

# 1809810

by David Thomas

EXCELLENT RESEARCH AND CONSISTENT CITATIONS  
THROUGHOUT. SOME LARGE TABLES FULL OF TEXT  
CIRCUMVENT THE WORD COUNT. EXCELLENT KNOWLEDGE  
AND CRITICAL ANALYSIS WAS EVIDENT THROUGHOUT THE  
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## *1. Executive Summary*

The project involved the design and simulation of a single-phase transformer and three-phase induction motor, supporting initial research undertaken into induction motors and methods of speed control. The overall aims were to predict voltage regulation and efficiency and perform open and short circuit testing to prove the transformer circuit theory, and acquire per-phase circuit parameters to assess motor performance over various speeds in known operation phases. The practicality of using the simulated motor circuit to predict performance under various loads was also tested. Calculated, practical and simulated results were compared throughout to ascertain successfulness of the project.

The basis of the single-phase transformer was to conduct two practical tests, consisting of iron loss and copper loss, also known as open and short circuit testing. Both involved connection of the transformer primary and secondary to a variable power supply, however in the iron loss circuit secondary connections were separated, in the copper loss they were connected, creating open and short circuit conditions respectively. Test conditions were created using a variable power dial to apply the correct AC input voltage in the iron loss circuit and secondary current in the copper loss circuit. In the copper loss circuit voltage had to be applied slowly to the primary circuit in order to prevent iron losses affecting the results.

A further three practical voltage regulation tests were conducted on the transformer equivalent circuit with simulated resistive, inductive, and capacitive loads added. For the voltage regulation tests, the transformer primary and secondary was connected to the variable power supply with a series of secondary connections to simulate each load. AC voltage and variable power dials to apply the required input voltage, created test conditions.

The basis of the three-phase induction motor was to conduct three practical tests, consisting of stator resistance, no load and blocked rotor tests, allowing calculation of required components to construct a motor equivalent circuit. The final two tests conducted involved externally driving the motor from synchronous, to above synchronous speed into a generating state, recording circuit values required for motoring RPM. Application of different torque values while driven at synchronous speed allowed for calculation of the slip value from recordings of circuit and motor values at the required stages.

## 2. Research

Induction motor use in industry has significantly increased due to increased cost-effectiveness, durability and ease of construction (Elfadili, 2010). They can operate across a wide capacity range from fractional to megawatt horsepower, enabling use across a wide range of applications (shodhganga, 2017).

| AC Induction Motors                                                                                                                                                                                                                                                                                |                                                                                                                                                                   |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Advantages                                                                                                                                                                                                                                                                                         | Disadvantages                                                                                                                                                     |
| Lower costs (no requirement for brushes)<br>Set up costs are reduced (no driver required)<br>Prolonged lifespans<br>Reliable and robust (operates in variable environmental conditions)<br>High efficiency<br>Simple design/construction<br>Start torque is higher.<br>Self-starting (three-phase) | Rotation slip can be caused by frequency.<br>Needs a start switch (single phase)<br>Speed control is difficult (requires power electrical converters – see below) |

*Table 1 - AC induction Motor Advantages/Disadvantages*

(Electricaltechnology, 2020) & (Elprocus, 2020) *Separate your sources when citing*

Induction motors are a type of electrical motor driven by an alternating current i.e. AC Motor (Electrical4u, 2020). Induction motors utilize rotating magnetic fields (electromagnetic induction) to convert electrical into mechanical energy, (shodhganga, 2017), powering devices such as small pumps and fans, to large scale industrial motors, conveyers, hoists cranes and much more (Anaheimautomation, 2020). They are constructed of two parts; a stator (stationary part fed by the AC supply) and rotor (rotating electromagnet part to which a mechanical load connects). Rotation of the electrical motor occurs as a result of the AC supply to the stator generating a uniform magnitude electromagnetic field (alternating flux around the stator), creating a magnetic force between the stator and rotor (Elprocus, 2020). The resultant electromagnetic torque, causing the rotor to rotate in the direction of the magnetic field, is responsible for the conversion of electrical into mechanical energy (shodhganga, 2017).

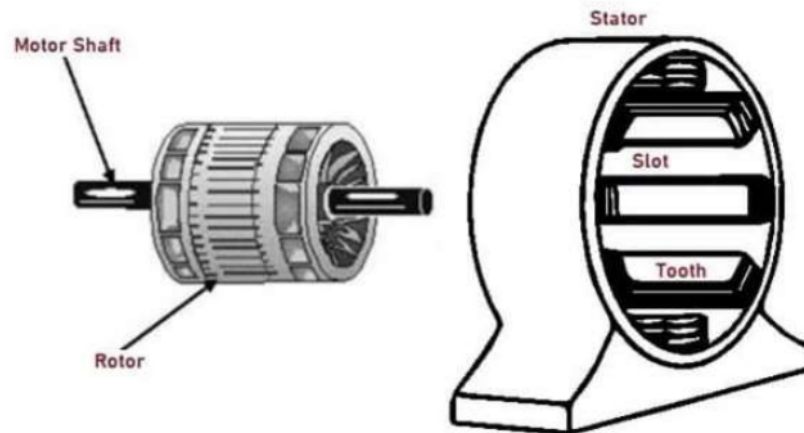
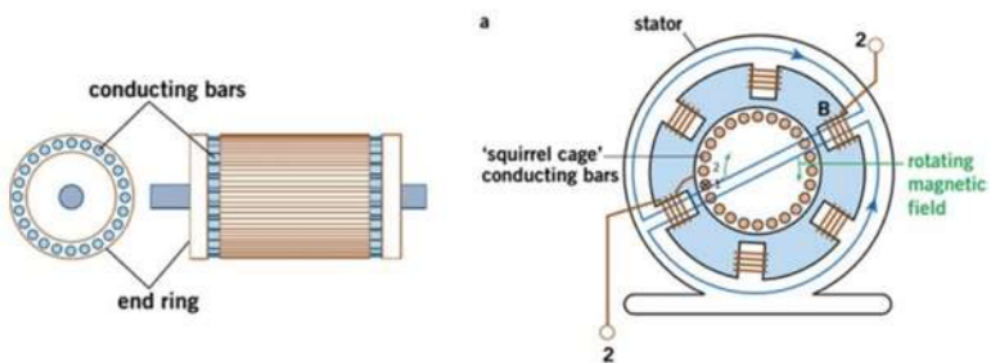


Figure 1 - Induction Motor  
(Ashrit, 2020)

The rotor speed constantly tries to attain that of the stator magnetic field (synchronous speed), however this is never achieved, hence the alternative name asynchronous motors (Elprocus, 2020).

Although both single and three-phase, the most common form encountered in industry is the three-phase induction motor (Elprocus, 2020), taking advantage of its low cost, robustness, reliability, and responsiveness to torque (shodhganga, 2017). Three-phase motors are self-starting, requiring no capacitor, and fall into two categories, the more common squirrel-cage or the slipring. Extensively used in domestic applications, single-phase induction motors can be found in some low power industrial applications such as compressors, pumps, and drilling machines (Elprocus, 2020).



*Construction was not part of the research task*

Figure 2 - Squirrel Cage Motor

(Schweber, 2017)

Since these tables are not considered as part of the word count, it may be better to put them in the appendix next time.

| Three Phase Induction Motors    |                                                                                                              |                                                                                                                                                                          |
|---------------------------------|--------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Type                            | Squirrel Cage                                                                                                | Slip-Ring                                                                                                                                                                |
| <b>Construction / Operation</b> | Cylindrical laminate core & angled slots on outer periphery<br>Rotor consists of rotor bars.                 | Cylindrical laminate core with rotor positioned within the slots.<br>Number of poles of stator & rotor winding are identical, with terminals connected to the slip rings |
| <b>Application</b>              | Often used where speed control is not required (however see below)<br><br>Pumps<br>Machine press<br>Conveyer | Used for application requiring a higher initial torque i.e. heavy loads.<br><br>Hoists<br>Cranes<br>Line shaft<br>Lifts                                                  |

Table 2 - Three Phase Induction Motors

(Elprocus, 2020)

The main disadvantage of induction motors (particularly squirrel cage) is they are inherently difficult to control, running at a constant speed across a load range, significantly limiting applications to known steady loads (Anaheimautomation, 2020). Many industrial processes however, such as assembly lines, require variable speed operation; addition of variable speed drives (VSD) enabling this (Anaheimautomation, 2020). Significant advances in power electronics, specifically reliable power electronic converters (PEC), has allowed expansion of induction machine applications by enabling control/variation of speed (Elfadili, 2010).

PECs (a form of solid-state electronics) essentially convert electrical energy generated by a power supply, into the optimal form required by a motor/load e.g. AC→DC, changing voltage and/or frequency (Siwakoti, 2018). PECs condition power to suit applications aiming to improve energy efficiency, power loss, reliability and cost-effectiveness. PEC block diagrams consist of four elements (see below), controlling and converting electrical power using components such as silicone-controlled rectifiers or insulated-gate bipolar transistors (Electronicshub, 2015). Construction varies from simple designs to series/cascades of connected converters involving multiple stages (Siwakoti, 2018).

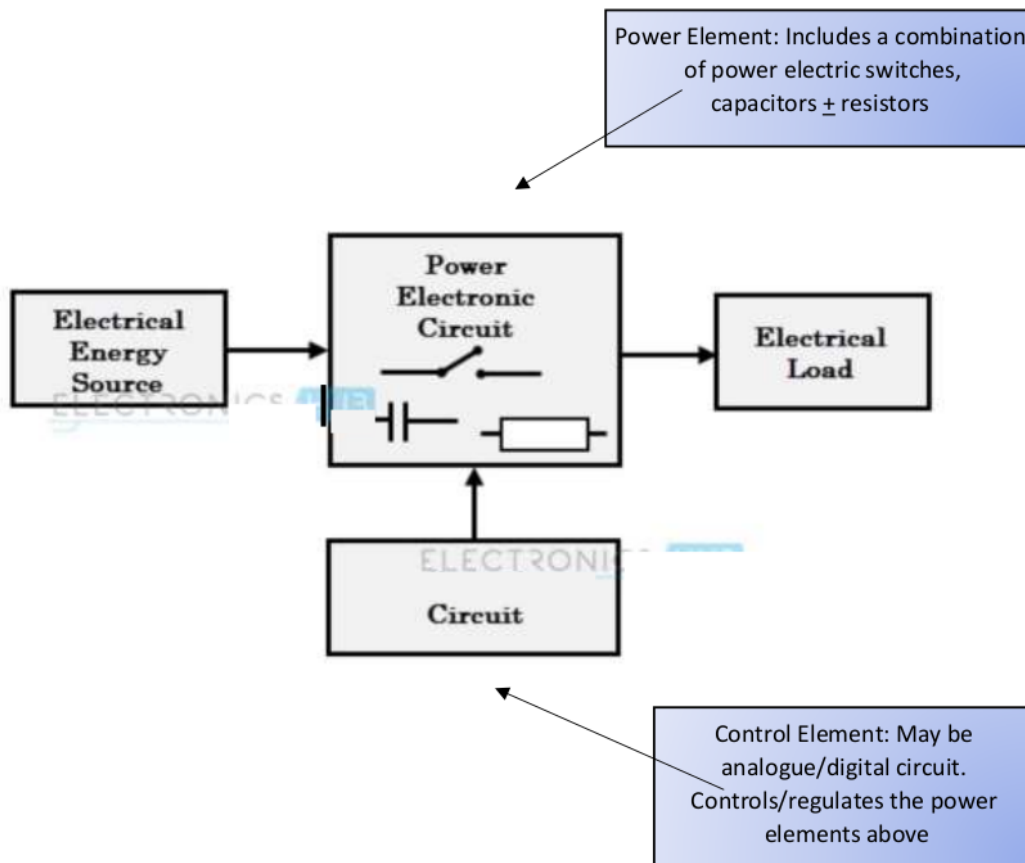


Figure 3 - Block Diagram of a Power Electronic Converter

(Electronicshub, 2015)

They can perform a number of different types of power conversion depending on the application (Electronicshub, 2015):

| Power Conversion                                                                                                  | Operation                                                                                                                                                                                                                           | Comment                                                                                                                                                                                                                                                             |
|-------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>AC-DC (Rectifier:<br/>Converts AC to DC<br/>current)</b>                                                       | Transformer (often step-down, altering primary AC supply to input), switching unit (AC switched to DC using diodes or thyristors) filter (filters pulse output), control block (regulates thyristor angle – not present in diodes). | Can be uncontrolled diode or controlled. Can be further subdivided e.g. three-phase half wave diode (lower power applications due to potential saturation of transformer core), three-phase full wave bridge diode (high power applications), phase controlled etc. |
| <b>DC-AC (Inverter:<br/>Converts DC to the<br/>required frequency and<br/>voltage AC, sine-like<br/>waveform)</b> | Fixed DC supply converted to variable AC i.e. connection between DC source & varied AC load.<br>Requires variation of thyristor trigger angle.                                                                                      | Can be single or three-phase, PWM or multilevel, voltage or current source.<br>Industry frequently use multilevel.                                                                                                                                                  |
| <b>DC-DC (Chopper:<br/>converts fixed DC input<br/>to variable)</b>                                               | Switching units e.g. thyristors.<br>Output DC voltage width varied by altering thyristor ON time (PWM)                                                                                                                              | DC applications requiring varied DC voltage converted from static DC source e.g. DC motors needed varied speed, electric vehicles                                                                                                                                   |
| <b>AC-AC (Cyclo/matrix<br/>converter).</b>                                                                        | Single phase – couple of anti-parallel thyristors plus control circuit                                                                                                                                                              | Used to start AC motors or regulate heater power                                                                                                                                                                                                                    |

*Table 3 - Types of Power Conversion*

(Electronicshub, 2015)

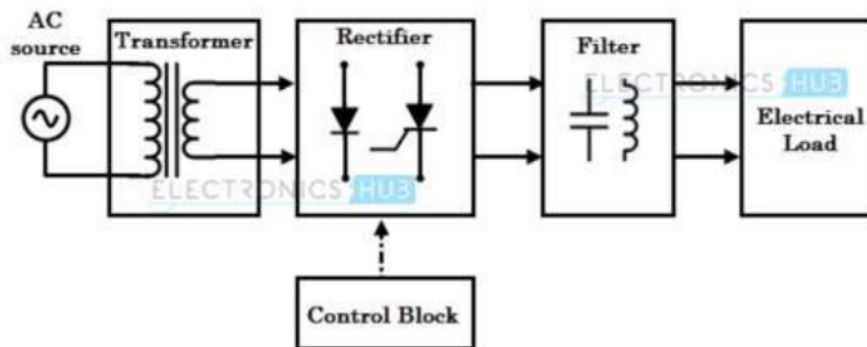


Figure 4 - AC-DC Rectifier Block Diagram

(Electronicshub, 2015)

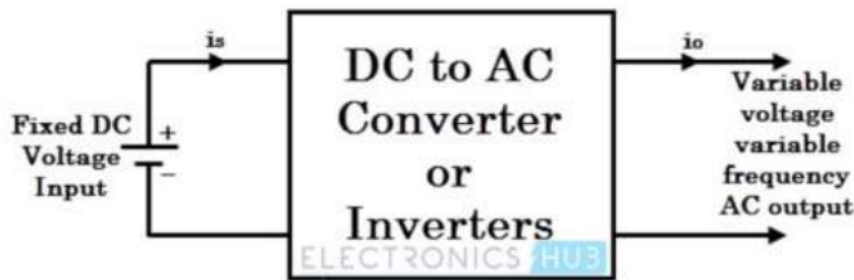


Figure 5 - DC to AC Inverter Block Diagram

(Electronicshub, 2015)

The most common industrial application of PECs is induction machine speed control in VSDs; varying drive speed to adjust flow within a process, offering energy savings over traditional methods (Anaheimautomation, 2020). Based on construction, there are a number of ways in which the speed can be controlled, loosely categorised as scalar, vector, direct-torque and Proportional-Integral-Derivative (PID) control (Meeti, 2017).

Scalar control methods are used for lower power machines, requiring less precise speed control, without sensors e.g. pumps/compressors (shodhganga, 2017). The most common method is Volts-Hertz, whereby both frequency and voltage are adjusted, usually maintaining a constant torque and varied speed. These systems have the advantage of reduced rotor resistance and higher efficiency. Other types can be seen below:

| Type of Scalar Speed Control     | Method                                                                                                                                                                                                                                                                | Comments                                                                                                                                                                                                                                                                                                               |
|----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Stator Voltage Control</b>    | Voltage varied, frequency constant.<br>Voltage varied by controlling inverter switches                                                                                                                                                                                | Speed range low for low-slip motors<br>Unsuitable with constant torque load<br>Power factor is low<br>Mainly useful for applications using low power e.g. fans                                                                                                                                                         |
| <b>Frequency Control</b>         | Frequency varied, voltage constant                                                                                                                                                                                                                                    | Rarely used due to limitations with motor current:<br>Low frequency: reactance reduced resulting in current being too high<br>High frequency: rotor current drops along with torque                                                                                                                                    |
| <b>Volts Hertz (V/F) Control</b> | Proportional change in frequency and stator voltage maintains constant air gap flux. This improves efficiency of run time<br>Variation in voltage and frequency allows variation in both torque and speed though commonly torque will be constant, and speed altered. | Most common scalar control<br>Used in industrial applications<br>Low rotor resistance due to low slip increases efficiency<br>Allows low starting current (soft start) improving machine lifespan and lower service costs as mechanical stress is reduced<br>Wide speed range allowing different setting for each load |

*Table 4 - Scalar Speed Control*

(shodhganga, 2017)

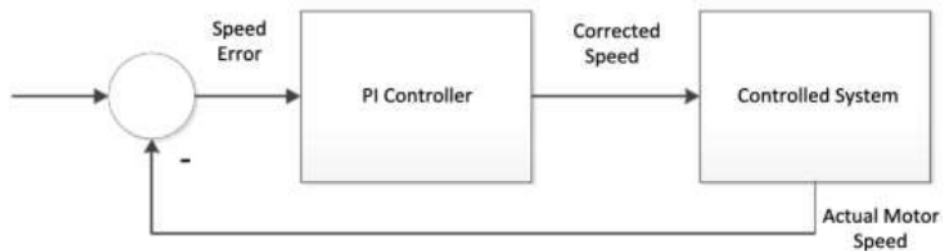


*Figure 6 - Diagram of V/F scalar control*

(Rahman, 2016)

Vector control can be direct or indirect and uses feedback control (Meeti, 2017). Speed control is provided by varying stator current space vectors. Optimum speed control is achieved by independent control of both magnetizing and torque-producing components of the stator current (Rahman, 2016), enabling prompt torque response (Meeti, 2017).

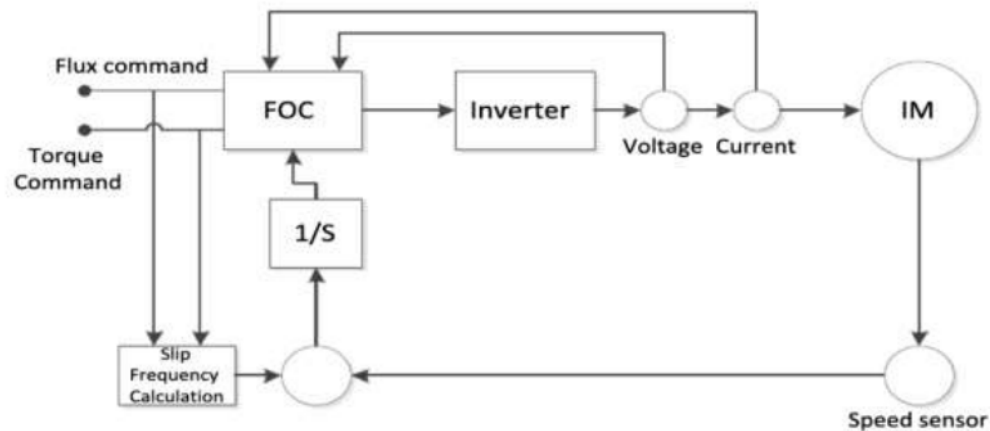


Figure 7 - Direct Vector Control

(Rahman, 2016)

Direct-Torque Control (DTC) controls speed using adjustable frequency converters. By altering the invert switch combination responsible for driving the stator vector to vary the stator flux, the desired torque is achieved (Meeti, 2017).

| DTC Stages |                                                                                                 |
|------------|-------------------------------------------------------------------------------------------------|
| 1          | Estimation of speed and torque                                                                  |
| 2          | Estimated and required values of speed compared                                                 |
| 3          | Reference torque signal created from PI controller from error signal received                   |
| 4          | Reference signal for stator flux created from approximated speed                                |
| 5          | Position of stator vector & torque/stator flux error describes to space vector of stator vector |

Table 5 - DTC Steps

(Meeti, 2017)

PID controls use a feedback system, differences between set and measured speeds creating a value of error, which is sent to the PI control. Pulse Width Modulation signals are created dependant on the error signal, which are then sent to the inverter. Speed/torque can be corrected to that desired, creating the necessary current and voltage (Meeti, 2017).

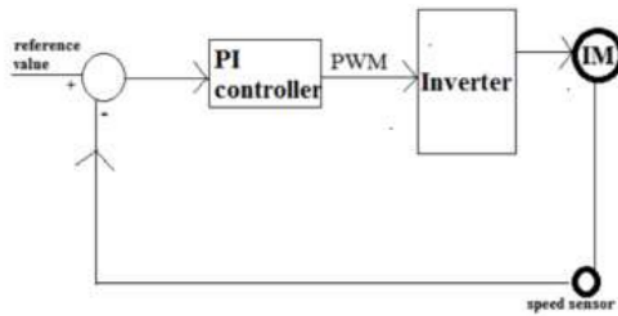


Figure 8 - PID Control

(Meeti, 2017)

| Feature                          | Scaler V/F Control            | Vector Control                                                | Direct Torque                                               |
|----------------------------------|-------------------------------|---------------------------------------------------------------|-------------------------------------------------------------|
| Speed Response                   | Varies at each load           | Good but a degree of overshoot                                | Most rapid                                                  |
| Torque Response                  | Larger torque at lower speeds | Less ripples seen<br>Faster response than DTC but spikes seen | Better than VC                                              |
| Transient Response               | Slow                          | Rapid                                                         | N/A                                                         |
| Flux Response                    | N/A                           | Load affects response. Slower than DTC                        | Stable response and faster than VC                          |
| Difficulty of implementation/use | Easy                          | Transformation complicates it                                 | Easy                                                        |
| Other                            |                               | Slight deviations in speed seen. Gradual rise in current      | Zero speed seen at some points. Current will abruptly fall. |

Table 6 - SCM, VCM, DTC Comparison

(Meeti, 2017)

The most common type of VSD for induction machine speed control is the Variable Frequency Drive (VFD), which falls into the various control methods described above, operating by altering electrical supply frequency. VFD provide a controlled increase in both voltage and frequency, while excess current is eradicated. By altering the speed to meet the attached motor load requirements, energy efficiency can be improved. Generated power is converted by the PEC in three separate steps: (Anaheimautomation, 2020).

- AC power converted to DC power (Converter)
- Power transistor switched on and off to produce a voltage waveform at the frequency needed
- Output voltage adjusted to the specified value by the above voltage waveform

### Advantages of VFD

- Minimal maintenance
- Reduces operating overheads
- Lifespan of the induction motor extended
- Protects equipment from exposure to excessive torque
- Allows control of process temperature without the addition of a dedicated controller.

Table 7 - Advantages of VFD

(Anaheimautomation, 2020)

Three commonly used VFD are described below, each consisting of a Converter, DC link and an Inverter, however construction and therefore manner by which the frequency and voltage are supplied to the motor vary.

| Type of VFD                          | Converter (AC→DC)                                                                                                                                                                                          | DC Link                                                                                   | Inverter (DC→AC)                                                                                                                                                                                                                                                                                                                        |
|--------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Current Source Inverter (CSI)</b> | Silicon-controlled rectifiers (SCR), Gate-commutated thyristors (GCT) or Symmetrical GCT (SGCT) convert incoming AC to variable DC voltage<br>Correct sequencing of SCR essential to maintain desired V/F. | Inductor regulates current ripple and stores energy utilized by motor                     | SCRs, Gate turn-off thyristors (GTO) or SGCT.<br>Thyristors are turned on and off (switch-like) generating Pulse Width Modulation (PWM) output regulating motor F/V.                                                                                                                                                                    |
| <b>Voltage Source Inverter (VSI)</b> | As with CSI, AC converted to DC voltage.<br>However, uses a diode rectifier bridge.                                                                                                                        | Capacitors used to remove DC voltage ripple and store energy                              | Insulated GCT (IGCT) / insulated gate bipolar transistors / Injection-enhanced gate transistors<br>Thyristors control V/F by acting as switches as with CSI                                                                                                                                                                             |
| <b>Pulse Width Modulation (PWM)</b>  | As with VFI, AC converted to DC voltage using a diode rectifier bridge.                                                                                                                                    | DC voltage ripple smoothed out using large capacitors. Also stabilizes the DC bus voltage | Six step inverter<br>High power IGBT which act like switches to regulate motor F/V.<br>Microprocessors controlled by transistors/motor IC which also ensure sequencing is correct.<br>Altering voltage pulse width creates an average power to supply to motor voltage.<br>Amount of +/- transitions every second defines the frequency |

Table 8 - VFD comparison

Useful tables, could be better in the appendix.

(Anaheimautomation, 2020)

| VFD | Advantages                                                                                                                                    | Disadvantages                                                                                                                                                                                               |
|-----|-----------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| CSI | Simplicity of circuit<br>Reliable<br>Current waveform clean<br>Regenerative Power Capability: Can absorb any power driven back from the motor | Require large, therefore costly, inductor<br>Relies on motor load<br>Poor power factor and power input high harmonics mean that design on input and output filters must be considered to reduce the effects |
| VSI | Simplicity of circuit<br>Can be used where multiple motors are required<br>Unlike CSI does not rely on motor load                             | As with CSI, the power factor is poor and harmonic generation high<br>Unlike CSI they have no regenerative power capability                                                                                 |
| PWM | Highly efficient (92-96%)<br>DC bus voltage creates high power factor<br>Preliminary costs are low<br>Compatible with set-ups using >1 motor  | As with VSI they have no regenerative power<br>Risk of generating heat in the motor and failure of the insulation due to high frequency switching                                                           |

*Table 9 - VFD Advantages & Disadvantages*

(Anaheimautomation, 2020)

PWM is one of the most widely used as it works with motors across a wide horsepower range for induction motors and can operate across a three-phase 230/460V supply, producing 2-400Hz output frequencies (Anaheimautomation, 2020).

With PEC developments and use of three-phase induction motors in industry ever increasing, factories must ensure incoming power supply is sufficient to maintain smooth, constant operation of end applications, and allow the induction motor rotating magnetic field to be produced (Cableorganizer, 2020). Three phase, 3/4 wire systems are the most common AC power distribution systems for factory supply, each phase connected in delta or star form (Daware, 2018). Conversion of mechanical energy into three ACs; one from each wind of an electrical generator at the power station creates three-phase AC power supply (Cableorganizer, 2020). In three-phase four-wire supply, there are four wires; three circuit conductor and one neutral. The three conductor wires carrying sinusoidal ACs of identical frequency, are positioned 120 degrees apart, allowing each to reach maximum voltage at a different time (Polly, 2020). The system uses one conductor wire as a reference; second and third currents delayed by one and two thirds respectively (Cableorganizer, 2020). This phase delay ensures a constant 415V supply can be provided, never dropping to zero, unlike single-phase power supply (Polly, 2020). Although most supplies will incorporate a neutral wire to allow a high voltage supply to also support lower voltage single phase uses, high voltage distribution systems may connect loads directly between phases and therefore not incorporate a neutral wire (three-wire) (Cableorganizer, 2020). Power supply to

factories will usually be supplied from the primary distribution system (Daware, 2018) incorporating transformers to change voltage (usually step-down), minimising losses, increasing or decreasing capacitance, induction or resistance as required. (Wickramarachchi, 2018)

| Three Phase Power Supply in Industrial Factories                                                      |                                                                  |
|-------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| Advantages                                                                                            | Disadvantages                                                    |
| Able to run more heavy electrical loads                                                               | Insulation costs higher                                          |
| Starters not required for 3-phase motors as the phase difference is adequate to supply initial torque | Unable to manage overload – resultant damage is costly to repair |
| More economical as transmission & distribution of power uses less conducting materials                |                                                                  |
| Power transfer is constant reducing vibrations from generators & motors                               |                                                                  |
| Allows a simpler motor design as 3-phase generates a magnetic field rotating in a specific direction  |                                                                  |

*Table 10 - Three Phase Power Supply in Industrial Factories*

(Polly, 2020)

The many advantages to three-phase induction machines means their use is ever increasing across industry, requiring a continuous, reliable three-phase power supply to ensure smooth and consistent operation. However, their non-linear nature has inherently resulted in induction motors being difficult to control (Elfadili, 2010). Substantial progress in power electronics technology, particularly dependable PECs, able to vary supply frequency, has offset these concerns, producing induction machines capable of variable speed control (Elfadili, 2010). VFDs are the current mainstay, however these systems still have a number of downfalls. Further refinement however is likely, with continued focus on PEC development as a means of providing electric renewable energy systems (Haque, 2016).

### 3. Transformer Investigation

#### 3.1 Iron Losses - Open Circuit

| Method Step | Description                                                                                                                     |
|-------------|---------------------------------------------------------------------------------------------------------------------------------|
| 1           | Appropriate PPE worn to undertake practical experiment.<br>Current government guidelines followed to maintain social distancing |
| 2           | Connect primary & secondary transformer to Variable Power Supply (VPS)                                                          |
| 3           | Separate secondary connects (creates open circuit)                                                                              |
| 4           | Select AC voltage                                                                                                               |
| 5           | Adjust variable power dial to apply input voltage for test conditions (primary voltage of 230VAC)                               |
| 6           | Nanovip tester used to measure primary and secondary winding values, of voltage, current, power and power factor.               |

Table 11 - Iron Loss Test Method

| 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 12 - Iron Loss Test Values

With practical values obtained (see above), component values (shown below) for the transformer equivalent circuit were calculated (appendix 7.1)

| Component Values |                 |       |
|------------------|-----------------|-------|
| Rc               | 1679.4 $\Omega$ |       |
| Xm               | 451.87 $\Omega$ | 1.44H |
| Ic               | 137mA           |       |
| Im               | 509mA           |       |
| V1               | 230V            |       |
| I1               | 527mA           |       |

Table 13 - Iron Loss Circuit Component Values

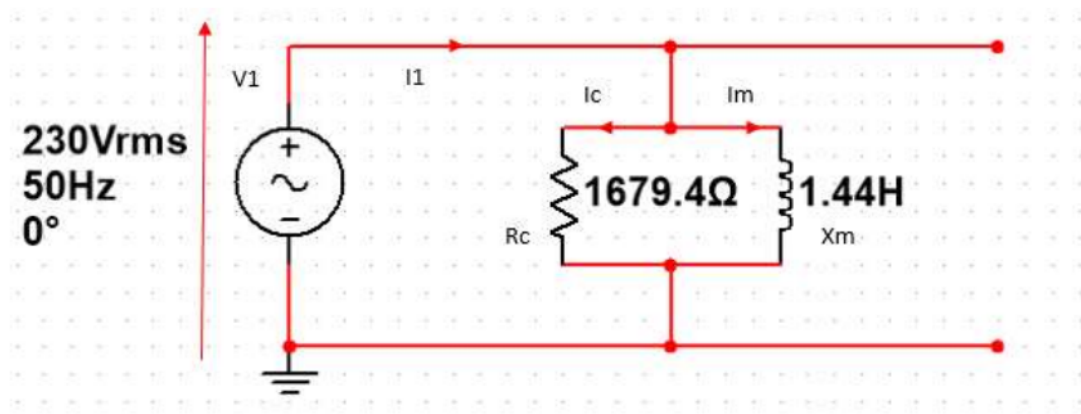


*Figure 9 - Iron Loss Equivalent Circuit*

The iron loss circuit illustrated above was designed and built using the calculated component values. To create the transformer equivalent circuit for testing and analysis, the copper loss equivalent circuit was also built and combined with the above.

### 3.2 Copper Losses - Short Circuit

| Method Step | Description                                                                                                                                                                |
|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1           | Appropriate PPE worn to undertake practical experiment.<br>Current government guidelines followed to maintain social distancing                                            |
| 2           | Connect primary & secondary transformer to Variable Power Supply (VPS)                                                                                                     |
| 3           | Connect secondary connections as one (creates short circuit conditions)                                                                                                    |
| 4           | Select AC voltage/current                                                                                                                                                  |
| 5           | Adjust variable power dial to apply input current for test conditions (Test voltage significantly reduced as not to have iron losses applied to the test)                  |
| 6           | Slow application of voltage to the circuit primary to allow a secondary current reading as close to the calculated value of 3.41A as possible (measured by Nanovip tester) |
| 7           | Nanovip tester used to measure primary and secondary circuit values                                                                                                        |

*Table 14 - Copper Loss Test Method*

| 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 15 - Copper Loss Test Values*

With practical values obtained (see above), component values (shown below) for the transformer equivalent circuit were calculated (appendix 7.2).

| Component Values |        |        |
|------------------|--------|--------|
| Z1E              | 5.221Ω |        |
| R1E              | 2.731Ω |        |
| X1E              | 4.45Ω  | 14.2mH |
| Z2E              | 1.194Ω |        |
| R2E              | 0.625Ω |        |
| X2E              | 1.018Ω | 3.24mH |
| I2               | 3.596A |        |

*Table 16 - Copper Loss Circuit Component Values*

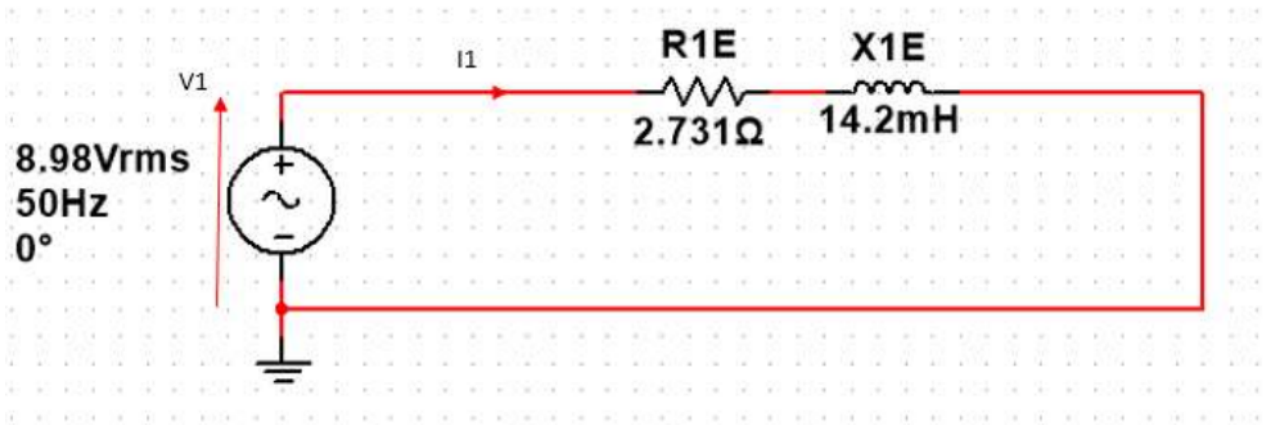


*Figure 10 - Copper Loss Equivalent Circuit*

The copper loss circuit illustrated above circuit was designed and built using the calculated component values. With both iron and copper loss equivalent circuits designed, these were combined to create a transformer equivalent circuit for testing and analysis.

### 3.3 Voltage Regulation - Load Test.

| Method Step | Description                                                                                                                                                                                                                                                    |
|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1           | Appropriate PPE worn to undertake practical experiment.<br>Current government guidelines followed to maintain social distancing                                                                                                                                |
| 2           | Connect primary & secondary transformer to Variable Power Supply (VPS)                                                                                                                                                                                         |
| 3           | Series of secondary connections made depending on load type:<br>a) $33\Omega$ load for resistive load,<br>b) $36.5\Omega$ resistor and $93\text{mH}$ inductor for inductive load<br>c) $28.3\Omega$ resistor and $48\mu\text{F}$ capacitor for capacitive load |
| 4           | AC voltage selected                                                                                                                                                                                                                                            |
| 5           | Adjust variable power dial to apply input voltage for test conditions (primary voltage of $230\text{VAC}$ )                                                                                                                                                    |
| 6           | Nanovip tester used to measure primary and secondary winding values, of voltage, current, power and power factor.                                                                                                                                              |

Table 17 - Voltage Regulation Test Methods

| 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                |

Table 18 - Voltage Regulation Test Values

With circuit values measured (shown above), copper loss equivalent circuit calculated component values, and  $33\Omega$  resistive load, the resistive load equivalent circuit were built using Multisim.

| Component Values |                 |                 |
|------------------|-----------------|-----------------|
| E2               | 113v            |                 |
| V2               | 108v            |                 |
| R2E              | $0.625\Omega$   |                 |
| X2E              | $1.018\Omega$   | $3.24\text{mH}$ |
| I2               | $3.596\text{A}$ |                 |
| ZL               | $33\Omega$      |                 |

Table 19 - Voltage Regulation Component Values

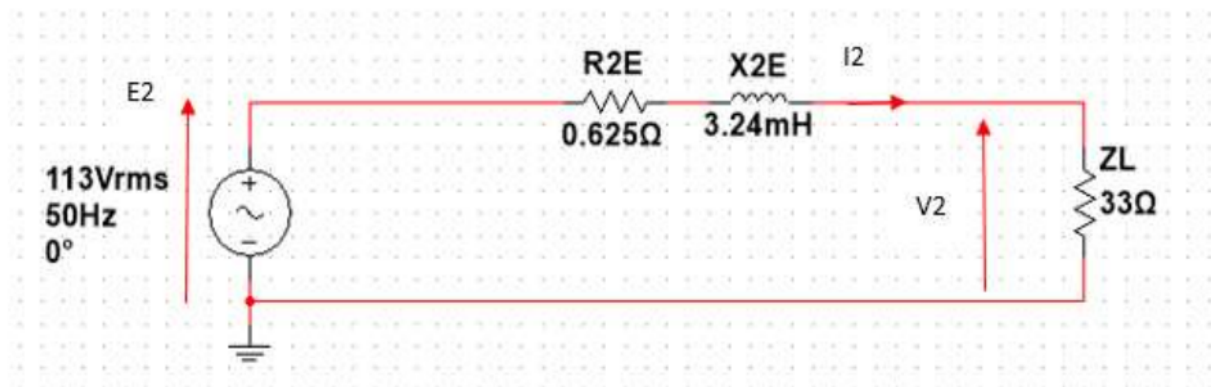


Figure 11 - Voltage Regulation Resistive Load Equivalent Circuit

Further voltage regulation tests were conducted to provide voltage regulation values for the transformer with inductive and capacitive loads. For the inductive load test, a 36.5Ω resistor and 93mH inductance was placed onto the circuit. For the capacitive load test, a capacitive load of 28.3Ω resistor and 48μF capacitor were added.

| Voltage Regulation - Full Load |     |                |                  |
|--------------------------------|-----|----------------|------------------|
|                                |     | Primary Values | Secondary Values |
| Voltage                        | V   | 230            | 110              |
| Current                        | I   | 1.55           | 2.26             |
| Power                          | W   | 208            | 177              |
| Power Factor                   | P.F | 0.58           | 0.72             |

Table 20 - Inductive Load Voltage Regulation Test Values

With circuit voltage values measured, shown above, and component values obtained from copper loss test results, along with the 36.5Ω resistive and 93mH load, the full load equivalent circuit was built using Multisim.

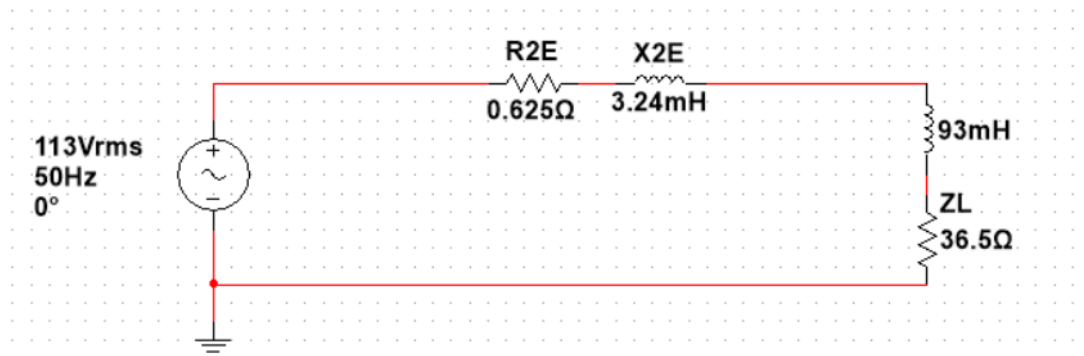


Figure 12 - Voltage Regulation Inductive Load Equivalent Circuit

| Voltage Regulation - Capacitive |     |                |                  |
|---------------------------------|-----|----------------|------------------|
|                                 |     | Primary Values | Secondary Values |
| Voltage                         | V   | 230            | 114              |
| Current                         | I   | 469mA          | 1.58             |
| Power                           | W   | 86.3           | 68.8             |
| Power Factor                    | P.F | -0.8           | -0.38            |

Table 21 - Capacitive Load Voltage Regulation Test Values

With circuit voltage values measured, shown above, and component values obtained from the copper loss test results, along with the 28.3Ω resistor and 48μF capacitance load, the overload equivalent circuit was built using Multisim.

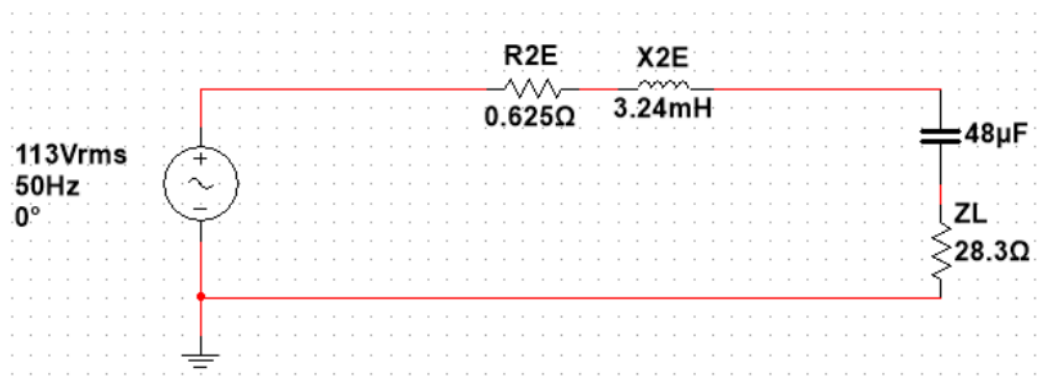


Figure 13 - Voltage Regulation Capacitive Load Equivalent Circuit

### 3.4 Testing & Analysis

Illustrated below, iron and copper loss circuits were combined to create the equivalent transformer circuit. Volt, amp and watt were added to the circuit to extract data from the simulation. The values were recorded for comparison and analysis.

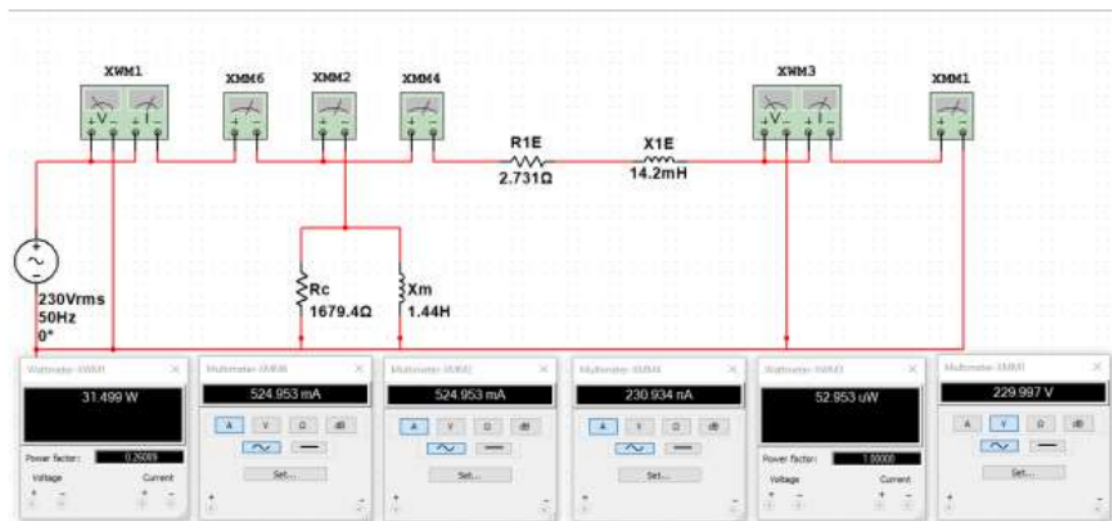


Figure 14 - Iron Loss equivalent Circuit

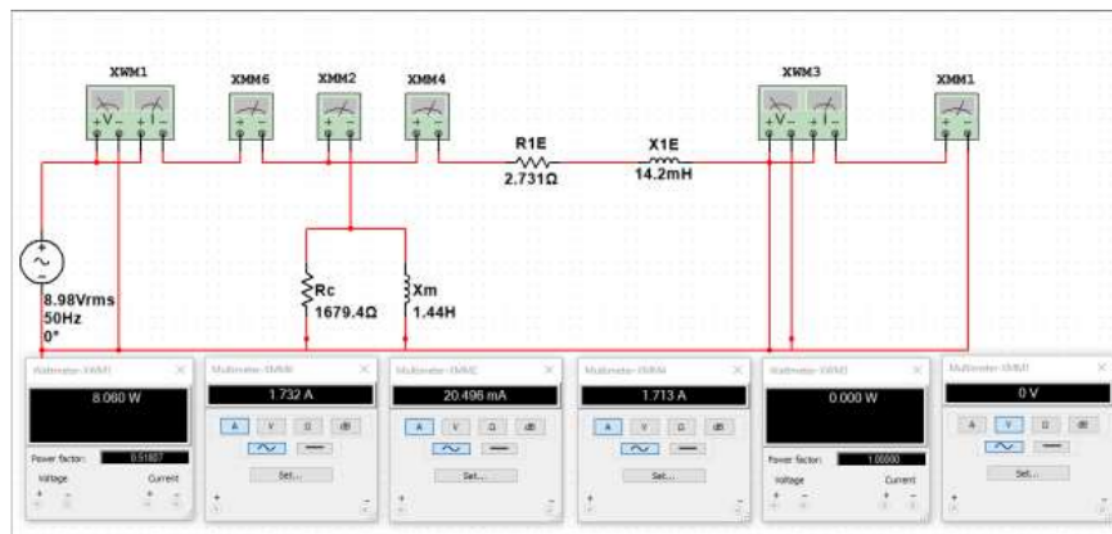


Figure 15 - Copper Loss Equivalent Circuit

For both iron and copper loss equivalent circuits, data extracted from the simulation was compared with practical values. Note, due to ratio of the transformer windings, voltage for the secondary is referenced to the primary and for the true value, would have to be halved. For the copper loss circuit, the secondary current is referenced to the primary current, and for the true value, would have to be doubled.

Shown below are practical and calculated values, as well as data from the transformer's data sheet (see appendix 7).

| 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                |

*Table 22 - Iron Loss Comparison Table*

For iron losses, primary simulated and practical values for voltage, power and power factor, when rounded to two decimal places, were identical. For primary current values, there was a difference of 15.95mA. When comparing secondary voltage practical values to simulated and data sheet values, a difference of 1.99v and 0.8v respectively was seen. Although not significant, these differences could be attributed to test conditions, cable resistance or volt drop. Although primary power values for practical and simulated circuits were identical, there was a significant difference between this and the data sheet value. No comparisons could be made to the primary values for current and power factor values from the datasheet, as those figures were not provided.

| 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                |

*Table 23 - Copper Loss Comparison Table*

For copper losses, primary voltage, and power factor, when rounded to two decimal places, were identical. The primary and secondary current values for practical and simulation differ by 0.012A and 0.006A respectively, whilst power differs by 0.02W. Each of these differences are negligible. The datasheet however does display a difference of 0.97W and 0.99W between practical and simulated values, respectively.

No comparisons could be made to the primary values for voltage, current and power factor, or for the secondary current values from the datasheet, as those figures were not provided.

For each of the resistive, inductive and capacitive loads, practical values, simulated values from the equivalent circuit, and calculated values for each of the load voltage regulation (appendix 7.3) were compared in tabulated form.

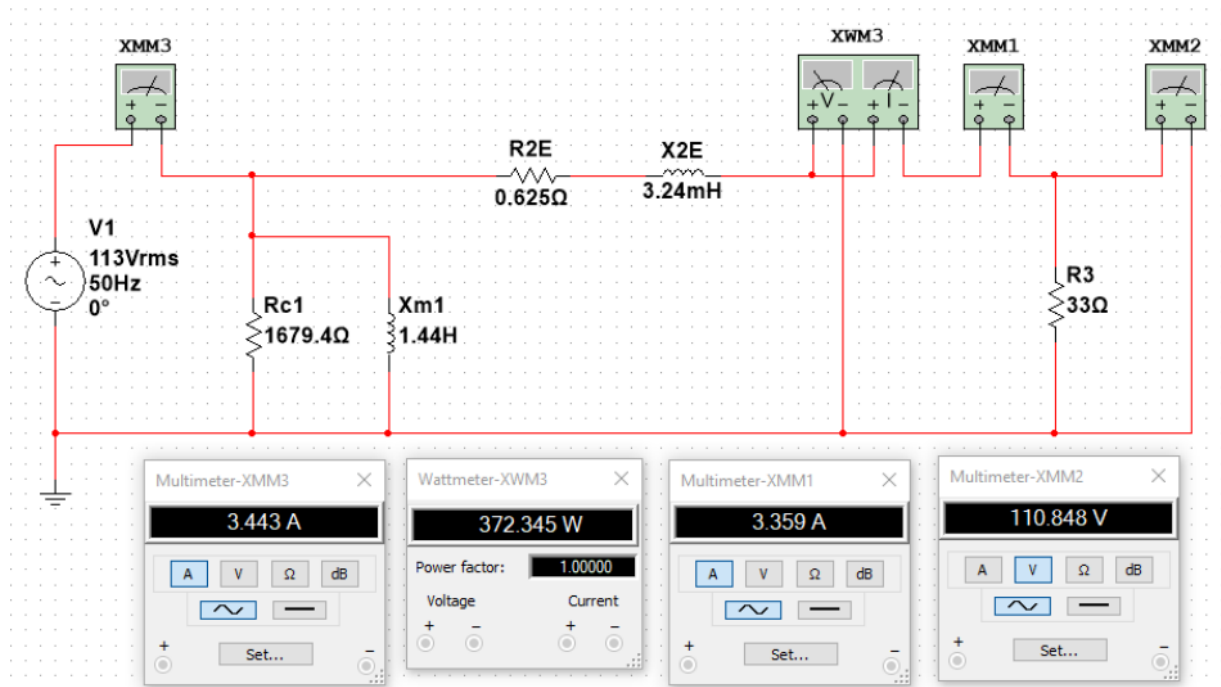


Figure 16 - Voltage Regulation - Resistive Load

| 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 24 - Resistive Voltage Regulation Comparison

There were no differences with the secondary power factor values, and minor differences (0.85V) in practical, simulated and calculated values for voltage. Further discrepancies existed between practical and simulated circuits; a difference

of 0.17A on the primary and 1.1A on the secondary current, as well as a difference of 195.35W in power on the secondary. These discrepancies in voltage, current and power could be a result of calculation rounding, component values, test equipment accuracy and practical test conditions.

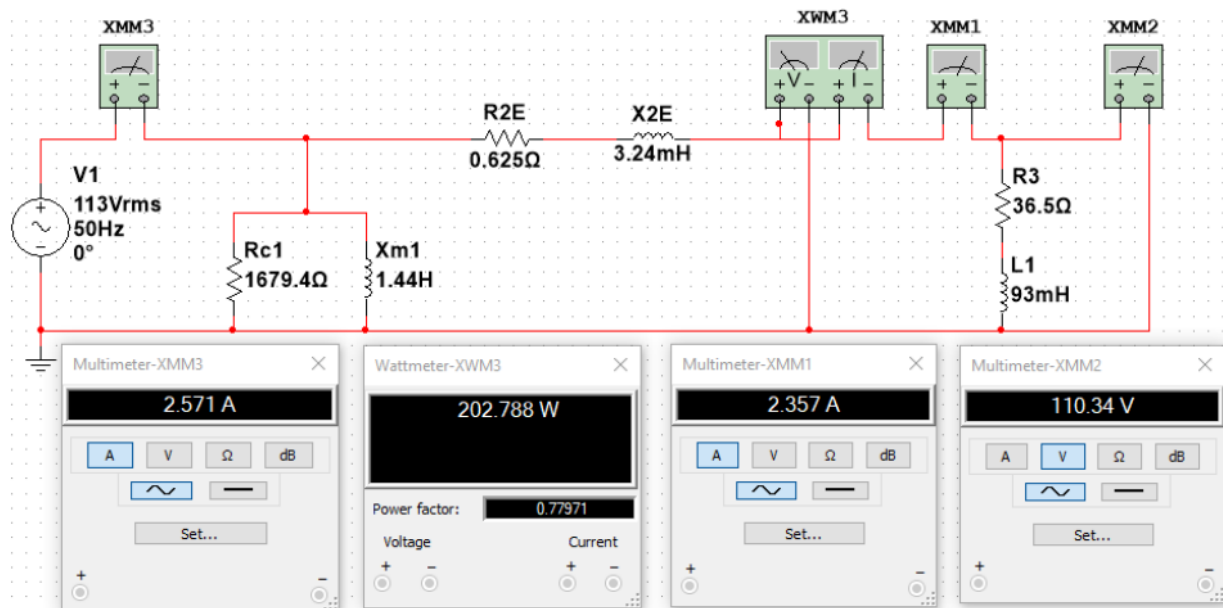


Figure 17 - Voltage Regulation - Inductive Load

| 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 25 - Inductive Voltage Regulation Comparison

There were minor differences between practical, simulated and calculated values for voltage, with a difference of 0.34v between all three. Further minor discrepancies between recorded values from practical and simulated circuits for primary and secondary current values existed, with a difference of 0.26A on the primary and 0.10A on the secondary. Differences for power and power factor in the secondary were also present, at 25.79W and 0.06P.F respectively. Although negligible, the discrepancies may be a result of calculation rounding for component values, test equipment accuracy and practical test conditions.

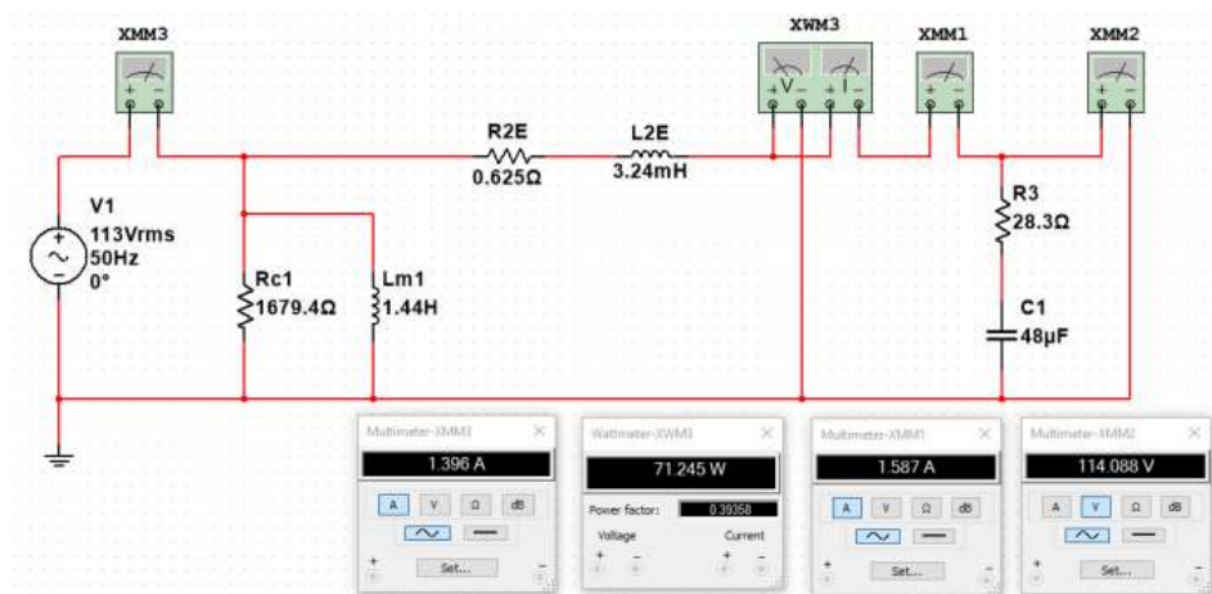


Figure 18 - Voltage Regulation - Capacitive Load

| 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 26 - Capacitive Voltage Regulation Comparison

There were minor differences in practical, simulated and calculated values for voltage, with 0.76V across all three results. Further differences exist between recorded values from practical and simulated circuits, with a difference in current of 229mA on the primary and 0.01A on the secondary. Differences in power and power factor on the secondary were also seen with 2.45W and -0.01P.F respectively. Although negligible, these discrepancies may be a result of calculation rounding for component values, test equipment accuracy and practical test conditions.

|            | 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%     |

*Table 27 - Percentage Voltage Regulation Comparison*

Using the secondary voltage value from the transformer no load voltage (E2) and the measured, simulated and calculated values (V2) of the transformer secondary windings, the percentage voltage regulation could be calculated (appendix 7.3), displayed above.

With resistive and inductive loads, the transformer operated at a loaded state, resulting in a lagging power factor and a lesser secondary voltage. When in use with capacitive load however, results differed as the transformer was leading power factor, resulting in a higher secondary voltage.

#### 4. Three Phase Induction Motor Investigation

##### 4.1 Stator Resistance

| Test Type                                                                                                                       | Description                                                                                                                                                                                                                                                                                                                                                                      |
|---------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Appropriate PPE worn to undertake practical experiment.<br>Current government guidelines followed to maintain social distancing |                                                                                                                                                                                                                                                                                                                                                                                  |
| <b>Stator Resistance Test</b>                                                                                                   | Low DC voltage applied to the stator winding of the motor; DC voltage meaning no induced voltage was present in the rotor circuit, resulting in no rotor current.<br>Motor connected in delta                                                                                                                                                                                    |
| <b>No Load Test</b>                                                                                                             | AC voltage was applied to the motor, the motor also externally driven to reach synchronous speed.<br>Motor connected in delta                                                                                                                                                                                                                                                    |
| <b>Blocked Rotor Test</b>                                                                                                       | Application of low AC voltage to the motor resulting in full load current on the stator windings (i.e. rotor of the motor locked)                                                                                                                                                                                                                                                |
| Ammeter and voltmeter used to measure voltage and current<br>at each of the three phases in all above tests                     |                                                                                                                                                                                                                                                                                                                                                                                  |
| <b>Torque/Slip Values</b>                                                                                                       | a) Motor externally driven, from synchronous speed to above synchronous speed into a generating state; circuit values recorded at the required value of motoring RPM.<br>b) The motor was driven at synchronous speed. Different values torque applied, the circuit and motor values recorded at the required stages. From these values the slip value is able to be calculated. |

Table 28 - Induction Motor Test Method

Shown below are practical values for stator resistance testing.

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

Table 29 - Induction Motor Stator Resistance Test

#### 4.2 No Load Test

Shown below are practical values for no load testing.

| 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         |

Table 30 - Induction Motor No Load Test

#### 4.3 Blocked Rotor Test

Shown below are practical values for blocked rotor testing.

| 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         |

Table 31 - Induction Motor Blocked Rotor Test

Calculated component values from the three induction motor tests, shown below, were used to create an equivalent induction motor circuit. (See appendices 7.3, 7.4 and 7.5 for calculations).

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

Table 32 - Equivalent Induction Motor Component Values

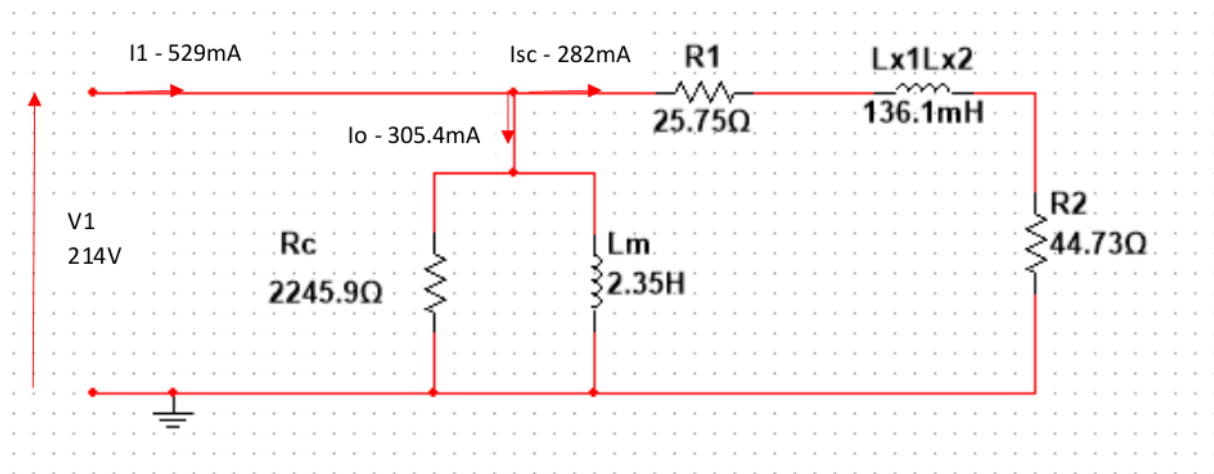


Figure 19 - Motor Equivalent Circuit

#### 4.4 Testing & Analysis

From the equivalent circuit calculated values, total torque values could be ascertained. Total torque for the motor could be altered by applying variant amounts of slip, a relative value and characteristic for asynchronous motors, by applying the following calculation:

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

*Equation 1 - Total Torque Equation*

Shown in the graph below, by applying varying amount of slip (appendix 7.7), motor torque values altered. When the slip value was <0, the rotor was forced to run faster than the magnetic field, resulting in the motor's mechanical power being transferred into electrical power; the generating range.

When 0-1, the rotor was being driven by the magnetic field and electrical power transferred into mechanical power; the motoring phase.

When >1, the motor entered the braking phase; the motor being driven in the opposite direction to the rotating magnetic field.

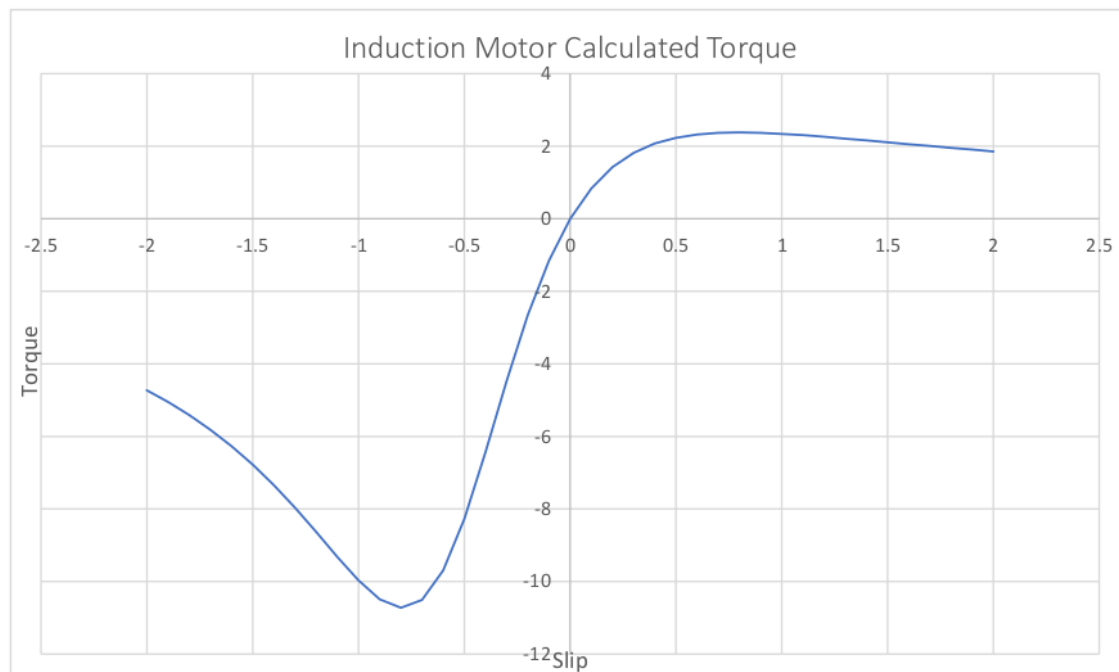


*Figure 20 - Induction Motor Calculated Torque Graph*

By applying varying torque values, the slip value could be calculated:

$$S = \frac{ns - nr}{ns}$$

Equation 2 - Slip Value Calculation

| Induction Motor Torque Tests for Slip Calculation |             |        |             |              |           |                    |
|---------------------------------------------------|-------------|--------|-------------|--------------|-----------|--------------------|
| 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 33 - Induction Motor Slip

Shown below, the linear graph shows calculated slip values are proportional to the applied value of torque in the practical experiment. Increasing the applied torque value gradually increases the slip value. Although there is an anomaly slip value at 0.1NM, this can be attributed to methods used to apply the torque values and measure the speed of the motor in the practical experiments.

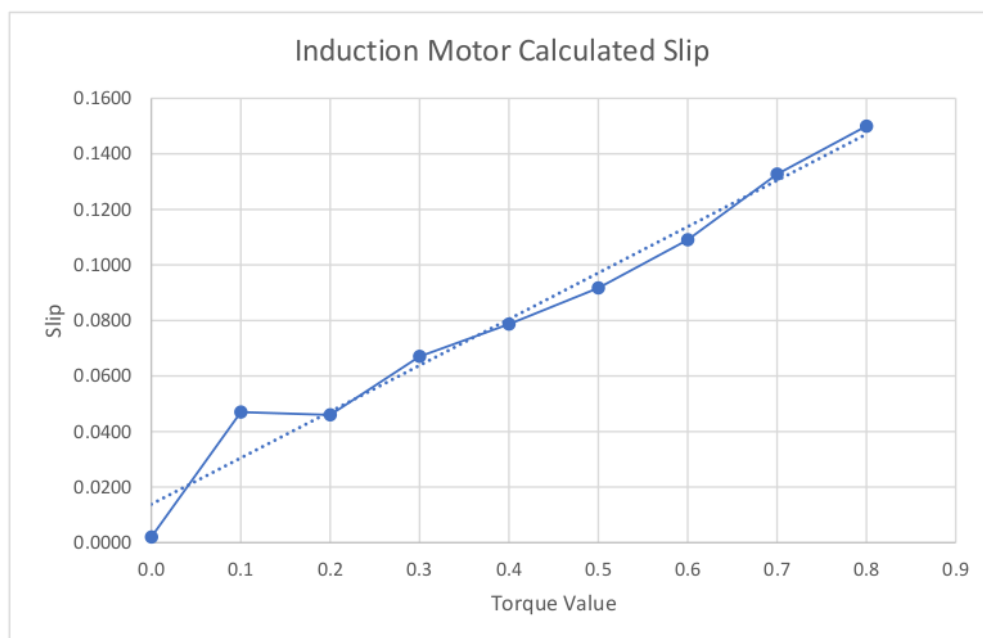


Figure 21 - Induction Motor Slip Graph

By externally driving the induction motor, it could be driven above synchronous speed and taken to generating phase.

| 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               |
| Above Synchronous Speed                 | 3100        | 216         | 628          | 81.2      | -0.34              |
| Above Synchronous Speed                 | 3198        | 217         | 843          | 187       | -0.59              |
| Above Synchronous Speed                 | 3302        | 218         | 1130         | 304       | -0.71              |

Table 34 - Induction Motor Synchronous Speed

Data displayed above and in the graph below, shows when the motor was driven above synchronous speed and was generating, the power factor value increased in proportion to the applied speed of the motor.

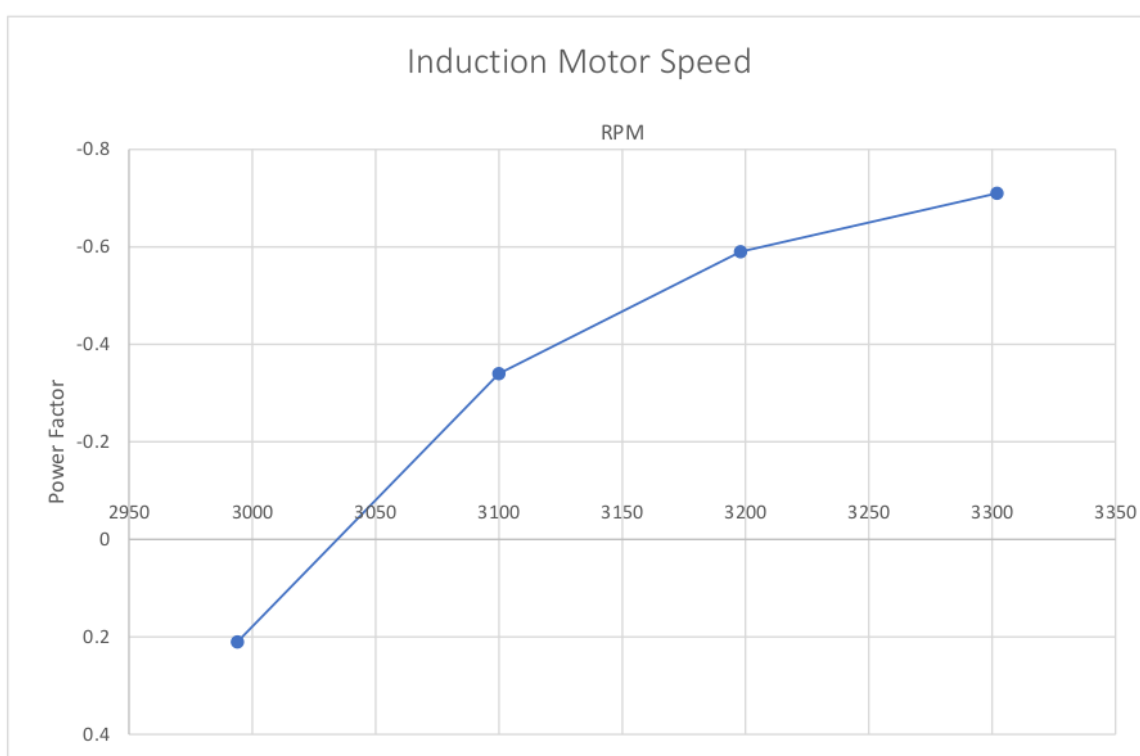


Figure 22 - Induction Motor Synchronous Speed Graph

## 5. Conclusions and Recommendations

The overall project was considered a success, with the design and build of both the single-phase transformer (including simulation) and three-phase induction motor successfully executed.

In both tasks the similarity between predicted, practical and simulated results proved the theory of the equivalent transformer circuit and demonstrated that the motor circuit design could be used to predict an induction motor performance, analogous to that stated in literature. This project has demonstrated that such technology can be used to design and test transformers and motors and determine the suitability of motor design for their intended application.

### *Good conclusions*

That being said, as with any theoretical project build, there are often small discrepancies between results, as evident in this project, however in all cases these were of minor significance, likely to be attributable to elements such as test conditions or equipment that affect readings obtained in the practical execution and did not undermine the success or indicate a failure of the project theory or execution.

To further refine results obtained throughout the project, it may be of benefit to undertake calibration of any testing equipment prior to use, allowing for more accurate readings of current, voltage etc. By ensuring accuracy of readings, this may improve results seen in the practical aspect, lessening any discrepancies between predicted, simulated and practical values. *Good points noted*

Another recommendation would be to increase the size of the motor used. During the tests intended to demonstrate motoring, generating and braking operations, the results were not as expected for the motoring phase i.e. the sinusoidal wave at 0-1 was flatter than anticipated. This may have been a result of the motor being too small.

## 6. Reference List

- Anaheimautomation, 2020. *www.anaheimautomation.com*. [Online]  
Available at: <https://www.anaheimautomation.com/manuals/forms/ac-motor-guide.php>  
[Accessed 08 01 2021].
- Ashrit, L., 2020. *www.electricalfundablog.com*. [Online]  
Available at: <https://electricalfundablog.com/induction-motor-asynchronous-motor/>  
[Accessed 09 01 2021].
- Cableorganizer, 2020. *www.cableorganizer.com*. [Online]  
Available at: <https://www.cableorganizer.com/learning-center/articles/three-phase-electric-power.html>  
[Accessed 09 01 2021].
- Daware, K., 2018. *www.electricaleasy.com*. [Online]  
Available at: <https://www.electricaleasy.com/2018>  
[Accessed 12 01 2021].
- Electrical4u, 2020. *www.electricaltechnology.org*. [Online]  
Available at: <https://www.electricaltechnology.org/2020/05/three-phase-induction-motor.html>  
[Accessed 10 01 2021].
- Electricaltechnology, 2020. *www.electricaltechnology.org*. [Online]  
Available at: <https://www.electricaltechnology.org/2020/05/three-phase-induction-motor.html>  
[Accessed 10 01 2021].
- Electronicshub, 2015. *www.electronicshub.org*. [Online]  
Available at: <https://www.electronicshub.org/4-different-power-electronic-converters/>  
[Accessed 11 01 2021].
- Elfadili, A. e. a., 2010. *www.researchgate.net*. [Online]  
Available at:  
[https://www.researchgate.net/publication/224162554\\_Induction\\_motor\\_control\\_through\\_ACDCAC\\_converters](https://www.researchgate.net/publication/224162554_Induction_motor_control_through_ACDCAC_converters)  
[Accessed 09 01 2021].
- Elprocus, 2020. *www.elprocus.com*. [Online]  
Available at: <https://www.elprocus.com/induction-motor-types-advantages/>  
[Accessed 09 01 2021].
- Haque, A., 2016. *www.sciencedirect.com*. [Online]  
Available at: <https://www.sciencedirect.com/topics/engineering/power-electronic-converter>  
[Accessed 07 01 2021].

Meeti, O., 2017. *www.media.neliti.com*. [Online]  
Available at: <https://media.neliti.com/media/publications/287669-advanced-control-methods-of-induction-motors-ff5aab83.pdf>  
[Accessed 08 01 2021].

Polly, 2020. *roboticsandautomationnews.com*. [Online]  
Available at: <https://roboticsandautomationnews.com/2020/05/20/difference-between-three-phase-and-single-phase-power/32320/>  
[Accessed 10 01 2021].

Rahman, 2016. *www.researchgate.net*. [Online]  
Available at: [https://www.researchgate.net/publication/337399862\\_A\\_REVIEW\\_ON\\_INDUCTION\\_MOTOR\\_SPEED\\_CONTROL\\_METHODS](https://www.researchgate.net/publication/337399862_A_REVIEW_ON_INDUCTION_MOTOR_SPEED_CONTROL_METHODS)  
[Accessed 10 01 2021].

Schweber, B., 2017. *www.powerelectronictips.com*. [Online]  
Available at: <https://www.powerelectronictips.com/basics-ac-dc-electric-motors-part-1-ac-dc/>  
[Accessed 11 01 2021].

shodhganga, 2017. *www.pdf4pro.com*. [Online]  
Available at: <https://pdf4pro.com/view/chapter-3-induction-motor-and-different-562a7.html>  
[Accessed 10 01 2021].

Siwakoti, Y. F. M. H. P. M., 2018. *www.sciencedirect.com*. [Online]  
Available at: <https://www.sciencedirect.com/science/article/pii/B9780128052457000019>  
[Accessed 10 01 2021].

Wickramarachchi, 2018. *www.medium.com*. [Online]  
Available at: <https://medium.com/@tharinduwickramarachchi/role-of-transformers-in-power-system-ad471d1f9595>  
[Accessed 12 01 2021].

## 7. Appendix

### Portable

| RS Part No                                |                   | 260-4244             | 260-4                |
|-------------------------------------------|-------------------|----------------------|----------------------|
| Transformer Type                          |                   | CM7501               | CM10                 |
| Continuous Output Rating (VA)             |                   | 375                  | 500                  |
| Intermittent, 5 mins on 15 mins off. (VA) |                   | 750                  | 1000                 |
| Primary Voltage (V)                       |                   | 230                  | 230                  |
| Frequency                                 |                   | 50/60Hz              | 50/60                |
| Off-Load Secondary Volts (V)              |                   | 113.8                | 114                  |
| Full-Load secondary Volts (V)             |                   | 109.6                | 110                  |
| Regulation at Continuous Rating           |                   | 4%                   | 4%                   |
| Efficiency at Continuous Rating           |                   | 90%                  | 90%                  |
| Iron Loss (Watts)                         |                   | 20.16                | 23.1                 |
| Copper Loss at Continuous rating          | Primary (Watts)   | 9.05                 | 14.1                 |
|                                           | Secondary (Watts) | 10.74                | 17.1                 |
| Insulation Resistance at 2kV for 1 Minute |                   | >200MΩ               | >200MΩ               |
| Flash Test Voltage for 1 minute           |                   | 2kV                  | 2kV                  |
| Primary Winding Resistance at 20°C        |                   | 1.79Ω                | 1.3Ω                 |
| Secondary Winding Resistance at 20°C      |                   | 0.52Ω                | 0.37Ω                |
| Winding Temperature Rise                  | Primary (°C)      | 96                   | 90                   |
|                                           | Secondary (°C)    | 89                   | 85                   |
| Primary Thermal Circuit Breaker Rating    |                   | 3Amp                 | 4Amp                 |
| Dimensions, Width x Depth x Height (mm)   |                   | 160x210x220          | 160x210x220          |
| Weight (Kg)                               |                   | 9                    | 10.1                 |
| Output Sockets                            |                   | 1x16A<br>BS EN 60309 | 1x16A<br>BS EN 60309 |

#### Materials and Construction

The enclosure is moulded from DMC (Dough moulded compound)

The enclosure for 399-6140 is sheet steel ventilated to IP22 and finished with a powder coat

The encapsulant used to retain the transformer is a flame retardant epoxy

Figure 23 - 230v-110v Transformer Data Sheet

### 7.1 Transformer Iron Losses Calculations

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

*Equation 3 - RC Value Calculation*

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

*Equation 4 - Ic Value Calculation*

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

*Equation 5 - Im Value Calculation*

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

*Equation 6 - Xm Value Calculation*

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

*Equation 7 - Xm Inductive Value Calculation*

## 7.2 Transformer Copper Losses Calculations

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

Equation 8 - Maximum Current for Transformer Secondary

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

Equation 9 - Z1E Value Calculation

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

Equation 10 - R1E Value Calculation

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

Equation 11 - X1E Value Calculation

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

Equation 12 - Z2E Value Calculation

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

Equation 13 - R2E Value Calculation

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

Equation 14 - X2E Value Calculation

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

Equation 15 - I2 Value Calculation

$$X1E = 2\pi fL = L1E = \frac{X1E}{2\pi f} = \frac{4.45}{2\pi \times 50} = 0.0142H \text{ or } 14.2mH$$

Equation 16 - X1E Inductive Value Calculation

$$X2E = 2\pi fL = L2E = \frac{X2E}{2\pi f} = \frac{1.018}{2\pi \times 50} = 0.00324 H \text{ or } 3.24mH$$

Equation 17 - X2E Inductive Value Calculation

### 7.3 Transformer Voltage Regulation Calculations

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

*Equation 18 - Resistive Load Circuit Cos & Sin Values*

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

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

*Equation 19 - Percentage Regulation Value Calculation*

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

*Equation 20 - Inductive Load Circuit Cos & Sin Values*

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

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

*Equation 21 - Voltage Regulation Calculation*

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

*Equation 22 - Capacitive Circuit Cos & Sin Values*

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

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

*Equation 23 - Voltage Regulation Calculation*

#### 7.4 Motor Stator Resistance Calculations

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

Equation 24 - R1 Value Calculation

#### 7.5 Motor No Load Calculations

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

Equation 25 - I0 Calculation

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

Equation 26 - PO Calculation

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

Equation 27 - Power factor Calculation

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

Equation 28 - Phase Angle Calculation

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

Equation 29 - Sin of phase Angle Calculation

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

Equation 30 - RC Calculation

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

Equation 31 - Xm Calculation

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

Equation 32 - Xm Inductive Value Calculation

## 7.6 Motor Blocked Rotor Calculations

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

Equation 33 - Isc Calculation

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

Equation 34 - Psc Calculation

$$\cos \phi_{sc} = \frac{P_{sc}}{V_{sc} \times I_{sc}} = \frac{6.4}{25.7 \times 282 \times 10^{-3}} = 0.8831$$

Equation 35 - Power Factor Calculation

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

Equation 36 - Phase Angle Calculation

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

Equation 37 - Sin of phase Angle Calculation

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

Equation 38 - Zsc Calculation

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

Equation 39 - R1 + R2' Calculation

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

Equation 40 - R2' calculation

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

Equation 41 - X1+X2' Calculation

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

Equation 42 - X1+X2' Inductive Value Calculation

### 7.7 Motor Torque Calculations

| Slip | Torque   | RPM  | Slip | Torque   | RPM   |
|------|----------|------|------|----------|-------|
| -2   | -4.72583 | 9000 | 0.1  | 0.836198 | 2700  |
| -1.9 | -5.0489  | 8700 | 0.2  | 1.420428 | 2400  |
| -1.8 | -5.41068 | 8400 | 0.3  | 1.815329 | 2100  |
| -1.7 | -5.81645 | 8100 | 0.4  | 2.072982 | 1800  |
| -1.6 | -6.27165 | 7800 | 0.5  | 2.233128 | 1500  |
| -1.5 | -6.78116 | 7500 | 0.6  | 2.324802 | 1200  |
| -1.4 | -7.34798 | 7200 | 0.7  | 2.368749 | 900   |
| -1.3 | -7.97062 | 6900 | 0.8  | 2.379637 | 600   |
| -1.2 | -8.63853 | 6600 | 0.9  | 2.3678   | 300   |
| -1.1 | -9.32451 | 6300 | 1    | 2.340515 | 0     |
| -1   | -9.97328 | 6000 | 1.1  | 2.302912 | -300  |
| -0.9 | -10.4883 | 5700 | 1.2  | 2.258616 | -600  |
| -0.8 | -10.7246 | 5400 | 1.3  | 2.210192 | -900  |
| -0.7 | -10.5069 | 5100 | 1.4  | 2.159452 | -1200 |
| -0.6 | -9.6941  | 4800 | 1.5  | 2.107678 | -1500 |
| -0.5 | -8.2772  | 4500 | 1.6  | 2.055768 | -1800 |
| -0.4 | -6.43466 | 4200 | 1.7  | 2.004351 | -2100 |
| -0.3 | -4.46677 | 3900 | 1.8  | 1.953857 | -2400 |
| -0.2 | -2.65235 | 3600 | 1.9  | 1.904576 | -2700 |
| -0.1 | -1.15088 | 3300 | 2    | 1.856694 | -3000 |

Table 35 - Calculated Torque

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GRADEMARK REPORT

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FINAL GRADE

GENERAL COMMENTS

Instructor

80/100

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PAGE 2

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QM

**Good Structure**

Report is structured exactly as stated in the assignment brief.

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**Text Comment.** Useful tables, could be better in the appendix.

**Text Comment.** Good conclusions

**Text Comment.** Good points noted

GRADING FORM: NEW CSG-RUBRIC

DAVID THOMAS

80

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



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. (16/20)

**16**

### 5. TRANSFERABLE SKILLS



Can communicate professionally confidently and consistently in a suitable medium for the audience.

**15**

Work is coherent, very fluent and is presented proficiently. Can work autonomously with initiative. Where relevant can work professionally within a team, showing leadership skills as appropriate, and meeting obligations.

Demonstrates excellent skills for employment requiring the exercise of personal responsibility and decision-making and an appetite for further development. (15/20)