

Assignment 1

by Gareth Wilkins

GOOD RESEARCH, BUT OVER-RELIANT ON (A HURLES 2013).
VERY GOOD KNOWLEDGE AND CRITICAL ANALYSIS WAS
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1. Executive summary

This report investigates polyphase machines utilised in industry and the distribution system. Industrial applications of the induction motor were researched and the methods of speed control available was investigated. The induction motor was found to be prevalent in industry due to its versatility and ruggedness. With the advancement in variable frequency drives AC motors hold a large segment of the variable speed motor market. Investigation was performed on the power systems necessary to allow the safe and continual supply of electrical power to the end users. Transmission lines, substations and circuit breaker operation was explored.

Practical experimentation was conducted in groups on a single-phase transformer and a polyphase motor. The tests performed on the transformer were the open circuit and short circuit test to obtain values for the equivalent circuit. These results allowed the comparison of the equivalent circuit and physical transformer voltage regulation under different loads. The three-phase motor was subjected to stator resistance, no-load and blocked rotor test to obtain values for the equivalent circuit. The equivalent circuit calculations and physical motor measurements involving the torque slip curve were compared. It was found that the transformer and three phase motor have similar qualities which resulted in the equivalent circuits being similar with only minor adaptations required to represent the motor.

A conclusion was produced observing the significant findings most notably the close relationship between the transformer and induction motor. Also, the equivalent circuit was discussed with its ability to predict the performance of machines. Recommendations were proposed such as improved test equipment and an additional braking test would have benefited the investigation.

2. Research

2.1 Induction machine speed control methods using power electronic converters

AC drive control generally necessitate complex control algorithms which are computed by microprocessors utilising fast switch power converters. To achieve variable speed control the frequency, voltage and current must be controlled (Rashid, 2014). The function of the electronic converter is to obtain electrical power from the utility source and supply the motor with the required voltage and frequency to attain the desired mechanical output. The desired mechanical output can be any system variable including motor speed, torque or position. The electronic converter has two distinct elements being the power stage and control segment. The power stage provides the energy flow to the motor and the control regulates the power flow (A Hughes, 2013). Correctly cited

Induction motors have various drive topologies with the most prevalent in industry comprising a diode bridge rectifier and a PWM voltage source inverter (VSI). The switching device utilised in the inverter bridge for lower powered inverters is the MOSFET. Insulated-gate bipolar transistors are employed for medium to large inverters where switching is performed at higher frequencies. It is worth noting the higher the switching frequency the greater the losses in the inverter resulting in decreased efficiency. Inverter operation varies with output frequency available from 0Hz up to several hundreds Hz. The form of control is the limiting factor for the low frequency constraint while the physical size of the power electronic and control restrict the higher frequencies (A Hughes, 2013). Correctly cited

The act of converting D.C to A.C. is known as inversion. Ideally inversion would produce a sinusoidal output voltage with the desired frequency and amplitude however due to the switching strategy imposed a voltage waveform of rectangular chunks is produced. Nevertheless a.c. motors are extremely tolerant to this coarse waveform and function satisfactorily. The majority of a.c. drives are connected to standard induction motors which were designed to operate at a fix speed (A Hughes, 2013). Correctly cited

The converter is fed control signals which indicates the desired output, while the feedback signal provides a measurement of the actual output. The desired and feedback signals are compared and adjustment to the output is performed to ensure the desired output is maintained. All drives utilise current feedback to regulate motor torque. The speed of the motor is derived from motor parameter measurements of voltage, currents and frequency calculated with the stored mathematical model of the motor (A Hughes, 2013).

2.2 Industrial applications of induction machines

The induction motor has extensive industrial and domestic applications estimated to account for approximately 50% of all electric consumption. (Hughes, 2016) The three-phase induction motor is extensively employed in industry due to its simplicity, ease of maintenance, ruggedness, and low price. (Wildi, 2014) The three-phase induction motor plays a vital role in industry driving machinery, fans, compressors to name a few of the many routine but critical tasks. This motor dominates the fixed speed market but with the obtainability and dependability of variable speed drives (VFDs) they also account for a significant stake of the controlled speed arena (A Hughes, 2013). Correctly cited

The torque/speed characteristic curve portrays the mechanical characteristic of a motor. The steady state torque speed curve, the effective inertia seen by the motor and the dynamic performance determine the selection of the appropriate motor and drive. Motor loads are typically categorised as “constant load” or “fan or pump type load” (A Hughes, 2013).

The hoist is a constant-torque load where the torque demanded differs with the load but not with the speed of hoisting. The steady state motor performance is obtained from the product of torque and angular velocity. (A Hughes, 2013)

The fan load torque characteristic is regularly approximated by assuming the torque required is proportional to the square of speed, with the power being proportionate to cube of speed. Nevertheless, this approximation is only true at high speeds where breakaway torque must be overcome during start up. Most fans are required to operate almost continuously at rated speed, therefore no speed control is needed and can be served by utility-frequency induction motors. The centrifugal pump has a similar characteristic to that of the fan. At start up the pump must overcome the viscosity of the liquid. Once this initial load has been overcome the load is proportionate to the square of the speed. (A Hughes, 2013) Correctly cited

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

The power supply system is the foundation of all industrial countries. The power system is an interconnection of complex networks which transmits and distributes generated electricity (Hughes, 2016). Generators are interconnected to provide overall stability to the system and delivers improved continuity of service. The interconnection improves stability as all generators connected share disturbances administered on the network. The generated electricity is transported via conductors being overhead transmission lines and underground cable. Transmission lines are categorised as extra-high voltage, high voltage, medium voltage, and low voltage. The organisation supplying electricity

has stringent regulatory responsibility to provide power to consumers with a stable nominal voltage and frequency set by the regulatory bodies (Wildi, 2014). Correctly cited

On the grid substations allow the interconnection of the generators. The substations comprise circuit breakers, fuses, and lightning arresters. These are important element of the network which protects the expensive apparatus and allow isolation in the event of fault conditions. Substations are divided into two categories being transmission systems and distribution systems. Transmission substations utilise step-up and step-down transformers to transfer electrical energy at high voltages to reduce losses (Wildi, 2014). Distribution substations receive medium voltage from the grid and step this down in reduction ratio of three. The distribution network in the United Kingdom receives 132KV which is stepped down to 33kV, 11kV and 3.3kV which is utilised by large industry. For smaller factories 415V three phase and 230V single phase is used.

Circuit breakers are a means of interrupting the flow of power under fault or normal operation. The most prominent circuit breakers are oil circuit breakers, air-blast circuit breakers, SF6 circuit breakers and vacuum circuit breakers (Wildi, 2014). Correctly cited

When connecting a large induction motor to the utility supply in a factory, the supply impedance must be considered. A supply with a high impedance value can result in a noticeable volt drop when the load is started resulting in interference to devices on the same supply. A weak supply would require some form of starter to limit the current drawn during start up. A high supply impedance value could be the result of the geographical location of the factory signifying a great distance from the main power system. A factory supplied with a low impedance could happily start a large induction motor with no effect on the supply (A Hughes, 2013). Correctly cited

3. Transformer Investigation

In an ideal transformer the winding resistance, leakage flux and core losses are disregarded, and the transformer voltages are established directly by the turns ratio of its winding. To produce an accurate model representation of the transformer the effect of winding resistance, leakage fluxes and finite exciting currents due to the finite and nonlinear permeability of the core must be considered. The equivalent circuit is perceived as an ideal transformer including external impedances. The equivalent circuit parameters are determined by two tests being the open-circuit and short-circuit tests. (Arthur E. Fitzgerald, 2003) Correctly cited

The open circuit and short circuit tests allow the efficiency and voltage regulation of a transformer to be analysed without physically loading the transformer. The accuracy provided by these tests provide far superior measurements compared with the direct measurement of the input and output power and voltage. The power required to perform these tests is modest compared to full load output of the transformer (Hughes, 2016). Correctly cited

3.1 Open circuit test

This test is performed to establish the equivalent shunt impedance. A supply is connected to the transformer at the specified voltage and frequency with the secondary open circuited (Arthur E. Fitzgerald, 2003). The ammeter connected provides the no load current value which provides an assessment of the magnetic quality of the ferromagnetic core and joints. The wattmeter value provides the core losses of the transformer (Hughes, 2016).

The measured practical values are shown in table 1. The values allowed the iron losses to be calculated which is shown in appendix A. The calculated values are shown in table 2. The iron losses equivalent circuit is shown in figure 1.

Table 1: Open circuit test results

Iron Losses			
		Primary Values	Secondary Values
Voltage	V	230	113
Current	A	527mA	0
Power	W	31.5	0
Power Factor	P.F.	0.26	0

Table 2: Equivalent circuit component values

Component Values		
Rc	1679.4 Ω	
Xm	451.87 Ω	1.44H
Ic	137mA	
Im	509mA	
V1	230V	
I1	527mA	

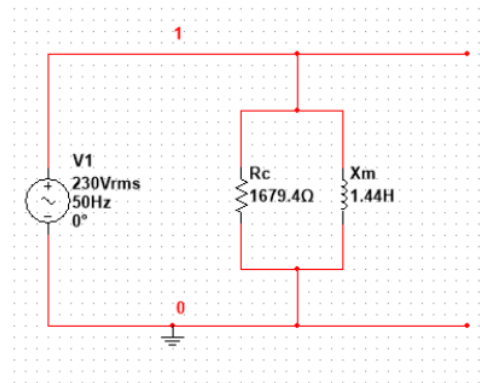


Figure 1: Iron losses equivalent circuit

3.2 Short circuit test

The purpose of this test is to determine the equivalent series impedance (Arthur E. Fitzgerald, 2003). A low voltage is supplied to the primary where the secondary is short circuited with an ammeter. The voltage is adjusted to allow full load current to flow in the primary and secondary. The i^2R losses of the windings are equivalent to that on full load. The power recorded on the wattmeter is the copper losses of the windings. (Hughes, 2016)

The measured practical values are shown in table 3. The calculations to obtain equivalent component values are shown in Appendix B.

Table 3: Short circuit test results

Copper Losses			
		Primary Values	Secondary Values
Voltage	V	8.98	0
Current	I	1.72	3.47
Power	W	8.08	0
Power Factor	P.F.	0.52	0

Table 4: Circuit component values for transformer copper losses

Component Values		
ZIE	5.221 Ω	
RIE	2.731 Ω	
XIE	4.45 Ω	14.2mH
Z2E	1.194 Ω	
R2E	0.625 Ω	
X2E	1.018 Ω	3.123mH
I2	3.596A	

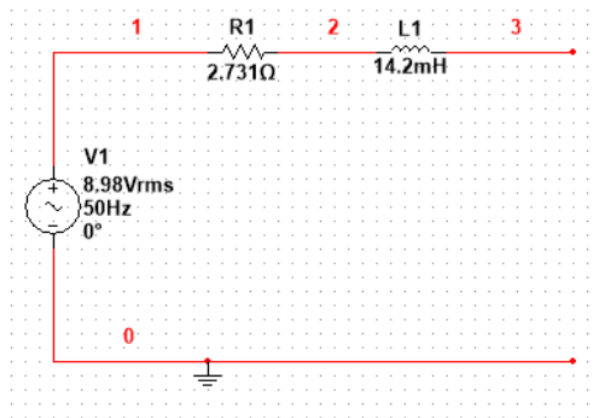


Figure 2: Transformer equivalent copper losses circuit

3.3 Transformer equivalent circuit

Following these tests and calculations an equivalent circuit is produced which provides a model of the physical transformer. This circuit is shown in figure 3. The accuracy of the equivalent circuit to the physical transformer will be evaluated by comparison of simulated and experimental values.

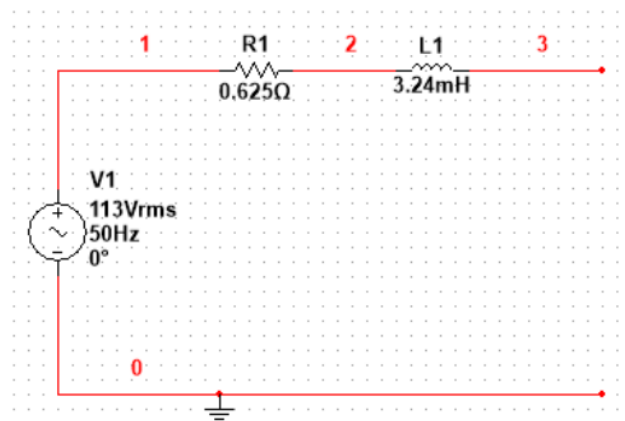


Figure 3: Transformer equivalent circuit

3.4 Voltage regulation

An important quality to a transformer is voltage regulation. Voltage regulation of a transformer is expressed as the deviation of the secondary voltage between no load and full load, conveyed as a per unit or percentage of the no load voltage with the primary assumed as being constant. (Hughes, 2016)
The power factor of the applied load determines the voltage regulation. (Wildi, 2014)

In this section the transformer under test will be subjected to three load variations being resistive, inductive, and capacitive.

3.4.1 Resistive

The secondary of the transformer was connected to a 33Ω load and the results in table 5 were obtained.

Table 5: Voltage regulation resistive load 33Ω

Voltage Regulation - Resistive			
		Primary Values	Secondary Values
Voltage	V	230	110
Current	I	1.78	3.23
Power	W	388	366
Power Factor	P.F	0.95	1

3.4.2 RL load

Connecting an inductive load to the secondary the measurements in table 6 were obtained.

Table 6: Voltage regulation inductive load

Voltage Regulation - RL Load			
		Primary Values	Secondary Values
Voltage	V	230	109
Current	I	1.55	2.26
Power	W	208	177
Power Factor	P.F	0.58	0.72

3.4.3 RC Load

Connecting a capacitive load to the secondary the measurement in table 7 were obtained.

Table 7: Voltage regulation capacitive load

Voltage Regulation - RL Load			
		Primary Values	Secondary Values
Voltage	V	230	114
Current	I	4.69	1.58
Power	W	86.3	68.8
Power Factor	P.F	-0.8	-0.38

3.5 Results and Evaluation

To determine the equivalent circuit accuracy simulations were performed and the results were tabulated to compare manufacturers data sheet, equivalent circuit, and measured values. The datasheet can be viewed in Appendix H.

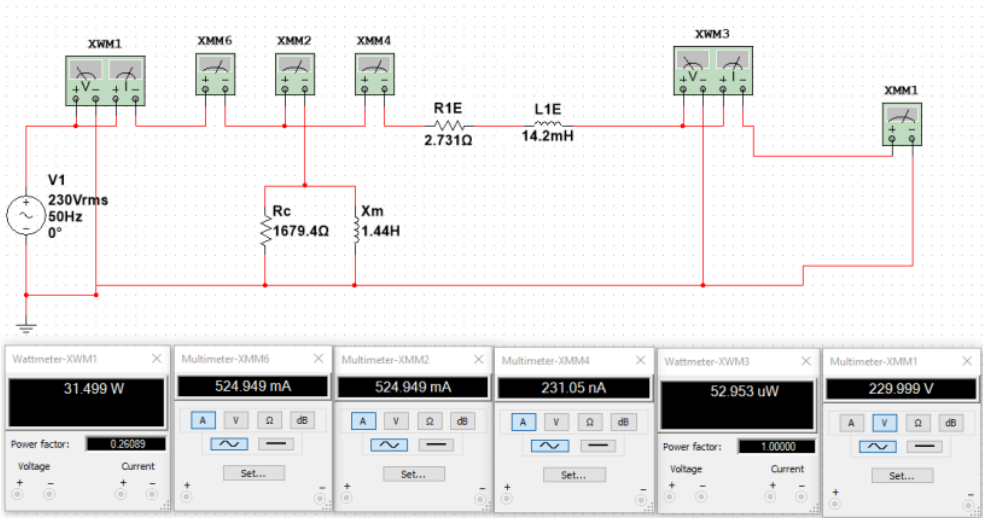


Figure 4: Simulation of Iron losses equivalent circuit measurements

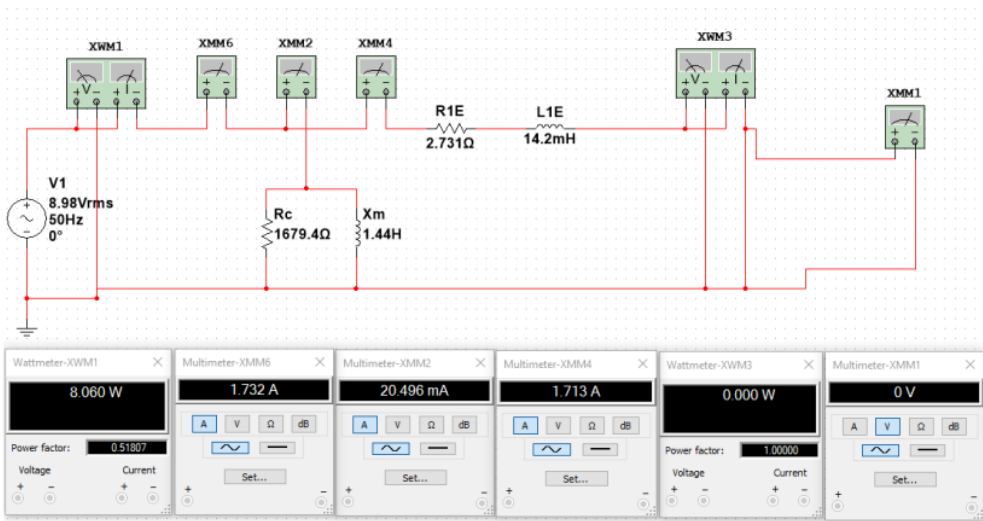


Figure 5: Simulation of Copper Losses equivalent circuit measurements

The iron losses findings are shown in table 8. All values are comparable without any significant anomalies. On the secondary there is a larger voltage present in the simulated and datasheet values compared with the measured. The current flowing in the primary is modestly different between the practical and simulated value. The power dissipated in the primary and the power factor measurement in the practical and simulated are indistinguishably close. The data sheet does not provide all the parameters to permit full comparison. All incongruities can be possibly attributed to measuring equipment used and test environment.

Table 8: Tabulated results to compare manufacturers data, equivalent circuit, and simulated values for iron losses.

Iron Losses							
		Practical Values		Simulated Values		Data Sheet Values	
		Primary Values	Secondary Values	Primary Values	Secondary Values	Primary Values	Secondary Values
Voltage	V	230	113	230	114.99	230	113.8
Current	I	527mA	0	542.95mA	0	N/A	0
Power	W	31.5	0	31.499	0	20.16	0
Power Factor	P.F	0.26	0	0.26089	0	N/A	0

The copper losses findings are shown in table 9. The measured and simulated results are similar without any notable abnormality. The data sheet only provided the primary power dissipated which was similar to that of the practical and simulated result.

Table 9: Tabulated results to compare manufacturers data, equivalent circuit, and simulated values for copper losses.

Copper Losses							
		Practical Values		Simulated Values		Data Sheet Values	
		Primary Values	Secondary Values	Primary Values	Secondary Values	Primary Values	Secondary Values
Voltage	V	8.98	0	8.98	0	N/A	0
Current	I	1.72	3.47	1.732	3.464	N/A	N/A
Power	W	8.08	0	8.06	0	9.05	0
Power Factor	P.F	0.52	0	0.518	0	N/A	0

The voltage regulation simulation results of an equivalent transformer circuit are shown in figures 6-8.

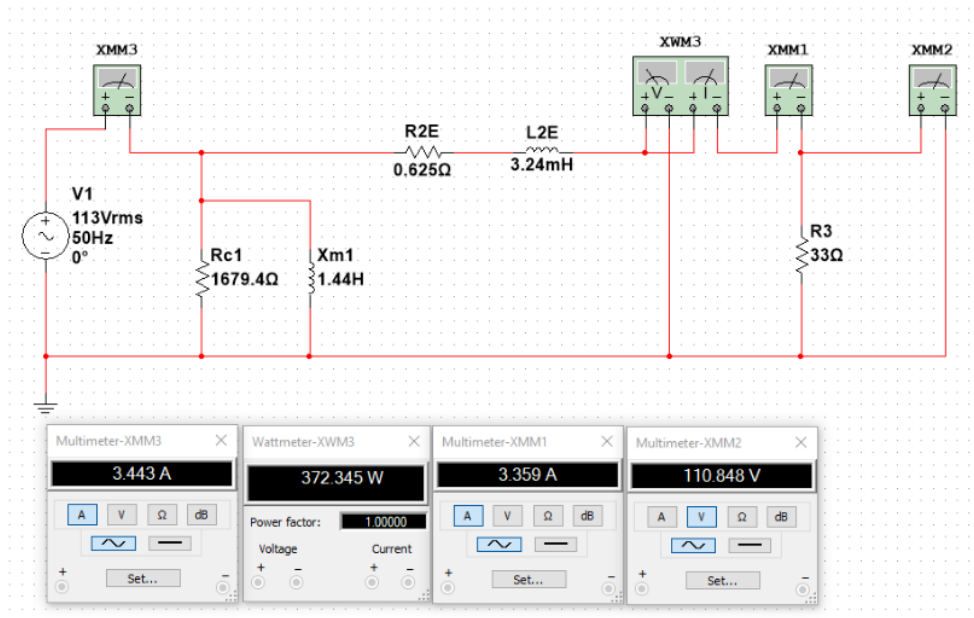


Figure 7: Simulation of transformer equivalent circuit subject to a resistive load.

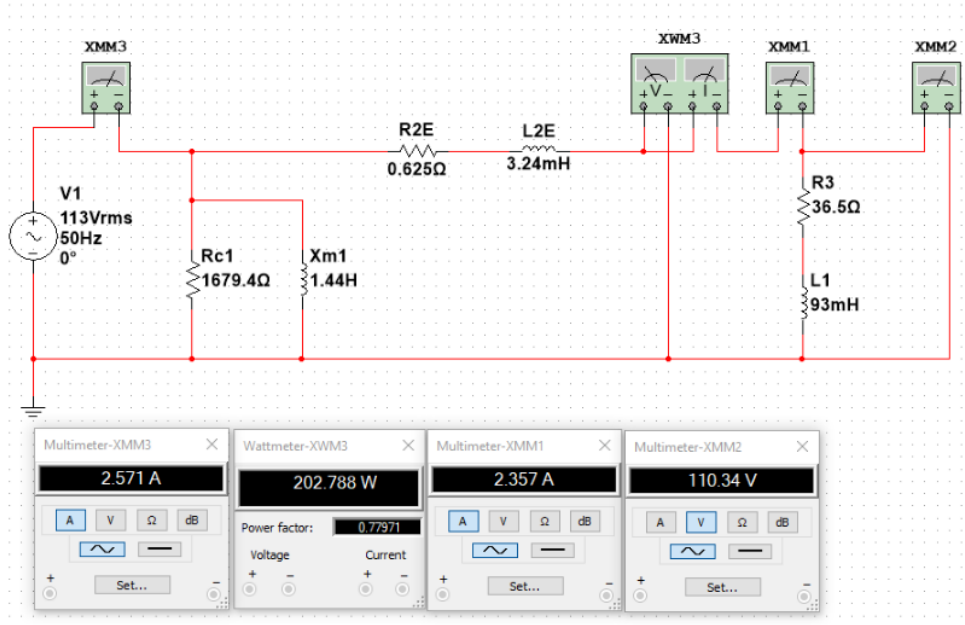


Figure 6: Simulation of transformer equivalent circuit subject to an inductive load.

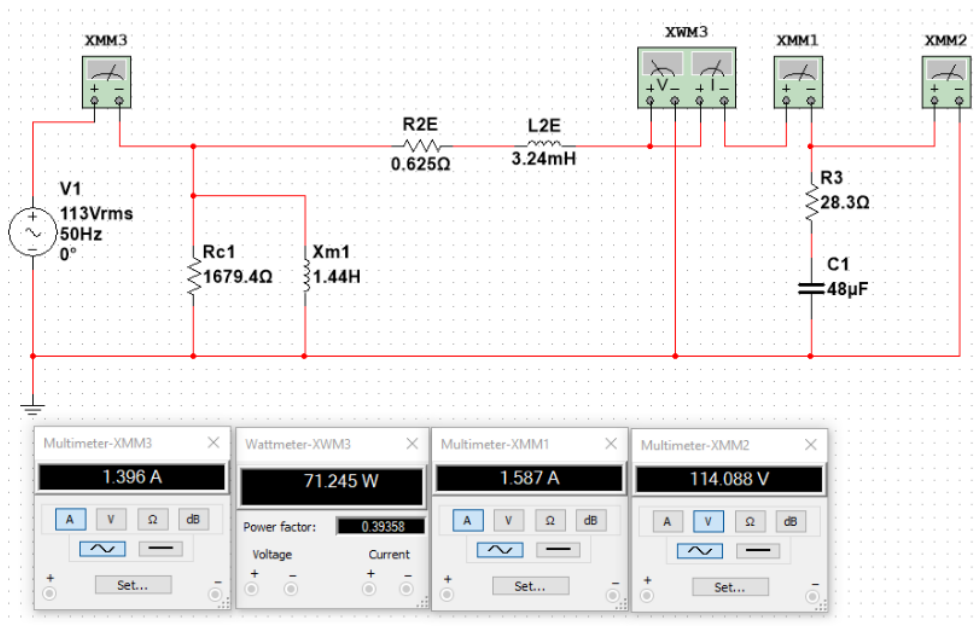


Figure 8: Simulation of transformer equivalent circuit subject to a capacitive load.

The results of the practical, simulated, and calculated results for the different load types have been tabulated to simplify comparison and can be seen in tables 10 – 12. Table 13 shows the voltage regulation percentage difference.

Table 10: Tabulated results to compare voltage regulation results when subject to a resistive load

Voltage Regulation - Resistive							
		Practical Values		Simulated Values		Calculated Values	
		Primary Values	Secondary Values	Primary Values	Secondary Values	Primary Values	Secondary Values
Voltage	V	230	110	N/A	110.85	N/A	110.06
Current	I	1.55	2.26	1.72	3.36	N/A	N/A
Power	W	208	177	N/A	372.35	N/A	N/A
Power Factor	P.F	0.95	1	N/A	1	N/A	N/A

Table 11: Tabulated results to compare voltage regulation results when subject to an inductive load

Voltage Regulation - Inductive							
		Practical Values		Simulated Values		Calculated Values	
		Primary Values	Secondary Values	Primary Values	Secondary Values	Primary Values	Secondary Values
Voltage	V	230	110	N/A	110.34	N/A	110.31
Current	I	1.55	2.26	1.29	2.36	N/A	N/A
Power	W	208	177	N/A	202.79	N/A	N/A
Power Factor	P.F	0.58	0.72	N/A	0.78	N/A	N/A

Table 12: Tabulated results to compare voltage regulation results when subject to a capacitive load

Voltage Regulation - Capacitive							
		Practical Values		Simulated Values		Calculated Values	
		Primary Values	Secondary Values	Primary Values	Secondary Values	Primary Values	Secondary Values
Voltage	V	230	114	N/A	114.09	N/A	114.76
Current	I	469mA	1.58	698mA	1.59	N/A	N/A
Power	W	86.3	68.8	N/A	71.25	N/A	N/A
Power Factor	P.F	-0.8	-0.38	N/A	-0.39	N/A	N/A

Table 13: Voltage regulation percentage result

	Resistive Load			Inductive Load			Capacitive Load		
	E2	V2	Percentage	E2	V2	Percentage	E2	V2	Percentage
Practical	113	110	2.73%	113	110	2.73%	113	114	-0.88%
Simulated	113	110.85	1.94%	113	110.34	2.41%	113	114.09	-0.96%
Calculated	113	110.06	2.67%	113	110.31	2.44%	113	114.76	-1.53%

It can be seen from table 13 that the practical, simulated and calculated results have provided a very similar trend. There are no obvious anomalies with the largest non-conformance being the resistive load with an error of 0.79%. This concludes that the equivalent circuit provides an accurate representation of the physical transformer.

4. Three-phase Induction Motor Investigation

The torque produced by a motor is generated by the coaction of a stator-bound flux wave and the induced rotor bound current wave. (Hughes, 2016). Correctly cited

To obtain the equivalent circuit parameters of the three-phase induction motor to determine its performance under load a series of tests are performed. The tests performed to acquire the per phase circuit parameters are the d.c. test, the no load test, and the blocked rotor test (Hughes, 2016). The no load test is like the open circuit previously performed on the transformer. The no-load test provides data regarding exciting current and no-load losses. The blocked rotor test provides data regarding the leakage impedance. (Arthur E. Fitzgerald, 2003) Correctly cited

4.1 Stator resistance

The stator resistance per phase value is obtained by applying a variable d.c. voltage across two terminals of the stator windings. The measured current and voltage and using ohms law provides the R_1 value. As the motor under test is connected in star the resistance measured is the value of two phases connected in series (Hughes, 2016).

The stator resistance experimental results are shown in table 14.

Table 14: Stator resistance practical measurements of three phase motor

Stator Resistance Test - DC Test		
	Voltage	Current
U1	11.8V	330mA
V1	11.8V	330mA
W1	11.8V	330mA

4.2 No load test

The no-load test provides data in relation to exciting current and no-load losses (Arthur E. Fitzgerald, 2003). This test involves running the motor externally to reach as close as possible synchronous speed which results in no torque being produced. With this slip is minimal and no current flows in the rotor circuit. With this test the power consumed provides the stator copper losses, the core losses and the friction and windage losses (Hughes, 2016).

The no load test results are shown in table 15.

Table 15: No load practical results of three phase motor

No Load Test - Open Circuit				
	Voltage	Current	Power	Power factor
L1	214V	529mA	61.2W	0.31
L2	214V	529mA	61.2W	0.31
L3	214V	529mA	61.2W	0.31

4.3 Blocked rotor test

This test provides information in respect to the leakage impedances (Arthur E. Fitzgerald, 2003). In this test sufficient voltage is applied to the stator of the motor to allow full circulation of full load current in the stator windings. As the rotor is stationary the value of slip is equal to one.

The blocked rotor experimental results are shown in table 16.

Table 16: Blocked rotor practical results of three phase motor

Blocked Rotor Test				
	Voltage	Current	Power	Power factor
L1	25.7V	489mA	19.2W	0.88
L2	25.7V	489mA	19.2W	0.88
L3	25.7V	489mA	19.2W	0.88

The values obtained allowed the calculations of equivalent circuit parameters to be calculated see Appendix F. The tabulated values are shown in table 17.

Table 17: Induction motor equivalent circuit component values

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

The equivalent circuit is shown pictorially in figure 9.

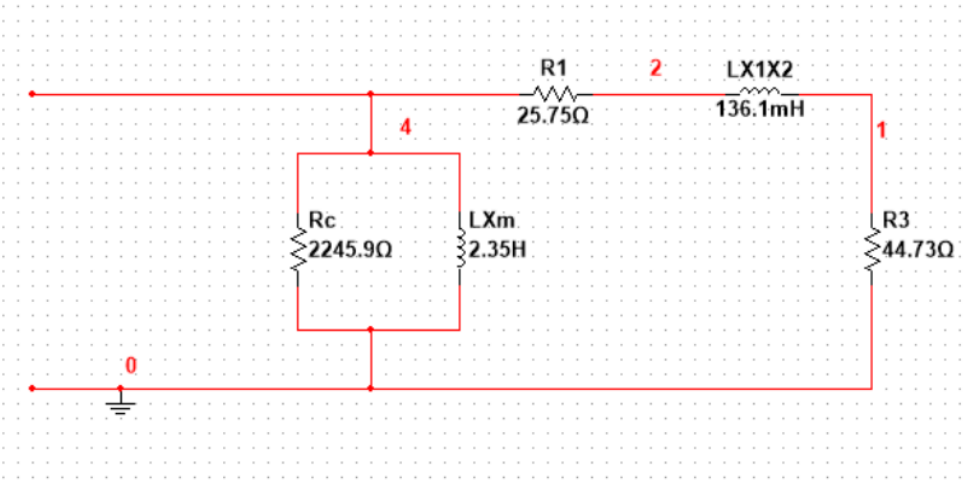


Figure 9: Induction motor equivalent circuit

4.4 Testing and Evaluation

The total torque of the motor can be calculated, and a total torque curve can be produced to illustrate the dynamic performance of the motor using the equivalent circuit. The total torque is dependant on the value of slip. The total torque curve is shown in figure 10. The formulae used and results can be viewed in Appendix G.

The variation of slip is achieved from the variation of speed. The value of slip is directly related to speed. The torque slip characteristic curve has three regions being low slip, medium slip and high slip. With a slip value below zero the rotor is rotating at a higher speed than synchronous speed resulting in the mechanical energy being converted to electrical energy. This mode of operation is termed regeneration mode. With a slip value between zero to one the motor is in motoring mode where the electrical energy is being converted to mechanical power. The torque produced is directly proportional to slip (Electrical4U, 2020). With a slip value greater than one the motor has entered braking mode. Braking is achieved by reversing two supply phases which makes the stator field rotate in the opposite direction. At the instantaneous moment of switchover, the rotor is rotating at almost synchronous speed and the stator field is rotating at synchronous speed in the opposite direction. Consequently, the variation from synchronous speed is two resulting in a slip value of almost 2 (Hughes, 2016).

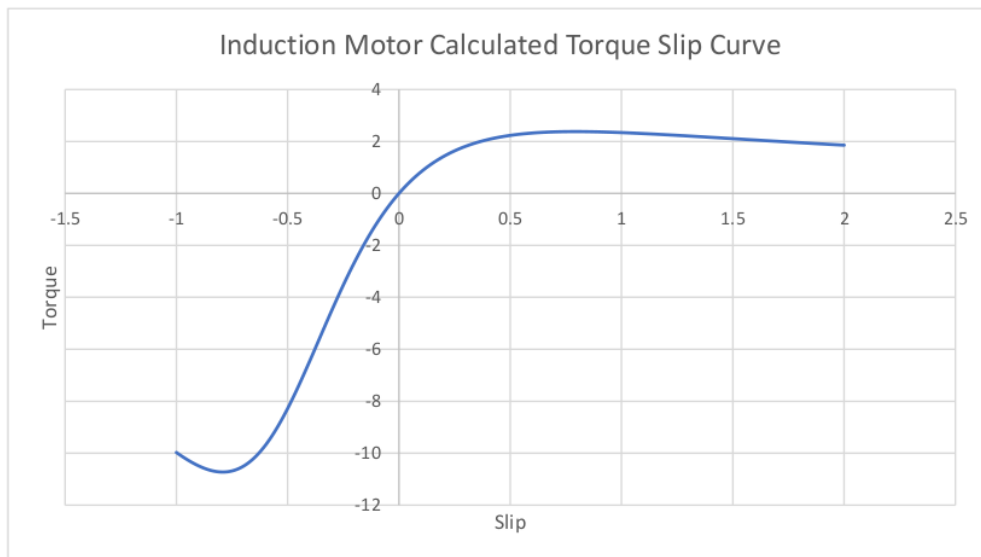


Figure 10: Induction motor torque-slip curve

The physical motor was subjected to different loads during its motoring mode. The results of introducing a load are shown in table 18.

Table 18: Practical results of three phase motor motoring phase.

Speed RPM	Fractional slip	Torque (nM)	Voltage	Current	Power (W)	p.f
2993	0.002333333	0	215	533mA	48.1	0.24
2880	0.04	0.1	213	610mA	144	0.64
2882	0.039333333	0.2	213	616mA	147	0.66
2823	0.059	0.3	213	698mA	193	0.75
2792	0.069333333	0.4	213	755mA	222	0.79
2736	0.088	0.5	213	860mA	263	0.84
2678	0.107333333	0.6	211	976mA	313	0.87
2600	0.133333333	0.7	211	1.14A	377	0.9
2514	0.162	0.8	211	1.29A	430	0.91

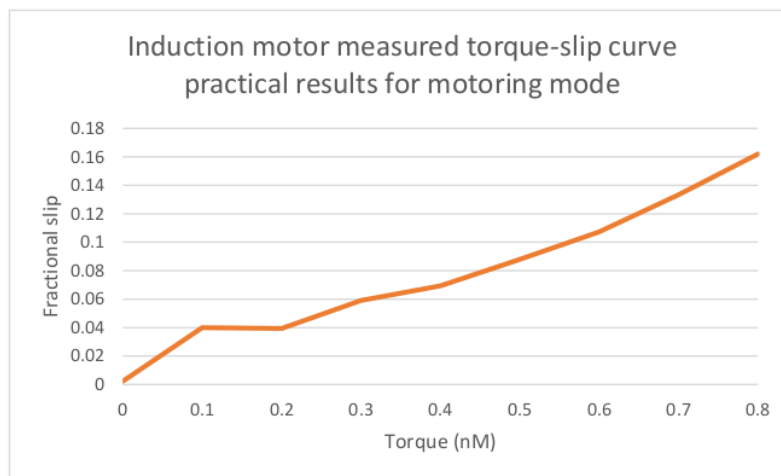


Figure 11: Induction motor torque-slip curve result by subjecting motor to incremental load.

The motor was coupled to a prime mover to evaluate its generating mode. The result are shown in table 18.

Table 19: Practical results of three phase motor generating phase.

Speed rpm	Fractional Slip	Volts	Amps	Power (W)	p.f
2993	0.0023	215	533mA	48.1	0.24
3100	-0.0340	216	620mA	77	-0.34
3200	-0.0667	217	827mA	182	-0.59
3300	-0.1000	217	1.09A	288	-0.7

A comparison of the equivalent circuit calculated results and physical motor measurement is shown graphically in figure 12.

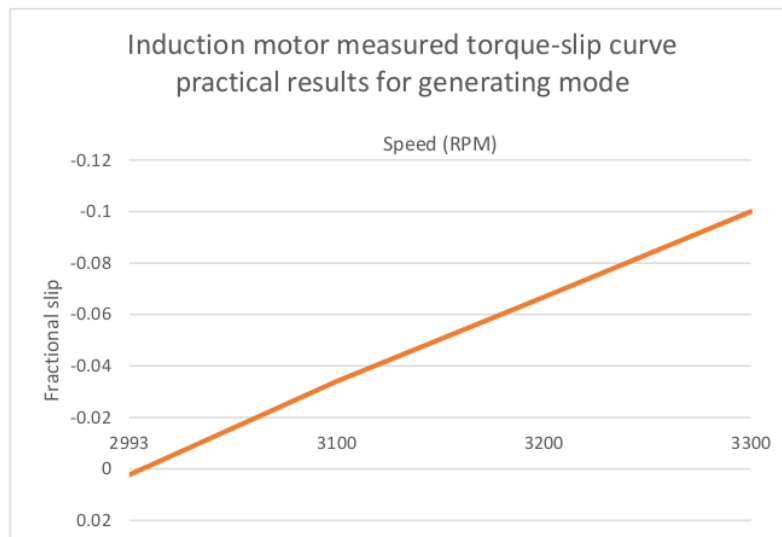


Figure 12: Induction motor fractional slip – rpm result from externally driving rotor.

5. Conclusions and Recommendations

The single-phase transformer investigation established that transformer performance cannot be accurately represented by the turns ratio as is the case with an ideal transformer. To provide the most accurate model of a real transformer an equivalent circuit must be constructed. The equivalent circuit component values must be obtained through physically testing the transformer by performing a short circuit and open circuit test. The open circuit test provides the equivalent shunt impedance being the iron losses of the transformer. The short circuit test provides the equivalent series impedance being the copper losses. With the equivalent circuit component values calculated the voltage regulation characteristic could be calculated. Through research it was predicted that voltage regulation would be affected by the applied load. This was the case it was found that a resistive and inductive load would pull down the voltage on the secondary. With a capacitive load the voltage on the secondary increases.

The three-phase motor investigation established the close relationship of the motor with the transformer. The stator is the primary winding where the rotor is the secondary winding. Due to these similarities the transformer can be adapted to represent the induction motor performance. To obtain the values for the equivalent circuit the stator resistance, no-load test and locked rotor test must be performed. To reiterate the similarities between the transformer and motor the no load test performs a similar test to the open-circuit test of the transformer which provides the exciting current and no-load losses. Also, the blocked rotor test provides information on leakage impedances comparable to the short circuit test of the transformer. With the equivalent motor circuit calculated the motor performance can be predicted. The operation of a motor can be portrayed by the torque-speed characteristic curve. This characteristic curve has three operating regions being the motoring, regenerating, and braking phases which is established by the slip value. Increasing the load torque retards the rotor thereby develops a larger slip which increases the electromagnetic torque allowing the motor to meet the load torque demand.

To comprehensively investigate the three-phase motor, it would have been beneficial to have performed the braking mode to physically demonstrate the effect of braking. The testing equipment provided acceptable results, but the practical experimentation could have benefitted from improved testing equipment within calibration.

6. Citation List

At this level, a much wider range of sources is expected.

A Hughes, B. D., 2013. *Electric Motors and Drives: Fundamentals, Types, and Application*. Fourth Edition ed. Oxford: Newnes.

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Electrical4U, 2020. *Electrical4U*. [Online]

Available at: <https://www.electrical4u.com/torque-slip-characteristics-of-induction-motor/> [Accessed 10 02 2021].

Hughes, E., 2016. *Electrical & Electronic Technology*. Twelfth Edition ed. Harlow: Pearson Education Limited.

Rashid, M. H., 2014. *Power Electronics: Devices, Circuits, and Applications*. Fourth Edition ed. Essex : Pearson Education Limited .

Wildi, T., 2014. *Electrical Machines, Drives, and Power Systems*. Sixth Edition ed. Essex: Pearson Education Limited.

Appendix A – Iron losses calculations

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

$$I_c = \frac{V_1}{RC} = \frac{230}{1679.4} = 137mA$$

$$I_o = I_c^2 + I_m^2 = I_o^2 = I_c^2 + I_m^2 = I_m^2 = I_o^2 - I_c^2 \\ = ((527 \times 10^{-3})^2 - (137 \times 10^{-3})^2) = 0.25896 = \sqrt{0.25896} = 0.509A$$

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

$$X_m = 2\pi fL = Lm = \frac{X_m}{2\pi f} = \frac{451.87}{2 \times \pi \times 50} = 1.44h$$

Appendix B – Copper losses calculations

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

$$Z1E = \frac{V1}{I1} = \frac{8.98}{1.72} = 5.221\Omega$$

$$R1E = \frac{Pin}{I1^2} = \frac{8.08}{1.72^2} = 2.731\Omega$$

$$X1E = \sqrt{Z1E^2 - R1E^2} = \sqrt{5.221^2 - 2.731^2} = 4.45\Omega$$

$$Z2E = \left(\frac{N2}{N1}\right)^2 \times Z1E = \left(\frac{110}{230}\right)^2 \times 5.521 = 1.194\Omega$$

$$R2E = \left(\frac{N2}{N1}\right)^2 \times R1E = \left(\frac{110}{230}\right)^2 \times 2.731 = 0.625\Omega$$

$$X2E = \left(\frac{N2}{N1}\right)^2 \times X1E = \left(\frac{110}{230}\right)^2 \times 4.45 = 1.018\Omega$$

$$I2 = \left(\frac{N1}{N2}\right)^2 \times I1 = \frac{230}{110} \times 1.72 = 3.596A$$

$$X1E = 2\pi fL = L1E = \frac{X1E}{2\pi f} = \frac{4.45}{2 \times \pi \times 50} = 0.0142A$$

$$X_{2E} = 2\pi fL = \frac{L_{2E}}{2\pi f} = \frac{1.018}{2 \times \pi \times 50} = 3.24mA$$

Appendix C - Voltage regulation calculations

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

$$\% \text{ Regulation} = \frac{I_2 (R_{2E} \times \cos\phi_2 \mp X_{2E} \sin\phi)}{V_2} \times 100 = V_2 = E_2 - I_2(R_{2E} \times \cos\phi_2 \mp X_{2E} \sin\phi)$$

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

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

$$\% \text{ Regulation} = \frac{I_2 (R_{2E} \times \cos\phi_2 \mp X_{2E} \sin\phi)}{V_2} \times 100 = V_2 = E_2 - I_2(R_{2E} \times \cos\phi_2 \mp X_{2E} \sin\phi)$$

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

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

$$\% \text{ Regulation} = \frac{I_2 (R_{2E} \times \cos\phi_2 \mp X_{2E} \sin\phi)}{V_2} \times 100 = V_2 = E_2 - I_2(R_{2E} \times \cos\phi_2 \mp X_{2E} \sin\phi)$$

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

Appendix D – Three phase motor stator resistance calculation

$$V = I \times R = R = \frac{V}{I} = \frac{11.8}{330mA} = 35.75\Omega$$

Appendix E – Three phase motor no Load Calculations

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

$$PO = \frac{1}{3} \times PNL = \frac{1}{3} \times 61.2 = 20.4W$$

$$\cos\phi = \frac{PO}{VO \times IO} = \frac{20.4}{214 \times 305.4 \times 10^{-3}} = 0.312$$

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

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

$$Rc = \frac{VO}{IO \times \cos\phi} = \frac{214}{305 \times 10^{-3} \times 0.312} = 2245.9\Omega$$

$$Xm = \frac{VO}{IO \times \sin\phi} = \frac{214}{305 \times 10^{-3} \times 0.9501} = 737.5\Omega$$

$$Xm = 2\pi fL = Lm = \frac{Xm}{2\pi f} = \frac{737.5}{2 \times \pi \times 50} = 2.35H$$

Appendix F – Three phase motor Blocked Rotor Calculations

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

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

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

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

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

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

$$R1 + R2' = Z_{cs} \times \cos\phi_{sc} = 91.13 \times 0.8831 = 80.48\Omega$$

$$R2' = (R1 + R2') - R1 = 80.48 - 35.75 = 44.73\Omega$$

$$X1 + X2' = Z_{sc} \times \sin\phi_{sc} = 91.13 \times 0.4692 = 42.76\Omega$$

$$X1 + X2' = 2\pi fL = Lm' = \frac{X1 + X2'}{2\pi f} = \frac{42.76}{2\pi \times 50} = 0.1361H$$

Appendix G – Three phase motor total torque calculation

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

R1	R2'	V1	X1+X2'	ws
35.75	44.44	214	43.28	314.156

s	T	speed rpm
2	1.856694	-3000
1.99	1.861416	-2970
1.98	1.866152	-2940
1.97	1.870904	-2910
1.96	1.87567	-2880
1.95	1.880451	-2850
1.94	1.885247	-2820
1.93	1.890058	-2790
1.92	1.894883	-2760
1.91	1.899722	-2730
1.9	1.904576	-2700
1.89	1.909443	-2670
1.88	1.914325	-2640
1.87	1.91922	-2610
1.86	1.924129	-2580
1.85	1.929051	-2550
1.84	1.933986	-2520
1.83	1.938935	-2490
1.82	1.943896	-2460
1.81	1.94887	-2430
1.8	1.953857	-2400

1.79	1.958855	-2370
1.78	1.963866	-2340
1.77	1.968888	-2310
1.76	1.973922	-2280
1.75	1.978967	-2250
1.74	1.984023	-2220
1.73	1.98909	-2190
1.72	1.994167	-2160
1.71	1.999254	-2130
1.7	2.004351	-2100
1.69	2.009457	-2070
1.68	2.014572	-2040
1.67	2.019695	-2010
1.66	2.024827	-1980
1.65	2.029967	-1950
1.64	2.035114	-1920
1.63	2.040268	-1890
1.62	2.045429	-1860
1.61	2.050596	-1830
1.6	2.055768	-1800
1.59	2.060945	-1770
1.58	2.066127	-1740
1.57	2.071313	-1710
1.56	2.076503	-1680
1.55	2.081695	-1650
1.54	2.08689	-1620
1.53	2.092086	-1590
1.52	2.097283	-1560
1.51	2.10248	-1530
1.5	2.107678	-1500
1.49	2.112873	-1470
1.48	2.118068	-1440
1.47	2.123259	-1410

1.46	2.128447	-1380
1.45	2.13363	-1350
1.44	2.138809	-1320
1.43	2.143981	-1290
1.42	2.149147	-1260
1.41	2.154304	-1230
1.4	2.159452	-1200
1.39	2.16459	-1170
1.38	2.169718	-1140
1.37	2.174832	-1110
1.36	2.179934	-1080
1.35	2.185021	-1050
1.34	2.190092	-1020
1.33	2.195146	-990
1.32	2.200182	-960
1.31	2.205197	-930
1.3	2.210192	-900
1.29	2.215164	-870
1.28	2.220111	-840
1.27	2.225033	-810
1.26	2.229927	-780
1.25	2.234792	-750
1.24	2.239626	-720
1.23	2.244428	-690
1.22	2.249194	-660
1.21	2.253925	-630
1.2	2.258616	-600
1.19	2.263267	-570
1.18	2.267875	-540
1.17	2.272438	-510
1.16	2.276954	-480
1.15	2.28142	-450
1.14	2.285833	-420

1.13	2.290192	-390
1.12	2.294493	-360
1.11	2.298734	-330
1.1	2.302912	-300
1.09	2.307023	-270
1.08	2.311066	-240
1.07	2.315036	-210
1.06	2.318931	-180
1.05	2.322747	-150
1.04	2.32648	-120
1.03	2.330128	-90
1.02	2.333685	-60
1.01	2.337149	-30
1	2.340515	2.6645E-12
0.99	2.343779	30
0.98	2.346936	60
0.97	2.349983	90
0.96	2.352915	120
0.95	2.355726	150
0.94	2.358412	180
0.93	2.360968	210
0.92	2.363389	240
0.91	2.365668	270
0.9	2.3678	300
0.89	2.36978	330
0.88	2.371601	360
0.87	2.373256	390
0.86	2.37474	420
0.85	2.376045	450
0.84	2.377165	480
0.83	2.378091	510
0.82	2.378818	540

0.81	2.379336	570
0.8	2.379637	600
0.79	2.379714	630
0.78	2.379557	660
0.77	2.379158	690
0.76	2.378507	720
0.75	2.377595	750
0.74	2.376411	780
0.73	2.374946	810
0.72	2.373188	840
0.71	2.371126	870
0.7	2.368749	900
0.69	2.366045	930
0.68	2.363002	960
0.67	2.359606	990
0.66	2.355845	1020
0.65	2.351705	1050
0.64	2.347172	1080
0.63	2.34223	1110
0.62	2.336865	1140
0.61	2.331061	1170
0.6	2.324802	1200
0.59	2.318071	1230
0.58	2.310849	1260
0.57	2.30312	1290
0.56	2.294864	1320
0.55	2.286061	1350
0.54	2.276693	1380
0.53	2.266737	1410
0.52	2.256173	1440
0.51	2.244977	1470
0.5	2.233128	1500
0.49	2.220601	1530

0.48	2.207371	1560
0.47	2.193413	1590
0.46	2.1787	1620
0.45	2.163205	1650
0.44	2.146901	1680
0.43	2.129757	1710
0.42	2.111743	1740
0.41	2.092829	1770
0.4	2.072982	1800
0.39	2.052168	1830
0.38	2.030354	1860
0.37	2.007505	1890
0.36	1.983582	1920
0.35	1.95855	1950
0.34	1.932368	1980
0.33	1.904997	2010
0.32	1.876396	2040
0.31	1.846521	2070
0.3	1.815329	2100
0.29	1.782776	2130
0.28	1.748814	2160
0.27	1.713396	2190
0.26	1.676473	2220
0.25	1.637995	2250
0.24	1.597911	2280
0.23	1.556166	2310
0.22	1.512708	2340
0.21	1.467481	2370
0.2	1.420428	2400
0.19	1.371491	2430
0.18	1.320612	2460
0.17	1.26773	2490
0.16	1.212783	2520

0.15	1.15571	2550
0.14	1.096446	2580
0.13	1.034929	2610
0.12	0.971092	2640
0.11	0.904871	2670
0.1	0.836198	2700
0.09	0.765008	2730
0.08	0.691233	2760
0.07	0.614806	2790
0.06	0.53566	2820
0.05	0.453728	2850
0.04	0.368945	2880
0.03	0.281245	2910
0.02	0.190562	2940
0.01	0.096834	2970
0	0	3000
-0.01	-0.1	3030
-0.02	-0.20323	3060
-0.03	-0.30973	3090
-0.04	-0.41956	3120
-0.05	-0.53277	3150
-0.06	-0.64941	3180
-0.07	-0.7695	3210
-0.08	-0.89309	3240
-0.09	-1.02021	3270
-0.1	-1.15088	3300
-0.11	-1.28511	3330
-0.12	-1.42292	3360
-0.13	-1.56431	3390
-0.14	-1.70926	3420
-0.15	-1.85777	3450
-0.16	-2.0098	3480
-0.17	-2.16533	3510

-0.18	-2.32431	3540
-0.19	-2.48667	3570
-0.2	-2.65235	3600
-0.21	-2.82126	3630
-0.22	-2.99332	3660
-0.23	-3.1684	3690
-0.24	-3.3464	3720
-0.25	-3.52717	3750
-0.26	-3.71055	3780
-0.27	-3.89639	3810
-0.28	-4.08451	3840
-0.29	-4.2747	3870
-0.3	-4.46677	3900
-0.31	-4.66048	3930
-0.32	-4.85559	3960
-0.33	-5.05187	3990
-0.34	-5.24904	4020
-0.35	-5.44682	4050
-0.36	-5.64494	4080
-0.37	-5.84309	4110
-0.38	-6.04097	4140
-0.39	-6.23827	4170
-0.4	-6.43466	4200
-0.41	-6.62982	4230
-0.42	-6.82343	4260
-0.43	-7.01515	4290
-0.44	-7.20466	4320
-0.45	-7.39162	4350
-0.46	-7.57572	4380
-0.47	-7.75663	4410
-0.48	-7.93405	4440
-0.49	-8.10767	4470
-0.5	-8.2772	4500

-0.51	-8.44237	4530
-0.52	-8.6029	4560
-0.53	-8.75855	4590
-0.54	-8.90908	4620
-0.55	-9.05428	4650
-0.56	-9.19395	4680
-0.57	-9.32792	4710
-0.58	-9.45602	4740
-0.59	-9.57812	4770
-0.6	-9.6941	4800
-0.61	-9.80387	4830
-0.62	-9.90736	4860
-0.63	-10.0045	4890
-0.64	-10.0953	4920
-0.65	-10.1797	4950
-0.66	-10.2577	4980
-0.67	-10.3294	5010
-0.68	-10.3948	5040
-0.69	-10.4539	5070
-0.7	-10.5069	5100
-0.71	-10.5539	5130
-0.72	-10.5948	5160
-0.73	-10.63	5190
-0.74	-10.6594	5220
-0.75	-10.6832	5250
-0.76	-10.7017	5280
-0.77	-10.7149	5310
-0.78	-10.723	5340
-0.79	-10.7262	5370
-0.8	-10.7246	5400
-0.81	-10.7185	5430
-0.82	-10.708	5460
-0.83	-10.6933	5490

-0.84	-10.6746	5520
-0.85	-10.652	5550
-0.86	-10.6258	5580
-0.87	-10.5962	5610
-0.88	-10.5633	5640
-0.89	-10.5273	5670
-0.9	-10.4883	5700
-0.91	-10.4466	5730
-0.92	-10.4023	5760
-0.93	-10.3556	5790
-0.94	-10.3066	5820
-0.95	-10.2555	5850
-0.96	-10.2024	5880
-0.97	-10.1475	5910
-0.98	-10.0909	5940
-0.99	-10.0328	5970
-1	-9.97328	6000

Appendix H – Transformer datasheet



Portable Safety Isolating Transformers

RS Part No	260-4244	260-4250	260-4272	260-4288	260-4294	260-4301	399-6140	310-2171
Transformer Type	CM7501	CM10001	CM15002	CM22502	CM33002	CM40002	CMH13	CMH1200/110
Continuous Output Rating (VA)	375	500	750	1125	1650	2000	3000	600
Intermittent, 5 mins on 15 mins off. (VA)	750	1000	1500	2250	3300	4000		1200
Primary Voltage (V)	230	230	230	230	230	230	230	230
Frequency	50/60Hz	50/60Hz	50/60Hz	50/60Hz	50/60Hz	50/60Hz	50/60Hz	50/60Hz
Off-Load Secondary Volts (V)	113.8	114.6	113.8	112	111.5	112.5	113.5	112.5
Full-Load secondary Volts (V)	109.6	110	109.6	108.4	108.3	108.9	109.9	109.5
Regulation at Continuous Rating	4%	4%	4%	3%	3%	3%	3%	4%
Efficiency at Continuous Rating	90%	90%	93%	93%	95%	93%	96%	94%
Iron Loss (Watts)	20.16	23.5	18	28	35	40	48	17.3
Copper Loss at Continuous rating	9.05	14.8	18.4	22.7	30	42.9	38	13
Insulation Resistance at 2kV for 1 Minute	>200MΩ	>200MΩ	>200MΩ	>200MΩ	>200MΩ	>200MΩ	>200MΩ	>200MΩ
Flash Test Voltage for 1 minute	2kV	2kV	2kV	2kV	2kV	2kV	2kV	2kV
Primary Winding Resistance at 20°C	1.79Ω	1.30	0.93Ω	0.53Ω	0.53Ω	0.24Ω	0.216Ω	1.73Ω
Secondary Winding Resistance at 20°C	0.52Ω	0.37Ω	0.25Ω	0.16Ω	0.16Ω	0.075Ω	0.04Ω	0.91Ω
Winding Temperature Rise	96	90	92	95	98	98	84	80
Primary Thermal Circuit Breaker Rating	3Amp	4Amp	6Amp	8Amp	10Amp	15Amp	15Amp	6Amp
Dimensions, Width x Depth x Height (mm)	160x210x220	160x210x220	160x210x220	190x240x260	190x240x260	270x320x280	230x300x370	175x75x175
Weight (Kg)	9	10.5	11.5	16	18	30	32	7
Output Sockets	1x16A BS EN 60309	1x16A BS EN 60309	2x16A BS EN 60309	2x16A BS EN 60309	2x16A BS EN 60309	2x16A BS EN 60309	1x32A BS EN 60309	1x16A BS EN 60309

Materials and Construction

The enclosure is moulded from DMC (Dough moulded compound) which is fibre glass with a Flame retardant compound and is self extinguishing (not 399-6140).

The enclosure for 399-6140 is sheet steel ventilated to IP22 and finished in golden yellow to BS4800 shade 08 E 51

The encapsulant used to retain the transformer is a flame retardant Polyurethane resin which incorporates a silica sand filler.

The bobbin is manufactured in nylon and is rated for operation at 140°C

The interwinding and screen insulation is nomex/polyester composite.

The winding wire is dual coated polyester, grade 2 rated for 200°C.

The mains cable fitted on the 500-3300 VA range has fitted a moulded 13 Amp plug with a 13 Amp fuse.

The mains cable fitted on 260-4301 & 399-6140 is supplied unterminated to allow the user to fit the required style of plug.

RS Tech - PPT Rev3.doc 14/12/2011

Assignment 1

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

75/100

PAGE 1

PAGE 2

QM

Good Structure

Report is structured exactly as stated in the assignment brief.

PAGE 3

PAGE 4

PAGE 5

QM

Correctly cited

Citation method conforms to Harvard standard, well done.

QM

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PAGE 6

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Text Comment. At this level, a much wider range of sources is expected.

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GARETH WILKINS

75

1. ENGAGEMENT WITH LITERATURE



Engagement with an appropriate range of literature, including sources retrieved independently. Some over-reliance on texts. Referencing may show minor inaccuracies or inconsistencies. (10/20)

10

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

16

some grasp of the broader field and wider concepts (16/20)

4. PRACTICAL APPLICATION



An advanced application of a range of established methods, materials, tools and/or techniques. The context of the application is well considered, and insightful. Consistent, accurate and logical application of theory to practice, making well-developed links between the two. Can identify problems and propose excellent, creative solutions outside the context in which they were first studied. (15/20)

15

5. TRANSFERABLE SKILLS



Can communicate with an exceptionally high level of professionalism, highly suitable for the audience. Work is exceptionally coherent, very fluent and is presented professionally. Can work exceptionally well within a team, showing leadership skills. Demonstrates exceptional skills for employment requiring the exercise of personal responsibility and decision-making and an appetite for further development. (18/20)

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