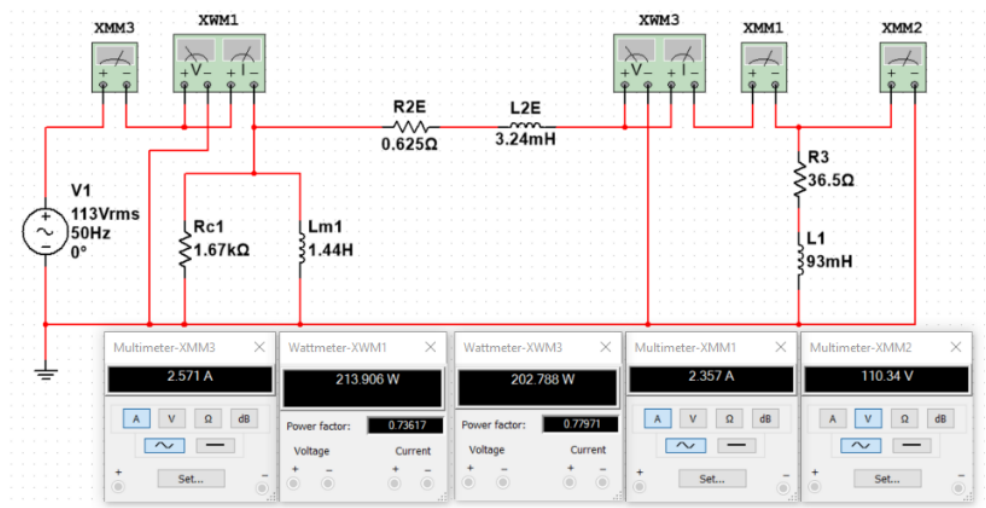


Figure 22 - Transformer RL Load Testing and Analysis

As seen in figure 22 and table 19 the RL complex load test was relatively accurate. A discrepancy of 0.3V was found between the experiment and the simulation and calculation. Discrepancies were also found between simulation and experiment, a 97mA current discrepancy along with a 25W power discrepancy and minor difference power factor difference of 0.06p.f. This is likely due to rounding errors in calculations or due to the Nanovip accuracy.

Voltage Regulation - Resistor Inductor Load						
	Primary			Secondary		
	Experiment	Simulation	Calculated	Experiment	Simulation	Calculated
Voltage	230V			110V	110.34V	110.3V
Current	1.55A			2.26A	2.357A	
Power	208W			177W	202W	
Power Factor	0.6p.f			0.72p.f	0.78p.f	

Table 19 - Transformer RL Load Testing Comparison Table

RC Load – Testing and Analysis

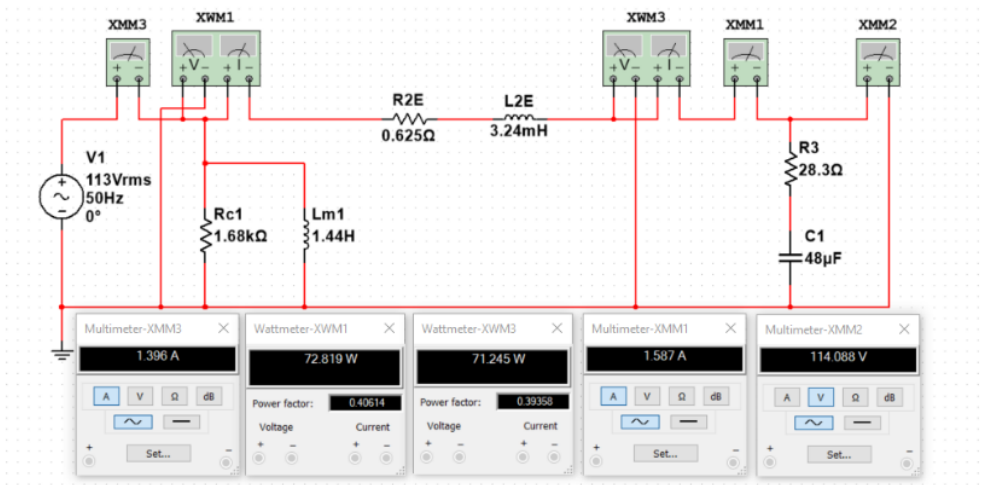


Figure 23 - Transformer RC Load Testing and Analysis

The final tested complexload is the RC load. For the RC load, the only minor discrepancy is for the power, this has an error of 2.25W between simulation and experiment. The voltage data is accurate throughout with the largest error being 0.1V. Current and Power Factor readings are identical. Discrepancies are likely due to the Nanovip accuracy and rounding errors when calculating the component values for the simulation. The output voltage of the RC load is higher than the no-load voltage, this is expected due to the capacitor resonating with the magnetizing inductance of the transformer causing an extra shunt capacitance increasing the output voltage.

Voltage Regulation - Resistor Capacitor Load						
	Primary			Secondary		
	Experiment	Simulation	Calculated	Experiment	Simulation	Calculated
Voltage	230V			114V	114.1V	114.76
Current	469mA			1.58A	1.587A	
Power	86.3W			69W	71.25W	
Power Factor	-0.8p.f			-0.39p.f	-0.39p.f	

Table 20 - Transformer RC Load Testing Comparison Table

Appendix 7.9 – Stator Resistance Test and Calculations

The first test is the 'Stator Resistance Test'. A Low DC Voltage of 11.8V is applied to the stator, As the applied voltage is DC there will be no voltage induced in the rotor and no current will flow, thus the per-phase circuit is reduced to the stators winding resistance, from applying this DC voltage to the motor and measuring the current drawn, the resistance can be calculated. Values obtained from this test is seen in the main report, whereas the calculation for R1 needed for the motor equivalent circuit is seen below.

For the stator resistance test, the value of R1 is calculated:

$$R1 = \frac{V}{I} = \frac{11.8}{330 \times 10^{-3}} = 35.75 \Omega$$

Appendix 7.10 – No Load Test and Calculations

The no load test is undertaken to find the magnetizing reactance, friction loss, winding loss and core loss resistance to be calculated, this is performed with no load on the motor shaft. Instead, a separate motor is connected to the primary motor's shaft in order to help the motor reach synchronous speed. Wattmeter's, Ammeters and Voltmeters were used in order to obtain per-phase readings of Power Factor, Wattage, Voltage and Current. Values obtained from the tests are seen in the main report, Calculations for the equivalent circuit values derived from this test are seen below.

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

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

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

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

$$\sin \phi(71.82) = 0.9501$$

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

$$X_m = \frac{V_0}{I_0 \times \sin \phi} = \frac{214}{305 \times 10^{-3} \times 0.9501} = 737.5 \Omega$$

$$X_m = 2\pi f L = L_m = \frac{X_m}{2\pi f} = \frac{737.5}{2\pi \times 50} = 2.35 \text{H}$$

Appendix 7.11 – Blocked Rotor Test and Calculations

The blocked rotor is undertaken by locking the shaft of the induction motor so that it cannot move and the rotor winding is short circuited through the slip rings. A low AC voltage is applied to the stator in order for full current to flow. Using Ammeters, Voltmeters and Wattmeter's values for current, wattage, power factor and voltage are obtained.

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

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

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

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

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

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

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

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

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

$$X_1 + X_2' = 2\pi f L = Lm' = \frac{X_1 + X_2'}{2\pi f} = \frac{42.76}{2\pi \times 50} = 0.1361 \text{H or } 136.1 \text{mH}$$

Appendix 7.12 – Three Phase Motor Equivalent Circuit

Figure 24 shows the equivalent circuit for the Three-Phase induction motor as derived by the three tests seen in appendix 6.9-6.11.

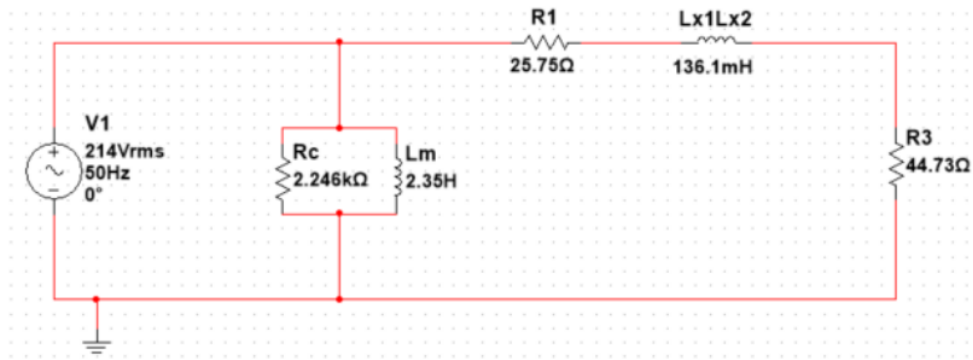


Figure 24 – Three-Phase Motor Equivalent Circuit

Appendix 7.13 – Torque vs Slip Test Results

Torque Vs Slip Test		
Slip	Torque	RPM
-2	-4.72583	9000
-1.9	-5.048904	8700
-1.8	-5.41068	8400
-1.7	-5.816453	8100
-1.6	-6.271652	7800
-1.5	-6.781164	7500
-1.4	-7.347979	7200
-1.3	-7.970616	6900
-1.2	-8.638534	6600
-1.1	-9.324506	6300
-1	-9.973284	6000
-0.9	-10.4883	5700
-0.8	-10.7246	5400
-0.7	-10.50694	5100
-0.6	-9.6941	4800
-0.5	-8.277202	4500
-0.4	-6.43466	4200
-0.3	-4.466766	3900
-0.2	-2.652348	3600
-0.1	-1.15088	3300
0	#DIV/0!	3000
0.1	0.8361983	2700
0.2	1.4204281	2400
0.3	1.8153295	2100
0.4	2.0729816	1800
0.5	2.233128	1500
0.6	2.3248022	1200
0.7	2.3687489	900
0.8	2.3796372	600
0.9	2.3678002	300
1	2.3405146	0
1.1	2.3029117	-300
1.2	2.2586162	-600
1.3	2.2101919	-900
1.4	2.1594521	-1200
1.5	2.1076775	-1500
1.6	2.055768	-1800
1.7	2.0043507	-2100
1.8	1.9538567	-2400
1.9	1.9045755	-2700
2	1.8566942	-3000

Table 21 – Torque Vs Slip Calculation Results

Appendix 7.14 - Induction Motor Synchronous Speed Test Results

Induction Motor Synchronous Speed Tests					
	Speed (rpm)	Voltage (V)	Current (mA)	Power (W)	Power Factor (P.F)
Synchronous Speed	2994	214	536	42.1	0.21
Over Synchronous Speed	3100	216	628	81.2	-0.34
Over Synchronous Speed	3198	217	843	187	-0.59
Over Synchronous Speed	3302	218	1130	304	-0.71

Table 22 - Induction Motor Synchronous Speed Tests Results

Appendix 7.15 – Induction Motor Slip Test Results

Induction Motor - Slip Test						
Speed (rpm)	Torque (Nm)	Slip	Voltage (V)	Current (mA)	Power (W)	Power Factor (P.F)
2994	0.0	0.0020	214	536	42.1	0.21
2859	0.1	0.0470	213	628	154	0.66
2862	0.2	0.0460	213	633	161	0.65
2799	0.3	0.0670	212	720	201	0.76
2764	0.4	0.0787	212	811	238	0.81
2725	0.5	0.0917	212	872	268	0.84
2673	0.6	0.1090	211	989	314	0.87
2602	0.7	0.1327	211	1120	368	0.89
2550	0.8	0.1500	211	1240	409	0.9

Table 23 - Induction Motor Synchronous Slip Test Results

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FINAL GRADE

GENERAL COMMENTS

Instructor

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PAGE 43

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PAGE 46

PAGE 47

GRADING FORM: NEW CSG-RUBRIC

THOMAS GRENNAN

77

1. ENGAGEMENT WITH LITERATURE



Exceptional engagement with an extensive range of relevant and credible literature. High-level referencing skills consistently applied. (17/20)

17

2. KNOWLEDGE AND UNDERSTANDING

- | | | |
|---|---|-----------|
|  | Excellent, detailed knowledge and highly critical understanding of the well-established concepts and principles of the subject and the main methods of enquiry. (16/20) | 16 |
|---|---|-----------|

3. COGNITIVE AND INTELLECTUAL

- | | | |
|---|---|-----------|
|  | Excellent critical evaluation and analysis of concepts and principles leading to logical, evidence-based, reasoned arguments and judgements. Explicit recognition of other stances and a strong awareness of the limits of their knowledge. A capacity for independent thought and ability to 'see beyond the question', suggesting some grasp of the broader field and wider concepts. (16/20) | 16 |
|---|---|-----------|

4. PRACTICAL APPLICATION

- | | | |
|---|---|-----------|
|  | Exceptional levels of application and deployment skills using established methods, materials, tools and/or techniques. Consistent, accurate and logical application of theory to practice, making highly developed links between the two. Can identify routine and non-routine problems and propose quite sophisticated, creative solutions outside the context in which they were first studied. (17/20) | 17 |
|---|---|-----------|

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. (16/20) Word count penalty applied (-5)