ENG460-Engineering Thesis

Dynamic Analysis of Three Phase Induction Motor in DigSilent Powerfactory

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Abstract

The starting of an induction machine is a highly dynamic process, which on weak systems may result in voltage fluctuations within the network, potentially leading to load damage. The voltage fluctuations that may lead to this load damage can result from the high starting current in the induction machine. Some of the methods used to prevent the voltage fluctuations that lead to damage, require reducing the voltage supplied to the motor during start up. However, there are many different starting methods that can be used to solve this issue in electrical systems. The main object of this thesis is to ensure that PowerFactory can assist the user to choose the most suitable starting methods. The machine parameters must be known before implementing the machine model in the simulation tool. Some practical tests are performed to estimate the machine parameters, and two of the available starting methods from the PowerFactory simulation tool were applied to the machine model. To simulate the dynamic behavior of an induction in PowerFactory requires knowing at least some of the parameters of what is known as the equivalent circuit. This information is generally not available on the name plate data. The other aspect of this report investigated methods than can be used to find this data.
Acknowledgements

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Nomenclatures

$IM = Induction\ Motor$

$R_1 = Per\ Phase\ Stator\ Resistance$

$R_2 = Per\ Phase\ Rotor\ Resistance$

$X_1 = Per\ Phase\ Leakage\ Reactance$

$X_2 = Per\ Phase\ Leakage\ Reactance$

$X_M = Per\ Phase\ Leakage\ Magnetizing\ Reactance$

$I_s = Per\ Phase\ Stator\ Current$

$I_2 = Per\ Phase\ Rotor\ Current$

$I_M = Per\ Phase\ Magnetizing\ Current$

$I_{fe} = Core\ Loss\ Current$

$V_a = Per\ Phase\ Voltage$

$P = Active\ Power$

$P_a = Per\ Phase\ Power$

$Q_a = Per\ Phase\ Reactive\ Power$

$V_N = Nominal\ Voltage$

$V_0 = Stator\ Voltage$

$V_{NL} = No - Load\ Voltage$

$V_{LR} = Locked\ Rotor\ Voltage$

$s = Slip$

$m = Number\ of\ Phase$

$\omega_s = Synchronous\ Speed$

$\omega_m = Rotor\ Speed\ (Motor\ Speed)$

$f = Rated\ Frequency$
\( p = \text{Number of Poles} \)

\( P_m = \text{Mechanical Power output of the motor} \)

\( P_n = \text{Rated Power} \)

\( T = \text{Developed Torque} \)

\( s_m = \text{Slip at maximum torque} \)

\( T_{\text{max}} = \text{Maximum Torque} \)

\( B_M = \text{Magnetizing susceptibility} \)

\( R_{fe} = \text{Core Loss Resistance} \)

\( G_{fe} = \text{Core Loss Conductance} \)

\( P_h = \text{Total core loss} \)

\( Mdm = \text{Motor Drive Machine} \)

\( DOL = \text{Direct – On – Line} \)

\( Z = \text{Impedance Per Phase} \)

\( R_{rA} = \text{Positive Per Phase Rotor Resistance} \)

\( X_{rA} = \text{Positive Per Phase Rotor Leakage Reactance} \)
1. Introduction

In this thesis, the equivalent model of a three phase induction motor is developed to analyze the dynamic behavior using computer based program DigSilent’s PowerFactory. The dynamic behavior of interest is that of the starting condition of an induction motor. The starting process of an induction motor is an extremely dynamic process, which may lead to adverse effects on the entire network. The main issues from the motor start that cause damage to the power system are the high inrush current. Other starting methods can be implemented to reduce the inrush current that occurs during startup of a direct-on-line (DOL) system.

It is possible to determine the most appropriate starting method by simulating the system under various starting methods, to find the most secure, economical and effective approach. It is not practical to test each starting method on an actual machine because of the likelihood of damage to the equipment.

First of all, the literature is reviewed, which identifies the associated problems of starting an induction motors. The literature describes the most common starting methods that will be used in this project. Several methods are identified in this review, some of which are then used in PowerFactory to investigate advantages and drawbacks of each.

The second section of the thesis covers the construction and basic operating principle of induction motors, including the model which is used to simulate the dynamic system. There are two starting methods that are well-accepted and will be used in the simulation of an asynchronous motor in PowerFactory. Conclusions are then drawn from the results obtained from the simulation studies.
1.1 Objective of the Project

The first objective of this project is to determine the dynamic characteristics of three phase induction motor in computer based program, DigSilent PowerFactory and to investigate the starting characteristics of an induction motor. The main points of interests are to investigate the waveforms of current, active power, reactive power, speed and torque under different starting conditions with the variable loads. The main aim of the project is to find the most appropriate starting method. It will identify the appropriate method for a specific motor by simulating two methods within the DigSilent PowerFactory environment.

1.2 Scope of Work

This project will undertake the following tasks:

- Research on details of starting characteristics of three phase induction motor
- Selection of a three phase induction motor
- Calculation of electrical parameters
- Modeling the asynchronous machine in the computer program DigSilent PowerFactory
- Implementation of model in PowerFactory
- Discussion of results from simulation of model
- Investigate the project outcome
- Suggestions for future work.
1.3 Literature Review

The literature review explains the detailed background of the three phase induction motor and some starting methods used for induction machines. The parameters and calculation methods that have been used in this report are listed in sections 2.3 & 2.4.

The starting of an induction motors poses a lot of problems which are quite challenging to solve in order to maintain a stable power supply. When it comes to choosing the starting method of machine, the technicians and engineers must take this into consideration. There are some tradeoffs that must be considered when investigating the dynamic characteristics during start up. They may include factors such as system efficiency, robustness, machine life span and equipment cost.

Thornton & Armintor (2003) explains that electromechanically energy conversion occurs by interchanging the energy between electrical system and mechanical system. This results from the magnetic coupling that occurs when a motor is connected to an electrical supply. The conversion from electrical energy to mechanical energy then takes place.

The basic working principles of a motor from the role of the stator, rotor, rotor slip, losses and torque characteristics machine are briefly described in Rockwell Automation (1996). The design measurement and operation characteristics of three phase induction machine are also briefly described in Rockwell Automation (1996). Bakshi & Bakshi, (2009) gives details of the construction of the stator, rotor and operation characteristics of a three phase induction machine.

The squirrel cage motor is the focus of this report. The rotor for these machines is a slotted cylindrical mechanism that consists of un-insulated copper or aluminum bars. The design of its mounting places is described briefly in Bakshi & Bakshi, (2009). Bakshi & Bakshi, (2009) describe the mathematical working steps on the production of torque for an induction motor with reference to a number of factors. The book also indicates the calculation of the torque equation, starting torque and the maximum torque equation.

The squirrel cage induction motor is used for 85% of industrial motors (Saravanan, Azarudeen, & Selvakumar, 2012) (Siang, Gobbi, & Sa'diah, 2003). Three phase induction motors with squirrel cage rotor types are preferred by many industries due to their robustness and economical cost (Chapman, 2005), (Kadhim, 2014), (Trzynadlowski, 2001), (Siang, Gobbi, & Sa'diah, 2003), (Wigington, 2010) and (Kjellber & Kling, 2003).

Some of the major problems that are associated with the startup of squirrel cage motors are discussed below:
Voltage Dip:

According to IEEE Standard 399 (1997), the voltage dip is the most widely studied effect of motor-starting, which is experienced in power system throughout industries. The voltage for motor starting depends on the motor and on the load torque characteristics (IEEE Std 399, 1997). The requirement that limit voltage dip during startup varies. It may be allowed to fall as low as 80% of the nominal voltage or have tighter regulations that limit the drop to only 95% or higher. According to NEMA Standards Publication MG 1 (2009), the minimum the voltage can dip to be approximately 80% of the rated voltage for a NEMA design B motor, which has a standard starting torque of 150% for a constant torque load. The torque will vary with the square of the voltage, 150% starting torque is at full rated voltage (IEEE Std 399, 1997).

Inrush Current:

During the starting operation, the motor can experience a high initial current called inrush current. This current can cause mechanical stress on bearings and belts and can lead to large power losses. The resistive and copper losses are proportional to the square of current, $I^2R$ and this effects the efficiency of motor (Wigington, 2010). The power losses are dissipated as heat which will cause the machine thermal stresses and can affect the stability of a machine, which may lead to financial costs (Wigington, 2010).

Power Factor and Reactive Power:

The product of amps and volts is called apparent power. However apparent power does not convert into useful power. Generally only active power contributes to useful work and even then not all active power delivered to a motor will be use full. Power can be broken down into three components, active, reactive and apparent, as is shown in Figure 1. Motors starting with full voltage impose a high reactive power requirement, with a low, lagging power factor, for a short period of time. The ratio decrease as the motor accelerates towards its steady state speed (Kay, Paes, Seggewiss, & Ellis, 2000). Power factor is the ratio of real power to apparent power. Low power factor creates problems mainly from the high-line currents that are required to meet the real power demand (Lawrence Berkeley National Laboratory, 2008). According to IEEE Standards 399 (1997), the typical values of power factor are approximately 0.2 for motors under 1000HP.
1.3.1 Starting Method of Three Phase Induction Motor

The above considerations are the most important when choosing the starting method for a motor. It is also noted that in the dynamic startup process the greatest impact and fatigue of the induction motor is caused, although this is largely less than the impact from the mechanical load of motor (Wigington, 2010). Thermal stress is also very important to take into consideration, because induction motors rotor bars fatigue determine the motor lifetime (Wigington, 2010). This report focuses on the dynamic system which does not relate to long term reliability.

There following methods are used for motor starting: full voltage start, reduced voltage start, incremental voltage start, soft-starter and variable frequency drives (Wigington, 2010) and (Patil & Porate, 2009). Only two of these methods are studied in this thesis, the reduced voltage method and the full voltage method. The PowerFactory software provides three starting methods, although only two options are available for the squirrel cage induction motor. The third option, the rotor resistance starting method, applies only for wound rotor motor types.

The instant power is supplied to an induction motor the slip is at unity (i.e. s=1). The slip-torque characteristics show that when the rotor resistance is low the starting torque is small, compared to the available maximum torque (Prasad, 2009).

Three phase induction motor starting methods are basically divided into three main categories

1. Full voltage starting method
2. Reduced voltage starting method
3. Variable frequency drives starting method (Zhang, Xueshen, Zhao, & Yang, 2012).

Starting process of induction motors for small to large size motors may produce voltage dips within the power systems. During these dips the power factor is low, typically between 10%-20% and a high current is drawn. The current can be as high as 6-10 times the rated value, leading to this
undesirable effect (Prates da Silveira, Pires, Lyrio de Almeida, & Junqueira Rezek, 2009). Therefore, several solutions are preferred to minimize the problem for different sizes of motors. The most common solutions which have been applied in most industrial applications are:

- Shunt Capacitors
- Reactor Start
- Wye-Delta Start
- Auto Transformer Start
- Frequency Variable Driver Start
- Soft Starter

These solutions, except the Capacitor Start method, basically depend on the reduction of voltage across the motor terminals. This reduces the locked rotor current as the voltage is related to the impedance of total system, which is very low at start up (Prates da Silveira, Pires, Lyrio de Almeida, & Junqueira Rezek, 2009). The Frequency Variable Driver and Soft Starter, which are Solid State solutions are the most complex and expensive, and also requires expert maintenance (Farr & Farr, 2007). Both FVD & Soft Starters are very manageable and are able to start the motor without any starting torque reduction, but, the starting torque will decrease quadratically with the reduction of the motor terminal voltage (Prates da Silveira, Pires, Lyrio de Almeida, & Junqueira Rezek, 2009).

To correctly implement a starting method requires a full and detailed analysis of the load characteristics. If the motor doesn’t accelerate at the rated speed over time then the thermal protection may trip and the motor will be stopped (Prates da Silveira, Pires, Lyrio de Almeida, & Junqueira Rezek, 2009). Other starting methods including three phase starting by a single phase motor are described in Badr, Halim & Alolah (1995), and are not included in this discussion. The associated problems in 3-phase asynchronous motor under voltage imbalance are described in Ansari & M (2009).

1.3.2 Full Voltage Methods

Full voltage methods include the direct-on-line (DOL) method and the capacitor method. Only the DOL full voltage method will implemented to the available starting methods in DigSilent’s PowerFactory version 14.

1.3.2.1 Direct-On-Line (DOL) Starting Method

Direct-on-line starting method is one of the easiest methods of starting a motor. For a DOL starter the stator windings of asynchronous motor are directly connected to the main power supply, by the process of single switch (Randermann, 2010). Its direct connection to the stator terminal of motor
makes it one of the most economical starting methods. When the full voltage is applied to a motor, a very large current will pass through the armature; this in turn can cause troublesome voltage change on the main power supply (Randermann, 2010). For this reason, the power supply industries are limiting the permissible rated powers of motor connected to the main power supply using this method (Randermann, 2010). Because of this limitation, the DOL starting method is generally more suitable for small motor types, relative to the size of system and generation, as it can’t induce a large voltage dip when starting & stopping (Pillay, Nour, Yang, Harun, & Haw, 2009). This method also imposes thermal stresses in the motor winding and causes momentary electro-dynamic forces, which with frequent DOL starting reduces the life of the windings (Randermann, 2010).

When the rotor of a motor is locked a very high current is experienced, which has a serious threat of possible thermal destruction. Therefore, it is very important that every motor has some form of protection. The protection device is connected to the motor in order to prevent any thermal overload occurring. This can be incorporated by using protection relays, which can be incorporated into protective circuit-breakers in combination with contactors (Randermann, 2010). Figure 2 below shows the schematic diagram of a DOL starter with the overload protection and contactors.

![Figure 2: Direct-on-Line Starter (clockwise, forward rotation)](image)
1.3.3 Reduced Voltage Starting
This starting method reduces the voltage to the motor windings during startup. Whilst this reduces
the current it also reduces the starting torque (Sace, 2008). The most common types of reduced
voltage starters are stator resistors, reactors, star-delta, auto-transformer and soft starter. These
methods intervene on the torque curve of the motors to adapt the load characteristics (Sace, 2008).
For this report only the star-delta starting method will be simulated.

1.3.3.1 Star-Delta (Y/\Delta) Starting Method
This type of starting is the most common and perhaps the best known system of reduced voltage
starting (Pillay, Nour, Yang, Harun, & Haw, 2009) (Sace, 2008). It starts the motor by reducing the
mechanical stresses and limiting the current values during start up. During the startup process, the
windings of motors are in star-connection, with each winding supplied with per phase voltage of $\frac{V_N}{\sqrt{3}}$
and in per phase current $I_Y = \frac{V_N}{\sqrt{3} \times Z_w}$ where $Z_w$ is impedance of the winding (Sace, 2008).

1.3.3.2 Star Phase (Y)
For the starting phase, the windings of the motor are star-connected; the main voltage supply ($V_N$)
on the individual windings is reduced by a factor of $\frac{1}{\sqrt{3}}$ (0.58) (Randermann, 2010). In star-
connected, inrush current and starting torque are reduced to almost one third of the rated values
for delta connection. The star-delta configuration is more suitable for small load torque
characteristics that increases with speed, such as fans, pumps or compressors (Sace, 2008)
(Randermann, 2010).

1.3.3.3 Changeover Phase
The changeover from star-connected to delta-connected occurs through the opening or closing of
the dedicated contactors (switch), the switching and calibration time of the changeover phase are
essential (Sace, 2008). In circuit configuration from star to delta changeover, the current drops to
zero and speed of motor decreases, depending on the load (Randermann, 2010). Now the full
voltage is applied to the motor windings, the delta connection causes a dramatic increase in current,
which can lead to voltage dips in weak and unreliable system supplies (Randermann, 2010). The
torque of the motor will also increase during the changeover, which will cause an extra loading on
the system (Randermann, 2010).
1.3.3.4 Delta Phase ($\Delta$)

After the changeover has been carried out, the last phase of starting is reached; it shows the condition of steady-state running in which the windings of the stator remain delta-connected.

The star to delta changeover is controlled by the contactor circuit or timing relay on the contactors (Sace, 2008) (Randermann, 2010). The time required for staying star connection is load dependent and has to continue until the motor has reached between 75% to 80% of its operating speed, to ensure that the least possible post-star connection acceleration occurs (Randermann, 2010). This post-acceleration is associated in delta configuration where high currents occur (Randermann, 2010).

The flowchart and control strategy of star-delta start is designed as shown below in Figure 3.

![Figure 3: Star-Delta Starting (Clockwise, forward rotation)](image)

The main circuit breaker act as a main power supply switch and the main contactor connects to the source voltage A, B & C to the primary terminal of the motor U1, V1 & W1. Initially, the star-contactor and main contactor are closed and then after a period of time, the star-contactor opens
and closes the delta contactor. Initially the star-contactor acts as short to secondary terminal U2, W2 & V2, this supplies 1/3 of direct-on-line current to the motor (Parmar, 2012)

### 1.4 Induction Machine

The induction machine is one of the most common motors in industrial applications and it is the workhorse of industry (Ishikawa & Murai, 1998), (Bakshi & Bakshi, 2009), (Chapman, 2005) and (Lindenmeyer, Dommel, Moshref, & Kundur, 2001). It has two main parts, a stator and a rotor, two different types of rotors are available: squirrel-cage rotor and wound-rotor (Shahl, 2010). Most industrial applications use squirrel-cage rotor induction motors.

#### 1.4.1 Stator

The stator is the stationary part of induction machine. The stator winding consists of three individual windings that overlap each other but are offset by an angle of 120° (Rockwell Automation, 1996). The stator is energized by the incoming current when it is connected to a power supply, and magnetizing current produces magnetic field that rotates at synchronous speed $\omega_S$ (Rockwell Automation, 1996) (Chapman, 2005).

#### 1.4.2 Rotor

The rotor is the rotating part of induction machine, and comes in two types: squirrel cage winding rotor and wound rotor (Rockwell Automation, 1996). Squirrel cage rotors consist of a slotted cylindrical rotor core sheet with aluminum bars which are connected at the front by rings to form a closed cage (Rockwell Automation, 1996).

When the rotor is in a stationary position it acts like a transformer with a short circuited secondary terminal. Thus, the stator winding acts as a primary winding and the rotor winding acts as a secondary winding (Rockwell Automation, 1996). Because the rotor is short circuited, the rotor current depends on its resistance and induced voltage, so the interaction between the magnetic flux and the current conductors in the rotor generate a corresponding torque of the rotating field (Rockwell Automation, 1996). The cage bars are designed like skew which is an offset pattern to the axis of rotation in order to prevent torque fluctuations (Rockwell Automation, 1996).

In the presence of small counter-torque, no-load losses, the rotor reaches a synchronous speed of the rotating field (Rockwell Automation, 1996). If the speed of rotor is the same as the synchronous
speed, a voltage can’t be induced and current will cease to flow and there will not be any more torque (Rockwell Automation, 1996).

When the induction motor operates, the rotor speed drops to the load speed and the slip (s) is defined here by the difference between the synchronous speed and load speed (Rockwell Automation, 1996).

**Slip** - The stator current creates a rotating magnetic field in the air gap and the rotational speed of the magnetic field is proportional to stator current frequency

\[ \omega_s = 2\pi f_s \]  \hspace{1cm} (1)

\( f_s \) is the stator current frequency in equation (1) (Hamon, 2010).

The rotating magnetic field, which is the stators magnetic field, rotates at the same speed of synchronous speed (\( \omega_S \)). The slip “s” of induction motor is defined when speed of rotor (\( \omega_m \)) is equal to mechanical speed.

\[ S = \frac{\omega_S - \omega_m}{\omega_S} \times 100\% \]  \hspace{1cm} (2)

And synchronous speed in rpm

\[ \omega_S = \frac{120 \times f}{P} \]  \hspace{1cm} (3)

### 1.4.3 Squirrel Cage Rotor

Three-phase induction motors are one of the most commonly used machines for industrial applications. This is due to its low cost that makes it very popular in industries compare to synchronous machines. They are the most rugged and robust to operate and require less maintenance (Gaucheron, 2004) and (Wigington, 2010). The induction machine response varies as changes occur in the operating state, for example the response to a dynamic load. The downsides of induction machines are the large starting currents. They are difficult to control and manage, which has led to the increased attention given to studying this aspect of power studies.

The squirrel cage rotor that makes up most of the induction machines usually consists of laminated core with a conductor running through each slot. This is very similar to a wound rotor. The conductors have heavy copper lightly insulated from the core and each end is short-circuited by a
pair of rings (Prasad, 2009). The slots of the rotor are in a skewed shape to help the motor during startup as well as a quieter running. Some squirrel cage rotor windings conductors and rings are made of aluminum which is casts into position when the core of rotor is assembled (Prasad, 2009). Some squirrel cage rotors are made of a solid cylinder without any conductor or slots, the cylinder steel itself acts as a conductor (Prasad, 2009). The squirrel cage rotor resistance is very small compared to the wound rotor and it is impossible to insert external resistance as the bars are permanently short-circuited to each other by the end rings (Bakshi & Bakshi, 2009).
2. System Model

2.1 Toshiba Motor

The Toshiba three phase induction motor has been chosen for this project. This machine is a Toshiba Premium Efficiency Motor model, which is a low voltage motor with a low output power. The manufacturers data sheet for the Toshiba motor is obtained from the Toshiba International Corporation website.

The specifications for the Toshiba (TSH01) Motor are given on the Name-Plate, which is reproduced in the Table 1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Toshiba (TSH01)</th>
<th>Mass (kg)</th>
<th>Insulation Class</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Output (kW)</td>
<td>0.37</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate Frequency (Hz)</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>1410</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage (Star Connected) (V)</td>
<td>415</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Load Current (Star Connected) (A)</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearing No. (DE)</td>
<td>6203ZZ</td>
<td>STD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearing No. (NDE)</td>
<td>6203ZZ</td>
<td>Serial No.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Toshiba; three phase induction motor Name-plate

The information given in the name-plate (Table 1) conforms to the NEMA standard. National Electrical Manufacturer Association (NEMA) defines the mounting parameters, dimensional parameters, basic performance and basic designs of a motor (NEMA Standards Publication MG 1, 2009). When the parameters are coded on the motor’s nameplate it provides the basic definition of what can be achieved. The minimum amount of information that is required when choosing an induction machines for a given application are:

- Manufacturer’s type
- Output Power (kW or Hp)
- Voltage
- RPM at rated load
- Frequency
- Number of phases
- Rated load current
- Frame designation
- Insulation system, maximum ambient temperature
- Design letter and rating
- Nominal efficiency and power factor

This information is usually available on the motors nameplate. Information on the motor nameplate is arranged into categories. The rated output (shaft) power can be achieved when supplied by the rated electrical input. The nameplate information describe how effective the motor works and how safe and reliable it is. The following section gives brief description of the motor nameplate data along with some applications of this motor.

2.1.1 Electrical input

Voltage:

The most important parameter is voltage; it shows the motors designed operating point. The current, power factor and efficiency are all defined on the nameplate for rated voltage and frequency. Different performance would likely to be produced by application at other than nameplate information.

Frequency:

The rated frequency for the Toshiba motor is 50Hz. If the nameplate shows more than one frequency, then parameters for all other operating points will differ, these should also be defined on the nameplate (Thornton & Armintor, 2003). Adjustable frequency drives (AFDs) are becoming more important for motor in term of frequency range; they should be carefully programmed so they do not violate information on the nameplate, particularly for motors in hazardous applications.

Phase:

Single phase and three-phase motors are both common. In an industrial setting three phase motors are more common. The number of phases is based on how many active lines are connected to the motor.

Current:

The rated load current represents the current that will be drawn when the motor is operating at nameplate voltage, frequency and load power. In case of unbalanced phases, under voltage
conditions, or combination of both, the current may deviate from the nameplate amperage (Thornton & Armintor, 2003).

**Power factor:**

Power factor represents a percentage, given as “P.F.” or PF on the nameplate. It is the ratio of active power to apparent power. The power factor displayed on the nameplate is for full load at rated voltage and frequency. It varies with the load on induction motor. Numerically it is equal to cosine of the angle that the input current lags the voltage. For percentage values this value is multiplied by 100. There are tradeoffs when designing an induction motor, for improved efficiency or other performance parameters, power factor sometimes suffers. The power factor can be improved by adding capacitors in parallel with the motor (Thornton & Armintor, 2003).

### 2.1.2 Mechanical Output

**Output Power:**

The output power is generally specified as “P [W] or HP” on the nameplate. This is the rated shaft mechanical power or output power of the motor. It is capable of delivering the torque at rated speed to a load. Equation (4) below represents the power calculation which is obtained from Toshiba (2009) and the rated torque can be obtained from equation (5).

\[
P(kW) = \frac{1.732 \times \text{Line Voltage} \times \text{Line Current} \times \text{p.f.} \times \left(\frac{\text{Motor Eff}}{100}\right)}{1000}
\]

\[
P(kW) = 0.746 \times \text{Horsepower}
\]

\[
\text{Power (kW)} = \frac{\text{Torque (Nm)} \times \text{Speed (rpm)}}{9550}
\]

**Full-Load speed:**

The full load speed is generally given in rev per minute (RPM) on the motor nameplate. It is the speed at which the rated torque is delivered at rated output power. It is sometimes called actual speed of the rotor or slip speed. For an induction motor it is not the synchronous speed. When the motor runs from a fixed frequency AC power supply, the synchronous speed is the speed of the
magnetic flux, which will be a ratio between the electrical frequency and the number of poles of the machine (Thornton & Armintor, 2003). The synchronous speed is always greater than induction motor name plate speed as slip is required to produce torque. The motor speed will decrease slightly as the load is increased.

**Design:**

Motor designs are assigned letters to identify certain characteristics. The given design “N” type of Toshiba motor is equivalent to Design B of NEMA motor type (Elgeland, 2014). It is important to know the design letter whenever replacing the parts of a motor, as some manufacturers assign the motor’s design letter but does not describe the industry standard. Design B, bounds the designer to limit inrush currents, this ensures that the user can expect certain currents during motor startup and therefore select suitable devices (Thornton & Armintor, 2003). NEMA Standards Publication MG 1 (2009)-explains the design which defines the torque and current characteristics of the motor

**2.1.3 Performance**

**Nominal Efficiency:**

Nominal efficiency (in percent) is defined as the power output divided by the power input multiplied by 100:

\[ \eta = \frac{\text{power output}}{\text{power input}} \times 100 \]

The nominal efficiency represented on the nameplate is an average efficiency of a number of like motors. The manufacturer defines the actual efficiency of induction motor so that it is guaranteed to be within a tolerance band of its nominal efficiency, but each manufacturer has different bands. NEMA has established its own allowable maximum variation, allowing an additional 20% of motor losses, such as stray load losses, friction losses, iron losses and windage losses (NEMA Standards Publication MG 1, 2009).

**Duty:**

Continuous three phase induction machines are designed for rated power. There are nine main duty types, from S1-S9 (IEC Standard 60034-1, 2004). S1 is a continuous duty types which operates with constant load with duration sufficient to reach thermal equilibrium (Rockwell Automation, 1996).
2.1.4 Reliability

Insulation Class:

Insulation classes are very often represented as “INSUL CLASS” on the nameplate. The letter defines the motor insulation class, depend on winding. This shows the thermal tolerance of the motor winding according to standard classification of industry. The insulation class letter on the Toshiba three phase inductions motor is “F” class. The designation letters (A, B or F) basically depend on the windings ability to survive a given operating temperature over a given time period. The performance or time period improves with higher classes which are categories in alphabetical order (Thornton & Armintor, 2003). Insulation class F has better and longer nominal life than class A at a given operating temperature and it may survive at higher temperature for a given nominal life span. Operating temperature is a result of the ambient conditions and factors such as energy losses that result in heat, which will raise the motor temperature (Thornton & Armintor, 2003).

Ambient Temperature:

The ambient temperature often represented as “AMB” on the nameplate, is usually given in degrees centigrade as a unit. The maximum ambient temperature on the listed nameplate of the motor shows the users that at that temperature the motor is capable of operating within the tolerance of maximum temperature rise for that insulation class type.

2.1.5 Construction

Frame:

Motors, like other devices, come in different sizes to match the application requirement. As the horsepower increases the frame size increases too. Frames are often represented as letters and numbers on the nameplate. The mounting dimensions of the frame size such as shaft height, shaft diameter and foot hole mounting pattern are important in frame sizing.

Bearings:

Bearing data gives information about the drive-end bearing and other side drive-end bearings. The information given on the nameplate varies from manufacturer to manufacturer. NEMA has not set any requirements for bearing data, although, manufacturers generally do provides bearings data on the nameplate. Bearings are used in a motor to reduce friction which allows high speed and high thrust operation and reduces temperature rise and noise.
2.2 General Equivalent Circuit

The model for a three phase induction motor consists of stator and a rotor which are magnetically connected as shown in Figure 4. The equivalent circuit is quite similar to a transformer, which has magnetically connected electrical systems. A transformer has a set of primary and secondary winding, for a motor the equivalent of the secondary windings is almost a short circuited (Shahl, 2010). Like a transformer a balanced AC voltage is supplied to the motor stator windings, this current induces a voltage in the rotor (Shahl, 2010). The applied voltage \( V_1 \) across phase A is equal to the sum of

- Induced voltage \( V_2 \)
- Voltage drop across the stator resistance \( I_1 R_1 \)
- Voltage drop across the stator leakage reactance \( I_1 jX_1 \)

\[
\begin{align*}
V_1 &= \text{Applied voltage to the stator per phase in Volts} \\
V_2 &= \text{Rotor phase voltage referred to the stator side in Volts} \\
I_1 &= \text{Stator or line current in Amp} \\
I_2 &= \text{Rotor current referred to stator in Amp} \\
I_m &= \text{Magnetizing current in Amp} \\
I_{fe} &= \text{Core loss current in Amp} \\
R_1 &= \text{stator winding resistance/phase} \\
R_2 &= \text{Rotor resistance per phase, referred to the stator side in Ohms}
\end{align*}
\]
\[ R_{fe} = \text{Core loss resistance per phase in Ohms} \]

\[ X_1 = \text{Stator leakage reactance per phase in Ohms} \]

\[ X_2 = \text{Rotor leakage reactance per phase, referred to the stator side in Ohms} \]

\[ X_m = \text{Magnatizing reactance in Ohms} \]

\[ Z = \text{Impedance per phase in Ohms} \]

\[ Z_2 = \text{Rotor impedance per phase, referred to the stator side in Ohms} \]

\[ s = \text{slip in per unit} \]

### 2.2.1 PowerFactory Induction Machine

The induction machine model in DigSilent PowerFactory is also called a type 2 asynchronous machine model and it has been available since version 12. The general induction machine model is given in Figure 5. It is basically the classical model type that includes slip (frequency) dependent rotor impedance.

The equivalent circuit diagram shows the stator currents and voltages in a steady reference frame, as instantaneous phasors. Rotor currents and voltages are given in a reference frame that rotates with mechanical frequency (DigSilent, 2013). The rotor impedance (Figure 6) is referred to the stator side, which is why the rotating transformer doesn’t have any winding ratios in Figure 5 (DigSilent, 2013). Also, the general induction machine model is not earthed, which is why there is no zero sequence equation.

![Figure 5: PowerFactory General Induction Machine Model](image-url)
$Z_{rot}$ is a frequency dependent and it can be modeled for squirrel cage induction machines on wide range of slip or speed.

Comparing Figure 5 with Figure 4:

\[ R_S = R_1 \]
\[ X_S = X_1 \]

$Z_{rot} = \text{Rotor Impedance}$

\[ R_{rA} = R_2 \]
\[ X_{rA} = X_2 \]

There are two types of input modes in PowerFactory for induction machines, one is electrical parameters mode and the second is the slip-torque and the slip-current characteristic mode, see Figure 7 & Figure 8.
Figure 7: PowerFactory basic data screen inputs

Figure 8: PowerFactory Load Flow/RMS Simulation input
When the input mode is set to “electrical parameter”, then the electrical parameters of the equivalent circuit diagram are entered in the “white boxes”. The highlighted values are automatically calculated from the entered parameters ($R_1, X_1, X_m, R_2$ and $X_2$) including rated mechanical (output) power, rated frequency, poles and inertia. After the values are entered, pressing the “calculate” button then PowerFactory starts conversion from the parameters. If PowerFactory doesn’t find conversion, then it will display an error message on the screen to indicate inconsistent input parameters.

When the input mode is set to “slip-torque/current characteristic” then some of the electrical parameters will be calculated automatically and will be displayed as greyed out values. However, the stator resistance and leakage reactance $R_1$ & $X_1$ still require an entry, as well as maximum torque, rated output power, power factor, efficiency, nominal speed, poles and inertia.

The electrical parameters are not provided in the nameplate of motor nor given in the data sheet (Toshiba, 2009). So the Toshiba three phase induction motor is tested in order to determine the electrical parameters.

2.2.2 Three Phase Motor Parameters Determination

A per phase equivalent circuit is shown in Figure 4, it is mainly developed in order to obtain an insight into induction motor operation. Toshiba model No # TSH01, three phase induction machine was chosen to perform the tests for the purpose of electrical parameters values. The book “Applied Intelligent Control of Induction Motor Drive” by (Chan & Shi, 2011) provides three tests to determine the electrical parameters of an induction machine. IEEE Standards 112 (2004), also explains the test procedure for three phase induction motors and generators, with a different approaches to determining the parameters.

A set of measurements were performed to achieve the electrical parameters of the Toshiba Motor. Method 1 was performed, but the provided power analyzers (PM300, PM6000 and Yokagawa) couldn’t provide accurate values for locked-rotor test. The rotor resistance was resulting in a negative value when the Yokagawa meter was used. The power analyzers did not perform well over low frequency ranges. However, the test was then performed with variable frequency drive (VFD), but still the results were negative values. Method2 &3 are to be performed on 25% of rated frequency, so the power analyzer could not be used to perform the test under this circumstance.

2.3 (Chan & Shi, 2011) Parameter Test

(Chan & Shi, 2011) Test method provides three tests which are dc, no-load and locked-rotor tests to determine the electrical parameters.
2.3.1 DC Test

This is the simplest method which measures the stator resistance. From Figure 9, the motor is supplied by the DC voltage across the two terminals and the DC voltage and current are measured, so that the stator resistance is obtained from equation (6). Table 2 below shows the measured values of the DC test for the motor.

\[ R_{DC} = \frac{V_{DC}}{I_{DC}} \]  \hspace{1cm} (6)

![Per-Phase Equivalent circuit for DC test](image)

The machine is Y-Connected, therefore

\[ R_{DC} = 2 \times R_{1Y} \]

And so the actual stator resistance can be calculated from equation (7)

\[ R_{1Y} = \frac{R_{DC}}{2} \]  \hspace{1cm} (7)

<table>
<thead>
<tr>
<th>Phases</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>25.85</td>
<td>0.99</td>
</tr>
<tr>
<td>b</td>
<td>26.43</td>
<td>1.01</td>
</tr>
<tr>
<td>c</td>
<td>26.5</td>
<td>1.02</td>
</tr>
<tr>
<td>Average</td>
<td>26.26</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Table 2: Calculated values of Voltage & Current of DC tests
2.3.2 No-Load Test

In this test the induction motor is operating at rated voltage and there is no connected load in order to measure the magnetizing reactance. The mechanical (rotor) speed is approximately equal to synchronous speed, assuming no mechanical friction or load. At rated frequency (50Hz), slip at no-load is close to zero and the rotor impedance reaches close to infinity. The current, voltage and input power are measured and the no-load impedance is calculated from equation (10). The equivalent circuit for no-load test is shown in Figure 10.

\[
\text{Figure 10: Equivalent Circuit for No-Load test}
\]

The following formulas are taken from Chan & Shi (2011).

Per Phase stator resistance

\[
R_1 = \frac{P_a}{I_{2NL}^2}
\]  \hspace{1cm} (8)

Per phase of nominal voltage

\[
V_a = \frac{V_N}{\sqrt{3}}
\]

Per phase of real power

\[
P_a = \frac{P}{3}
\]
Per phase of reactive power

\[ Q_a = \sqrt{(V_a I_a)^2 - P_a^2} \]

\[ X_n = \frac{Q_a}{I_a^2} \]  \hspace{1cm} (9)

As \( s = 0 \), therefore the magnetizing reactance can be measured from the following equation (10)

\[ X_n \approx X_1 + X_m \]  \hspace{1cm} (10)

The measured values of voltage, current, active power and reactive power are shown in Table 3.

Table 3: Measured Values of voltage, current and power of No-Load Test

<table>
<thead>
<tr>
<th></th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Power (W)</th>
<th>Reactive Power (Var)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Phase</td>
<td>413.300</td>
<td>0.689</td>
<td>50.550</td>
<td>490.000</td>
</tr>
<tr>
<td>Per Phases</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>238.200</td>
<td>0.662</td>
<td>20.170</td>
<td>157.050</td>
</tr>
<tr>
<td>b</td>
<td>238.900</td>
<td>0.717</td>
<td>21.040</td>
<td>169.650</td>
</tr>
<tr>
<td>c</td>
<td>238.800</td>
<td>0.688</td>
<td>9.336</td>
<td>163.950</td>
</tr>
<tr>
<td>Average</td>
<td>238.633</td>
<td>0.689</td>
<td>16.849</td>
<td>163.550</td>
</tr>
</tbody>
</table>

2.3.3 Locked-Rotor Test

The rotor was blocked physically by a piece of metal hooked to the shaft of motor for this test. A low voltage was applied so that the rated current was flowing in the stator winding. As the rotor (mechanical) speed is zero, then the applied slip is equal to unity (S & T, 2014). The rotor impedance becomes much smaller than the magnetizing impedance. As a consequence, the current flow can be neglected in the magnetizing impedance and only the stator and rotor impedances are involved in the equivalent electric circuit, as shown in Figure 12 (S & T, 2014). The voltages, currents and input powers are measured by blocking the rotor, so the impedances can be calculated by the following formulas taken from Chan & Shi (2011).

Per phase voltage
\[ V_a = \frac{V_{LR}}{\sqrt{3}} \]

Phase current

\[ I_a = I_{avg} \]

Per phase active power

\[ P_a = \frac{P}{3} \]

Per phase reactive power

\[ Q_a = \sqrt{(V_a I_a)^2 - P_a^2} \]

The stator resistance \( R_1 \) was already determined by the DC resistance test, so from the locked-rotor measured values the rotor impedance can be calculated.

Toshiba three phase induction machine is design “N” type on the nameplate as Roberts (2003) shows that the design “N” type of motors are equivalent to design “B” of NEMA class motor. As the Chan & Shi (2011) provides the NEMA motor classification to calculate the impedances so the design letters are necessary according to NEMA class motors. Information is given in Bhatia (2011) about the nameplate values and comparisons of the NEMA and IEC standards (International Electromechanical Commission) standards.

The following equations (11) & (12) are used to calculate the stator and rotor leakage reactance for class B motor.

\[ X_1 = 0.4 \times \frac{Q_a}{I_a^2} \quad (11) \]
\[ X_2 = 0.6 \times \frac{Q_a}{I_d^2} \] (12)

![Figure 11: Equivalent circuit of locked-rotor test](image1)

![Figure 12: Simplified Equivalent circuit of locked-rotor test](image2)

Table 4 shows the measure values of locked-rotor test.

<table>
<thead>
<tr>
<th></th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Power (W)</th>
<th>Reactive Power (Var)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3 Phase</strong></td>
<td>92.128</td>
<td>1.019</td>
<td>96.040</td>
<td>134.150</td>
</tr>
<tr>
<td><strong>Per Phases</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a)</td>
<td>53.320</td>
<td>1.018</td>
<td>32.680</td>
<td>44.360</td>
</tr>
<tr>
<td>(b)</td>
<td>53.340</td>
<td>1.036</td>
<td>32.480</td>
<td>45.700</td>
</tr>
<tr>
<td>(c)</td>
<td>52.910</td>
<td>1.002</td>
<td>30.880</td>
<td>44.090</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>53.190</strong></td>
<td><strong>1.019</strong></td>
<td><strong>32.013</strong></td>
<td><strong>44.717</strong></td>
</tr>
</tbody>
</table>
Simplifying equation (10) from no-load test to measure the magnetizing reactance

\[ X_m = X_n - X_1 \]  \hspace{1cm} (13)

\[ R = \frac{P_n}{I_a^2} \]

\[ R_r = R - R_1 \]

Comparing Figure 11 & Figure 12 to make an equation (14) and calculate the rotor resistance.

\[ R_r + jX_r = \frac{(R_2 + jX_2) \times jX_m}{(R_2 + jX_2) + jX_m} \]

\[ R_r \approx \frac{R_2X_m^2}{(R_2 + (X_2 + X_m)^2} \]

\[ R_2 = R_r \times \left( \frac{X_2 + X_m}{X_m} \right)^2 \]  \hspace{1cm} (14)

2.4 IEEE Standard 112 Test

IEEE recommends four methods for testing the stator reactance and resistance. They are:

a) Method 1: A locked-rotor test where the frequency supplied to the motor is 25% of the motor’s rated frequency. The voltage supplied to the motor will be the voltage at which the current delivered to the motor is equal to the motor’s rated full load current.

b) Method 2: A locked-rotor test where three frequencies are supplied to the motor (25%, 50% and 100% of the motor’s rated frequency). For each test the voltage supplied to the motor will be the voltage at which the current delivered to the motor is equal to the motor’s rated full load current. The results are tabulated to generate a curve from which the equivalent stator resistance and reactance can be determined (IEEE, Std 112, 2004).

c) Method 3: A motor with no load connected is supplied at rated frequency, at a reduced voltage, such that the slip speed of the motor is equal to the rated full load slip. For this test
the slip of the motor has to be measured very accurately to obtain accurate equivalent impedance results.

d) Method 4: This test is performed when all other methods cannot be practically implemented. This test is also a locked-rotor test where the only frequency supplied to the motor is at the motor’s rated frequency. The voltage supplied to the motor will be the voltage at which the current delivered to the motor is equal to the motor’s rated full load current (IEEE, Std 112, 2004).

To find the complete motor equivalent circuit parameters, a no load test must be carried out regardless of the method used. This report used IEEE method 4 to find the equivalent circuit.

For the no load test the PM300 power analyzer was used to measure voltage, current, active and reactive power.

The no-load test used per-phase measurements as per IEEE guidelines to determine the equivalent circuit parameters. The reactive power was determined using Equation (15) from the average measured per-phase voltage, current and active power shown in Table 5.

\[ Q_0 = \sqrt{(m * V_0 * I_0)^2 - P_0^2} \]  \hspace{1cm} (15)

Where \( m \) is the number of phases (three for this motor).

<table>
<thead>
<tr>
<th>Table 5: No-Load test at synchronous speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Vo (V)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>3-Phase</td>
</tr>
<tr>
<td>Per Phases</td>
</tr>
<tr>
<td>a</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>Average</td>
</tr>
</tbody>
</table>

Equation (16) was used to calculate the reactive power from the locked rotor test at rated frequency (50Hz) and at a reduced voltage (~97V). The measured values from the locked-rotor test along with the calculated reactance are shown in Table 6.
\[ Q_L = \sqrt{(m \cdot V_L \cdot I_L)^2 - P_L^2} \tag{16} \]

Table 6: Locked rotor test at rated frequency

<table>
<thead>
<tr>
<th>Locked-Rotor Test (Rated Current &amp; Frequency)</th>
<th>Voltage VLR (V)</th>
<th>Current ILR (A)</th>
<th>Power PL (W)</th>
<th>Frequency (Hz)</th>
<th>Apparent Power (VA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3-Phase</strong></td>
<td>96.734</td>
<td>1.071</td>
<td>107.025</td>
<td>49.956</td>
<td>179.475</td>
</tr>
<tr>
<td><strong>Per Phases</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a )</td>
<td>55.863</td>
<td>1.056</td>
<td>35.370</td>
<td>49.957</td>
<td>59.006</td>
</tr>
<tr>
<td>( b )</td>
<td>55.311</td>
<td>1.074</td>
<td>35.943</td>
<td>49.957</td>
<td>59.387</td>
</tr>
<tr>
<td>( c )</td>
<td>56.374</td>
<td>1.084</td>
<td>35.712</td>
<td>49.955</td>
<td>61.082</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>55.849</strong></td>
<td><strong>1.071</strong></td>
<td><strong>35.675</strong></td>
<td><strong>49.956</strong></td>
<td><strong>59.825</strong></td>
</tr>
</tbody>
</table>

Table 7: Reduced voltage slip test of measured values

<table>
<thead>
<tr>
<th>Impedance (Slip) Test (1411 RPM)</th>
<th>Voltage Vs (V)</th>
<th>Current Is (A)</th>
<th>Power Ps (W)</th>
<th>Frequency (Hz)</th>
<th>Power Factor</th>
<th>Reactive Power Qo (Var)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3-Phase</strong></td>
<td>51.28</td>
<td>0.129</td>
<td>7.677</td>
<td>50.028</td>
<td>0.669</td>
<td>8.536</td>
</tr>
<tr>
<td><strong>Per Phases</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a )</td>
<td>29.621</td>
<td>0.128</td>
<td>2.564</td>
<td>50.028</td>
<td>0.674</td>
<td>2.810</td>
</tr>
<tr>
<td>( b )</td>
<td>29.542</td>
<td>0.130</td>
<td>2.584</td>
<td>50.028</td>
<td>0.671</td>
<td>2.858</td>
</tr>
<tr>
<td>( c )</td>
<td>29.649</td>
<td>0.129</td>
<td>2.528</td>
<td>50.028</td>
<td>0.661</td>
<td>2.868</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>29.604</strong></td>
<td><strong>0.129</strong></td>
<td><strong>2.559</strong></td>
<td><strong>50.028</strong></td>
<td><strong>0.669</strong></td>
<td><strong>2.845</strong></td>
</tr>
</tbody>
</table>

The magnetizing and stator reactances are calculated using an iterative approach from the values obtained from the no-load and locked-rotor test. To perform the iterations a MATLAB code shown in Appendix 8.2 was used.

\[ X_M = \frac{mV_0^2}{Q_0 - (mI_0^2X_1)} \times \frac{1}{\left(1 + \frac{X_1}{X_M}\right)^2} \tag{17} \]

where \( X_m \) is the magnetizing reactance.

\[ X_L = \frac{Q_L}{m \cdot I_L^2 \times \left(1 + \frac{X_1}{X_2} + \frac{X_1}{X_M}\right)} \times \left(\frac{X_1}{X_2} + \frac{X_1}{X_M}\right) \tag{18} \]

where \( X_L \) is the stator reactance.
Using the IEEE guidelines for method 4, for a motor of design B, the relationship between $X_1$ and $X_2$ is given by:

$$\frac{X_1}{X_2} = 0.67.$$  \hfill (19)

The iteration begins by setting $X_1 = X_L$, $X_1 = 1$ and $X_m = 10$. The iteration was stopped when convergence was achieved.

The obtained values of magnetizing and stator reactance were then used to find the rotor leakage reactance and rotor resistance. This also required an iterative approach. The IEEE formulas given for the iteration process are expressed as (IEEE, Std 112, 2004):

$$X_{2L} = \frac{X_L}{\left(\frac{X_1}{X_2}\right)} \hfill (20)$$

Where $X_{2L}$ is the rotor leakage reactance.

$$G_{fe} = \frac{P_h}{(m \cdot V_0^2)} \left(1 + \frac{X_1}{X_M}\right)^2 \hfill (21)$$

$$R_{fe} = \frac{1}{G_{fe}} \hfill (22)$$

$$\theta_1 = \cos^{-1}(pf) \hfill (23)$$

$$V_2 = \sqrt{(V_1 - I_1(R_1\cos\theta_1 - X_1\sin\theta_1))^2 + (I_1(R_1\sin\theta_1 + X_1\cos\theta_1))^2} \hfill (24)$$

$$\theta_2 = \arctan\frac{-I_1(R_1\sin\theta_1 - X_1\cos\theta_1)}{V_1 - I_1(R_1\cos\theta_1 - X_1\sin\theta_1)} \hfill (25)$$

$$I_e = \frac{V_2}{X_M} \hfill (26)$$
\[ I_{fe} = \frac{V_2}{R_{fe}} \]  

\[ I_2 = \sqrt{(I_1 \cos \theta_1 - I_e \sin \theta_2)^2 + (-I_1 \sin \theta_1 + I_e \cos \theta_2 + I_{fe} \sin \theta_2)^2} \]  

\[ Z_2 = \frac{V_2}{I_2} \]  

\[ R_2 = s \sqrt{(Z_2^2 - X_2^2)} \]

Where \( R_2 \) is the rotor resistance.

The iteration begins by setting \( X_{2L} = X_2 \) and \( R_1 = 13.04 \) (Chan & Shi, 2011). The iteration was stopped when convergence was achieved. The results obtained after the iterative approach are shown in Table 8 and are compared with the values obtained from the Chan & Shi method.

<table>
<thead>
<tr>
<th>Methods</th>
<th>( R_1 ) (( \Omega ))</th>
<th>( X_1 ) (( \Omega ))</th>
<th>( X_m ) (( \Omega ))</th>
<th>( R_2 ) (( \Omega ))</th>
<th>( X_2 ) (( \Omega ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chan &amp; Shi Test</td>
<td>13.04</td>
<td>16.85</td>
<td>327.70</td>
<td>20.66</td>
<td>25.28</td>
</tr>
<tr>
<td>IEEE Std Test</td>
<td>13.04</td>
<td>17.57</td>
<td>327.74</td>
<td>20.96</td>
<td>26.23</td>
</tr>
<tr>
<td>Difference</td>
<td>0.00%</td>
<td>4.10%</td>
<td>0.01%</td>
<td>1.40%</td>
<td>3.62%</td>
</tr>
<tr>
<td>Average</td>
<td>\textbf{13.04}</td>
<td>\textbf{17.21}</td>
<td>\textbf{327.72}</td>
<td>\textbf{20.81}</td>
<td>\textbf{25.75}</td>
</tr>
</tbody>
</table>
2.5 Moment of Inertia

The moment of inertia is a relationship between electrical torque, mechanical torque, rotor speed and mass and shape of the spinning rotor. It can often be quite complex to calculate the moment of inertia of a rotor, particularly if the shape, size and distribution of mass cannot be directly measured. The moment can be determined if the mechanical torque, electrical torque and the rotor rate of change of speed are known, as described by equation (31). The original objective was to calculate the moment of inertia in such a way; however time and equipment constraints prevented this from being achieved.

\[
J \frac{d\omega}{dt} = T_e - T_m \tag{31}
\]

where:
- \( J = \text{Moment of Inertia (kgm}^2\)\)
- \( T_e = \text{Electrical Torque (N.m)}\)
- \( T_m = \text{Mechanical Torque (N.m)}\)
- \( \omega = \text{Angular Speed (rad/s)}\)

The moment of inertia of a rotor will have a significant influence on the dynamic performance. Therefore it is very important to know this parameter when simulating the starting characteristics of a motor. Fortunately the gravitational flywheel effect for the motor of interest was given in the specification manual.

The moment of inertia can be calculated from the gravitational flywheel effects (\(GD^2\)) by equation (32) (Toshiba, 2009) (TECO Australia, 2014).

\[
J = \frac{GD^2}{4} \tag{32}
\]

For the Toshiba 370 Watt motor \(GD^2 = 0.01kgm^2\).

Therefore

\[
J = \frac{0.01}{4} = 0.0025kgm^2
\]
3. Torque Characteristic

Figure 13 shows the torque characteristics of a squirrel cage induction machine. The parameters given in these characteristics are defined below.

\[ T_A = \text{Locked rotor torque, stop or breakaway torque.} \]

\[ T_n = \text{Rated torque at rated power } P_n \text{ and rated speed } n_n \text{ during operation.} \]

The rated torque in a standard motor is delivered under continuous operation without exceeding its temperature limit (Rockwell Automation, 1996).

\[ T_K = \text{Pull out torque,} \]

This is the maximum torque that the motor can deliver. If the power is increased from the rated rotor load, then slip will continue to increase, speed will decrease and the motor will deliver higher torque (Rockwell Automation, 1996).

\[ T_L = \text{Load torque / counter torque or mechanical torque} \]

This shows the load during the acceleration.

\[ T_M = \text{motor torque or acceleration torque} \]
\[ T_D = Acceleration\ torque. \] This shows the difference between the motor torque and load torque

The rated torque is delivered from continuous duty that operates in S1 mode and rated load with a properly sized motor rotates at rated speed.

Rated torque \((T_n) = 9555 \times \frac{P_n}{\omega_m}\)

However it can be determined by electrical parameters of the motor:

\[
Rated\ Torque\ (T_n) = \frac{\sqrt{3} V \times I \times \cos\phi \times \eta \times 9.55}{n}
\]

Where:

\[ V = Per\ Phase\ voltage \]

\[ I = Per\ Phase\ current \]

\[ \cos\phi = Power\ factor \]

\[ \eta = Efficiency \]

\[ n = Motor\ speed \]

The locked rotor torque or starting torque is always greater than the rated torque and also during acceleration; the motor torque must always remain higher than the mechanical/load torque as seen from Figure 13. The motor operates at constant speed at the intersection point of both torques, at point A in Figure 13. The working point A may increase above the nominal working point \(A_n\) if it is overloading and it is allowable just for a short period without over heating the motor (Rockwell Automation, 1996).
3.1 Torque-Slip/Speed Characteristics

The equation of torque is given in equation (33) (Shahl, 2010)

\[
\tau = \frac{3I_2^2 R_2}{s\omega_s}
\]

Where:

\( I_2 = \text{Rotor current} \)

\( R_2 = \text{Rotor resistance} \)

\( \omega_s = \text{Synchronous speed} \)

\( s = \text{slip} \)

The above torque equation at different slips can be calculated by simplifying the equivalent circuit model. The stator part of induction motor is replaced by Thevenin equivalent circuit (Shahl, 2010) as shown in Figure 14.

![Figure 14: Thevenin Equivalent circuit of an Induction motor model](image)

The stator impedance and magnetizing reactance of equivalent circuit were replaced by a Thevenin equivalent circuit with the stator phase voltage by its Thevenin equivalent.

The equations from (34) to (41) were obtained from (Shahl, 2010)

\[
V_{TH} = \frac{jX_m}{R_1 + j(X_1 + X_m)} \times V_1
\]

\[
V_{TH} = |V_{TH}|
\]
When the impedances are replaced then the Thevenin equivalent impedances

\[ Z_{TH} = (R_1 + jX_1)||jX_m \]

\[ Z_{TH} = R_{TH} + jX_{TH} = \frac{jX_m(R_1 + jX_1)}{R_1 + jX_1 + jX_m} \]  \hspace{1cm} (35)

From above circuit in Figure 14, the rotor current calculation was simplified

\[ I_2 = \frac{V_{TH}}{Z_{TH} + Z_2} \]

\[ I_2 = \frac{V_{TH}}{(R_{TH} + \frac{R_2}{S}) + j(X_{TH} + X_2)} \]  \hspace{1cm} (36)

Squaring the rotor current from above expression, then insert in torque equation (33)

\[ I_2^2 = \frac{V_2^2}{(R_{TH} + \frac{R_2}{S})^2 + (X_{TH} + X_2)^2} \]

Simplifying the torque equation (33)

\[ \tau = \frac{3V_{TH}^2}{(R_{TH} + \frac{R_2}{S})^2 + (X_{TH} + X_2)^2} \times \frac{R_2}{S} \times \frac{1}{\omega_{syn}} \]  \hspace{1cm} (37)

Where \( \omega_{syn} = 1500 \times \frac{2\pi}{60} \) in rad/s

As maximum torque occurs when the synchronous speed is constant and slip is same at maximum air-gap power so from the Thevenin circuit, the maximum torque occur when

\[ \frac{R_2}{S} = \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2} \]  \hspace{1cm} (38)

Re-arranging equation (38) then it obtained the slip so that pull-out torque or maximum torque can be calculated.
\[ S_{\text{max}} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}} \]  

So the Thevenin torque equation (33) becomes, after substituting the pull-out slip,

\[ T_{\text{max}} = \frac{3V_{TH}^2}{2\omega_{\text{syn}} \left[ R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2} \right]} \]  

As the starting torque is proportional to \( V_{TH}^2 \) so that starting torque becomes

\[ T_{\text{start}} = \frac{3V_{TH}^2 R_2}{\omega_{\text{syn}} \left[ (R_{TH} + R_2)^2 + (X_{TH} + X_2)^2 \right]} \]  

- When the stator and rotor leakage inductances are increased then the starting torque reduces
- When the stator frequency is increased then the starting torque reduces
- When the rotor resistance is increased then at first the starting torque also increases but will decrease after some time (Shahl, 2010).

As \( T_{\text{start max}} = T_{\text{max}} \) when \( R_2 = X_1 + X_2 \).
4. Mechanical Load

When the motor operates with the average rated speed and rated torque the motor is sized correctly. The motor can provide the rated mechanical power and the rated current will be drawn from the supply.

Driven machine or loads are mechanical devices that are used to machine or shape materials, such as centrifuge, conveyor system, pumps, fans and machine tools etc. The structured details of motor driven machines are not generally considered for the motor design. But Rockwell Automation (1996) explains that it is usually described exactly by the

- Torque characteristics \( T_L = f(n) \) OR \( T_L = f(t) \)
- Speed as a function of time \( n = f(t) \)
- By the maximum allowable acceleration/deceleration
- Entire moment of inertia, relative to the drive shaft.

The load torque will usually vary from no-load to full-load. The moment of inertia will not differ but depending on the torque curve, the load torque may increase as a function of rotor speed.

4.1 PowerFactory Mechanical Loads

There are three different mechanical loads applied to the induction motor which are selected from the global library in PowerFactory. The sample load models are described as Motor Drive Machines (Mdms), in three forms: Mdm_1, Mdm_3 and Mdm_5. PowerFactory provides three different sizes of simple loads such as fan, pump and compressor. The induction motor output speed \( \omega_{load} \) which is used as input speed to measure the applied torque.

4.1.1 Mdm_1

The first model is Mdm_1, which is one of the built-in models; equation (42) in PowerFactory describes this model (DigSilent, 2013).

\[
T_L = T_{Cont} + K \omega_{load}^2
\]  
\[(42)\]

This shows the square of motor speed (output speed) and initial constant torque and also the \( K \) is the coefficient of the mechanical load in order to reach the rated torque. Figure 15 below shows the speed-torque curve that is associated with the above equation (42).

From PowerFactory

\[
x_{mdm} = mdmlp * speed^{mdmex-1}
\]
Where:

The input power of the motor driven machine is the speed of the motor in p.u

\[ x_{mdm} = \text{output of the motor driven machine is torque in p.u} \]

\[ mdmlp = \text{Proportional factor in p.u} \]

\[ mdmex = \text{Exponential factor} \]

\[
\text{speed (p.u)} = \frac{n_m}{n_s}
\]

\[
\text{speed (p.u)} = \frac{1410}{1500} = 0.94 \text{ p.u}
\]

The load is taken from DigSilent (2013) provided by one of the built-in load which is given the values of exponential factor 3 and proportional factor 0.5pu.

![Figure 15: Torque-Speed characteristic Curve for Mdm_1](image)

4.1.2 Mdm_3

Mdm_3 is the second mechanical load, centrifugal pump is applied to the induction motor from the global library of PowerFactory. Figure 16 shows the speed-toque curve with the associated load equation (43) (DigSilent, 2013)

\[
T_{load} = T_0(1 - \omega_{load})^5 + T_{rated}\omega_{load}^2
\]

(43)

where \( T_0 = \text{initial torque of mechanical load} \)
\[ T_{\text{rated}} = \text{rated torque of mechanical torque} \]

Equation (43) is a realistic equation for most mechanical loads and is used in the simulation as a mechanical load. The induction motor and the dip characteristics shown in equation (43) is a 5th order term that leads at low speed. This type of load is also called quadratic torque load and is one the most common torque load types used in industry, and the torque is square of speed (Rakesh, 2003).

![Figure 16: Speed Torque Curve for Mdm_3](image)

There have been conflicting opinions and claims regarding the effect of replacing a standard efficiency motor with an energy efficient motor on a centrifugal type load.

For centrifugal pumps and fans, the torque varies as the square of the speed, because power varies with torque and with speed (Thornton & Armintor, 2003). Centrifugal pumps are the most common drive type used for pumping applications because of its low cost, reliable and ease to maintain. They also generally have long operational life (Energy Efficiency and Renewable Energy, 2008).
4.1.3 Mdm_5

This is the so-called constant torque load type. In this type the motor driven machine torque results from mechanical friction that remains constant over wide range of speeds (Rockwell Automation, 1996). The torque requirement is independent of speed in this type of load (Cowern, 2014).

Mdm_5 is the third mechanical load. A screw compressor is applied to the induction motor from the global library of PowerFactory. Figure 17 shows the speed-torque curve. The values of speed and torque are automatically calculated by PowerFactory algorithm which is given in the torque-speed characteristics of the screw compressor load.

The torque speed characteristic is defined by the following formula by (DigSilent, 2013)

\[ P_M = |\omega| \times \text{torque(speed)} - \omega \times (1 - \text{load}) \]

![Figure 17: Speed-Torque Curve for Mdm_5](image)
5. Simulation Results

Simulations were carried out in DigSilent’s PowerFactory using the values obtained from the motor equivalent circuit. MATLAB code was also produced to help verify the PowerFactory result. The main purpose of the simulation was to analyze and compare the dynamic performance of the Toshiba motor connected to loads of different types and how to determine whether the dynamics could be improved by utilizing a simple star-delta starter. A comparison of the dynamics between Chan & Shi method and IEEE method was also carried out.

5.1 Equivalent Circuit Parameters Calculation

The electrical parameters of the three-phase induction machine are verified in sections 2.3 and 2.4 above. Two different methods were performed to determine the electrical parameters of the Premium Toshiba Motor. The first experiment was based on the method outline in (Chan & Shi, 2011), the second method was based on the IEEE standards (IEEE, Std 112, 2004). These measured values obtained from each method were implemented in MATLAB and PowerFactory for further verification. The results from MATLAB and PowerFactory were very similar. The coding used for the MATLAB coding is shown in Appendix 8.2.

Version 14.0 of the PowerFactory software only provides two default starting options for a squirrel cage induction motor. They are the direct-on-line or star-delta starting methods.

5.2 Direct-on-Line Starting Method

The simulation for the direct-on-line starting method was carried out for the equivalent motor circuit measurements obtained from both the Chan & Shi and IEEE methods. Given that the values obtained from the Chan & Shi and IEEE showed very little variation, the simulation was carried out using the average equivalent circuit. The PowerFactory software was used to carry out the simulation using the equivalent circuit values shown in Table 8.

In this section, the direct-on-line starting method was analyzed using the PowerFactory results from the equivalent circuit parameters obtained from the average values found from the Chan & Shi and IEEE methods. All simulations were carried out at rated voltage (415V) and frequency (50Hz). Three load types were connected to identical induction motors to assess the impact the loads have on the dynamic behavior of motor startup. The three loads included loads with torque curves typical of an exhaust fan (PowerFactory Mdm_1), centrifugal pump (Mdm_3) and a screw compressor (Mdm_5). Figure 18 shows the transient behavior of the motor current, active power, reactive power, rotor speed, electrical torque and power factor. The DOL starter was switched on at $t = 0.1\text{ seconds}$. 
The current plot shown in Figure 18 a) demonstrates the very large inrush current that occurs with DOL motor starting. The peak current observed is close to 5.5A or almost five times the rated motor current. The starting current profile is very similar for each of the load types.

Plot Figure 18 b) shows per unit speed. The steady state operating speed is reached very quickly (less than 0.2 seconds) for each of the load types. This is a result of the very low rotor and loads moment of inertia. All motors operate above the nominal operating speed of 0.95pu at around 0.97pu, suggesting they are fairly lightly loaded.

Figure 18 c) shows a comparison of the mechanical torque generated by the motor. It is one of the few plots that clearly distinguish the three load types. The highest torque is developed with the centrifugal pump and the smallest by the exhaust fan.

The active power is shown in Figure 18 d). During the transient event there is very little to distinguish between the three load types. At steady state each of the motors operates at a different active power ranging from 178W-248W. This is well below the motors 370W rating, which again suggests the motors are lightly loaded.
Figure 18 e) shows the reactive power and Figure 18 f) shows the corresponding power factor. The plots indicate a high reactive power component during motor startup and a very high reactive power component at steady state. Therefore, each motor has very poor power factor regulation. There is however a clear trend that shows the power factor improves with increased load. However, the highest steady state power factor observed was still below 50%.

The comparison is made from the calculated values of current, active power, reactive power and speed which are given in Table 9, Table 10, Table 11 and Table 12. The values were obtained from PowerFactory using a DOL starter and the average equivalent motor circuit from the Chan & Shi and IEEE measurements.

| Table 9: Current Measured values for average test with different Loads |
|-----------------------------|-----------------------------|
| (Current ) on Mdm_1 (Exhaust Fan Load) | (Current ) on Mdm_3 (Centrifugal Pump Load) | (Current ) on Mdm_5 (Screw Compressor Load) |
|                               | Average Test                | Average Test                                | Average Test                                |
| Max Current (kA) | Steady Current (kA) | Max Current (kA) | Steady Current (kA) | Max Current (kA) | Steady Current (kA) |
| Times (s)         | 0.00550000              | 0.00408447     | 0.00550000              | 0.09259677     | 0.09259677     |
| Current Magnitude (kA) | 0.09259677     | 0.00072985     | 0.00072985     | 0.00072985     | 0.00085357     |
| Max Current (kA) | 0.00550000              | 0.00408447     | 0.00550000              | 0.09259677     | 0.09259677     |
| Steady Current (kA) | 0.09259677     | 0.00072985     | 0.00072985     | 0.00072985     | 0.00085357     |
| Times (s)         | 0.00550000              | 0.00408447     | 0.00550000              | 0.09259677     | 0.09259677     |
| Current Magnitude (kA) | 0.09259677     | 0.00072985     | 0.00072985     | 0.00072985     | 0.00085357     |
### Table 10: Active Power Measured values for average test with different Loads

<table>
<thead>
<tr>
<th></th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max Power (MW)</strong></td>
<td>0.02259677</td>
</tr>
<tr>
<td><strong>Steady Power (MW)</strong></td>
<td>0.11259680</td>
</tr>
<tr>
<td><strong>Active Power (MW)</strong></td>
<td>0.00192153</td>
</tr>
<tr>
<td><strong>Times (s)</strong></td>
<td>0.02259677</td>
</tr>
</tbody>
</table>

#### (Active Power ) on Mdm_1 (Exhaust Fan Load)

<table>
<thead>
<tr>
<th></th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max Power (MW)</strong></td>
<td>0.02259677</td>
</tr>
<tr>
<td><strong>Steady Power (MW)</strong></td>
<td>0.11259680</td>
</tr>
<tr>
<td><strong>Active Power (MW)</strong></td>
<td>0.00192153</td>
</tr>
<tr>
<td><strong>Times (s)</strong></td>
<td>0.02259677</td>
</tr>
</tbody>
</table>

#### (Active Power ) on Mdm_3 (Centrifugal Pump Load)

<table>
<thead>
<tr>
<th></th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max Power (MW)</strong></td>
<td>0.02259677</td>
</tr>
<tr>
<td><strong>Steady Power (MW)</strong></td>
<td>0.11259680</td>
</tr>
<tr>
<td><strong>Active Power (MW)</strong></td>
<td>0.00191790</td>
</tr>
<tr>
<td><strong>Times (s)</strong></td>
<td>0.00550000</td>
</tr>
</tbody>
</table>

#### (Active Power ) on Mdm_5 (Screw Compressor Load)

<table>
<thead>
<tr>
<th></th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max Power (MW)</strong></td>
<td>0.02259677</td>
</tr>
<tr>
<td><strong>Steady Power (MW)</strong></td>
<td>0.11259680</td>
</tr>
<tr>
<td><strong>Active Power (MW)</strong></td>
<td>0.00191790</td>
</tr>
<tr>
<td><strong>Times (s)</strong></td>
<td>0.00550000</td>
</tr>
</tbody>
</table>

### Table 11: Reactive Power Measured values for average test with different Loads

<table>
<thead>
<tr>
<th></th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max Reactive Power (MW)</strong></td>
<td>0.00550000</td>
</tr>
<tr>
<td><strong>Steady Reactive Power (MW)</strong></td>
<td>0.12259680</td>
</tr>
<tr>
<td><strong>Reactive Power (MW)</strong></td>
<td>0.00260242</td>
</tr>
<tr>
<td><strong>Times (s)</strong></td>
<td>0.00550000</td>
</tr>
</tbody>
</table>

#### (Reactive Power ) on Mdm_1 (Exhaust Fan Load)

<table>
<thead>
<tr>
<th></th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max Reactive Power (MW)</strong></td>
<td>0.00550000</td>
</tr>
<tr>
<td><strong>Steady Reactive Power (MW)</strong></td>
<td>0.12259680</td>
</tr>
<tr>
<td><strong>Reactive Power (MW)</strong></td>
<td>0.00260242</td>
</tr>
<tr>
<td><strong>Times (s)</strong></td>
<td>0.00550000</td>
</tr>
</tbody>
</table>

#### (Reactive Power ) on Mdm_3 (Centrifugal Pump Load)

<table>
<thead>
<tr>
<th></th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max Reactive Power (MW)</strong></td>
<td>0.00550000</td>
</tr>
<tr>
<td><strong>Steady Reactive Power (MW)</strong></td>
<td>0.12259680</td>
</tr>
<tr>
<td><strong>Reactive Power (MW)</strong></td>
<td>0.00260242</td>
</tr>
<tr>
<td><strong>Times (s)</strong></td>
<td>0.00550000</td>
</tr>
</tbody>
</table>

#### (Reactive Power ) on Mdm_5 (Screw Compressor Load)

<table>
<thead>
<tr>
<th></th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max Reactive Power (MW)</strong></td>
<td>0.00550000</td>
</tr>
<tr>
<td><strong>Steady Reactive Power (MW)</strong></td>
<td>0.12259680</td>
</tr>
<tr>
<td><strong>Reactive Power (MW)</strong></td>
<td>0.00259981</td>
</tr>
<tr>
<td><strong>Times (s)</strong></td>
<td>0.00550000</td>
</tr>
</tbody>
</table>
Table 12: Speed Measured values for average test with different Loads

<table>
<thead>
<tr>
<th>(Speed ) on Mdm_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Test</td>
</tr>
<tr>
<td>Steady Speed</td>
</tr>
<tr>
<td>Times (s)</td>
</tr>
<tr>
<td>Speed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(Speed ) on Mdm_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Test</td>
</tr>
<tr>
<td>Steady Speed</td>
</tr>
<tr>
<td>Times (s)</td>
</tr>
<tr>
<td>Speed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(Speed ) on Mdm_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Test</td>
</tr>
<tr>
<td>Steady Speed</td>
</tr>
<tr>
<td>Times (s)</td>
</tr>
<tr>
<td>Speed</td>
</tr>
</tbody>
</table>
5.3 Star-Delta Starting Method

The simulation for the direct-on-line starting method was carried out for the equivalent motor circuit measurements obtained from both the Chan & Shi and IEEE methods. Given that the values obtained from the Chan & Shi and IEEE showed very little variation, the simulation was carried out using the average equivalent circuit. The PowerFactory software was used to carry out the simulation using the equivalent circuit values shown in Table 8.

In this section, the star-delta starting method was analyzed using the PowerFactory results from the equivalent circuit parameters obtained from the average values found from the Chan & Shi and IEEE methods. All simulations were carried out at rated voltage \(415\text{V}\) and frequency \(50\text{Hz}\). Three load types were connected to identical induction motors to assess the impact the loads have on the dynamic behavior of motor startup. The three loads included loads with torque curves typical of an exhaust fan (PowerFactory Mdm_1), centrifugal pump (Mdm_3) and a screw compressor (Mdm_5). Figure 19 shows the transient behavior of the motor current, active power, reactive power, rotor speed, electrical torque and power factor. The start-delta starter was switched on at \(t = 0.1\text{seconds}\) and transitioned from start connected to delta connected at \(t = 0.24\text{seconds}\).
Figure 19: Current, Active Power, Reactive Power, Speed, Torque and Power Factor curves at 0.37kW output power

The plot in Figure 19 a) current, at startup there is a significant decrease in current in comparison with the DOL starting method. The in rush current is only 1.9A compared with 5.5A of the DOL starter. The peak current occurs during the transition to delta operation at $t = 0.24$ seconds. The maximum current observed was 3.8A, which is still significantly lower than the DOL method. The star-delta starting method does not affect the steady state operating points.

Plot Figure 19 b) shows per unit speed. Generally a start-delta starter would transition into run mode (delta connected) at between 75-80% of the motors rated speed (Randermann, 2010). It can be seen from Figure 19 b) that the compressor does not reach 75% of the rated speed before switching to delta mode. However, so that an accurate comparison could be made all motors were switched at the same instant. Using the start-delta did extend the time taken to reach steady state operating speed, adding an average of around 0.1 seconds when compared with the DOL method. The steady state operating speed is still reached very quickly (less than 0.3 seconds) for each of the load types. This again is a result of the very low rotor and loads moment of inertia.
Figure 19 c) shows a comparison of the mechanical torque generated by the motor. When looking at the start-delta plot alone it is very difficult to see any effect to the torque curves. However, when compared with the DOL the plot appears to be stretched, but little to no difference between maximum and minimum points.

The active power is shown in Figure 19 d). During the transient event there is very little to distinguish between the three load types and as all other plots the steady state operating point is identical to the DOL method. The plot of Figure 19 d) is comparable to the current plot, showing a significantly lower starting and peak power compared with the DOL starting method.

Figure 19 e) shows the reactive power and Figure 19 f) shows the corresponding power factor. Compared with the DOL starter the reactive power during startup is significantly reduce, although, the peak reactive current at the star to delta transition is still quite high at 2500Var. As with all other plots the steady state values are unaffected and each motor operates with a poor power factor.

Table 13, Table 14, Table 15 and Table 16 are used to compare the calculated values of current, active power, reactive power and speed. The values were obtained from the PowerFactory simulations using a star-delta starter and the average motor equivalent circuit from the (Chan & Shi, 2011) and (IEEE, Std 112, 2004) measurements.
Table 13: Current Measured values for average test with different Loads

<table>
<thead>
<tr>
<th>Times (s)</th>
<th>Current Magnitude (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0055000</td>
<td>0.0013732</td>
</tr>
<tr>
<td>0.1425968</td>
<td>0.0006936</td>
</tr>
<tr>
<td>0.1525968</td>
<td>0.0022794</td>
</tr>
<tr>
<td>0.2025968</td>
<td>0.0007136</td>
</tr>
</tbody>
</table>

Table 14: Active Power Measured values for average test with different Loads

<table>
<thead>
<tr>
<th>Times (s)</th>
<th>Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02259677</td>
<td>0.00065998</td>
</tr>
<tr>
<td>0.14259680</td>
<td>0.00039869</td>
</tr>
<tr>
<td>0.15259680</td>
<td>0.00084076</td>
</tr>
<tr>
<td>0.22259680</td>
<td>0.00086470</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Times (s)</th>
<th>Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02259677</td>
<td>0.00065964</td>
</tr>
<tr>
<td>0.14259680</td>
<td>0.00044003</td>
</tr>
<tr>
<td>0.15259680</td>
<td>0.00093163</td>
</tr>
<tr>
<td>0.24259680</td>
<td>0.00038399</td>
</tr>
</tbody>
</table>
### Table 15: Reactive Power Measured values for average test with different Loads

<table>
<thead>
<tr>
<th>(Reactive Power ) on Mdm_1 (Exhaust Fan Load)</th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Times (s)</td>
<td>Reactive Power (MW)</td>
</tr>
<tr>
<td><strong>Startup Reactive Power (MW)</strong></td>
<td>0.0055000</td>
</tr>
<tr>
<td><strong>Pull-up Reactive Power (MW)</strong></td>
<td>0.1425968</td>
</tr>
<tr>
<td><strong>Max Reactive Power (MW)</strong></td>
<td>0.1525968</td>
</tr>
<tr>
<td><strong>Steady Reactive Power (MW)</strong></td>
<td>0.2325968</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(Reactive Power ) on Mdm_3 (Centrifugal Pump Load)</th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Times (s)</td>
<td>Reactive Power (MW)</td>
</tr>
<tr>
<td><strong>Startup Reactive Power (MW)</strong></td>
<td>0.0055000</td>
</tr>
<tr>
<td><strong>Pull-up Reactive Power (MW)</strong></td>
<td>0.1425968</td>
</tr>
<tr>
<td><strong>Max Reactive Power (MW)</strong></td>
<td>0.1525968</td>
</tr>
<tr>
<td><strong>Steady Reactive Power (MW)</strong></td>
<td>0.2325968</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(Reactive Power ) on Mdm_5 (Screw Compressor Load)</th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Times (s)</td>
<td>Reactive Power (MW)</td>
</tr>
<tr>
<td><strong>Startup Reactive Power (MW)</strong></td>
<td>0.0055000</td>
</tr>
<tr>
<td><strong>Pull-up Reactive Power (MW)</strong></td>
<td>0.1425968</td>
</tr>
<tr>
<td><strong>Max Reactive Power (MW)</strong></td>
<td>0.1525968</td>
</tr>
<tr>
<td><strong>Steady Reactive Power (MW)</strong></td>
<td>0.2325968</td>
</tr>
</tbody>
</table>

### Table 16: Speed Measured values for average test with different Loads

<table>
<thead>
<tr>
<th>(Speed) on Mdm_1</th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Times (s)</td>
<td>Speed</td>
</tr>
<tr>
<td><strong>Pull-Up Speed</strong></td>
<td>0.1425968</td>
</tr>
<tr>
<td><strong>Steady Speed</strong></td>
<td>0.2025968</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(Speed) on Mdm_3</th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Times (s)</td>
<td>Speed</td>
</tr>
<tr>
<td><strong>Pull-Up Speed</strong></td>
<td>0.1425968</td>
</tr>
<tr>
<td><strong>Steady Speed</strong></td>
<td>0.2125968</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(Speed) on Mdm_5</th>
<th>Average Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Times (s)</td>
<td>Speed</td>
</tr>
<tr>
<td><strong>Pull-Up Speed</strong></td>
<td>0.1425968</td>
</tr>
<tr>
<td><strong>Steady Speed</strong></td>
<td>0.2025968</td>
</tr>
</tbody>
</table>
5.4 Electrical Torque Curves

The average equivalent circuit model obtained from the (Chan & Shi, 2011) & (IEEE, Std 112, 2004) methods were used to generate a torque speed plots in both MATLAB and PowerFactory. This was carried out in order to verify the calculated parameters were accurate, as PowerFactory does not disclose the formulas used to generate the torque curves.

5.4.1 Torque Curves

Figure 20 shows the electrical torque curve generated by the MATLAB code. The code used to generate the plot is shown in the Appendix section 8.2. Figure 21 shows the electrical torque curve automatically generated in PowerFactory. These two curves indicate the high starting torque initially increased at the startup of motor and reached to the maximum torque. After the maximum torque the declines slowly where it shows the stability point of motor.

![Figure 20: Matlab Torque vs. Speed Curve](image-url)
Table 17: Starting and Maximum torque difference from Matlab and PowerFactory

<table>
<thead>
<tr>
<th>Curves</th>
<th>Startup Torque (p.u)</th>
<th>Maximum Torque (p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matlab</td>
<td>2.7255</td>
<td>3.3631</td>
</tr>
<tr>
<td>PowerFactory</td>
<td>2.7443</td>
<td>3.3863</td>
</tr>
<tr>
<td>Difference</td>
<td>0.6838%</td>
<td>0.6842%</td>
</tr>
</tbody>
</table>

Table 17 shows a comparison of some of the key points on the torque speed curves. The difference between the achieved starting torque and maximum torque values from PowerFactory and Matlab are very small (less than 1%).
6. Conclusion

It cannot be said which of the starting method is best without more specific starting requirements. Furthermore, there are other starting methods that have not been modelled and simulated in this report that could be considered. The applied simulation method from this thesis investigated and compared two starter methods, the DOL method and the star-delta method. This was carried out using the computer simulation software PowerFactory. This software is not an alternative to practical knowledge as the result can very easily produce an inaccurate simulation if data is not carefully entered. However, a competent user with a feel for the expected results could use this software to quickly compare starting methods which would help make a decision on the most appropriate starting method.

The PowerFactory software does have other limitations. Without extensive training on the use of the software, factors such as equipment life span and running/operational costs are not easily analysed. These are factors that would need to be considered when implementing a motor into a new or existing project. The models implemented in this report have also ignored factor such as flux leakage, flux saturation. Special attention may be required to these areas for some applications.

A general conclusion can however be drawn from the starting tests performed in this report. Direct-on-line starters have a significant impact on the power system. They can result in voltage dips in the system during motor start up. This is due to the high starting inrush current resulting from the high starting torque. It does however have the shortest time taken to reach steady state.

Star-delta starters can also have significant impact on the power system voltage, although generally not to the same extent as a DOL starter, as the inrush current is reduced. The drawback of this method is a reduction in the starting torque and the longer time required reaching steady state operation. Starting time and starting torque are important factors in most motor applications, so these are factors than need to be taken into consideration. It should be noted that there wasn’t any specific object for optimizing the starting procedure in this thesis.

This thesis mainly analysed and discussed the dynamic behaviour of a specific three phase induction motor. The key involvement of the project was to calculate the parameters of the equivalent motor circuit so that this analysis could be carried out. DigSilent’s PowerFactory computer software proved to be a very helpful tool in analysing the DOL and star-delta starting methods, but it should not be the only approach used. Future work could use later versions of the PowerFactory software or investigate other starting methods which would require building models within the more advanced features of the software.
7. Bibliography


8. Appendix

8.1 Appendix A

Toshiba manufacturer data sheet is taken from the (Toshiba, 2009), it gives the details of the three phase induction machine that were used in this thesis which shows in Figure 22: Toshiba Manufacturer Data Sheet for equivalent circuit.

PERFORMANCE DATA

PREMIUM EFFICIENCY PERFORMANCE DATA AT 415V - 50Hz

<table>
<thead>
<tr>
<th>Output kW</th>
<th>RPM Frame Number</th>
<th>Full Load Current (A) @ 415V</th>
<th>Full Load Current (A) @ 400V</th>
<th>Full Load Current (A) @ 380V</th>
<th>Full Load Torque (N.m)</th>
<th>Efficiency (%)</th>
<th>Power Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.37</td>
<td>2000 D1T</td>
<td>0.97</td>
<td>0.87</td>
<td>0.89</td>
<td>0.68</td>
<td>521</td>
<td>72.9</td>
</tr>
<tr>
<td>1.00</td>
<td>2000 D1M</td>
<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
<td>0.81</td>
<td>465</td>
<td>73.6</td>
</tr>
<tr>
<td>4.00</td>
<td>2000 D0H</td>
<td>1.40</td>
<td>1.40</td>
<td>1.40</td>
<td>1.11</td>
<td>333</td>
<td>67.1</td>
</tr>
</tbody>
</table>

Figure 22: Toshiba Manufacturer Data Sheet for equivalent circuit.

The Figure 23 is used to connect the PM300 Power analyzer connection to three-phase power supply.

Figure 23: PM300 Three-Phase Power Analyser Connection
8.1.1  (Chan & Shi, 2011) Electrical Parameters

**DC Test:** The calculated value of stator resistance from the measured values of dc test

<table>
<thead>
<tr>
<th>Phases</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>R1 (Ω)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>25.85</td>
<td>0.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>26.43</td>
<td>1.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>26.5</td>
<td>1.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>26.26</td>
<td>1.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 18: DC test calculated values**

**No-Load Test Results:** The calculated value of magnetizing impedance from the measure values of no-load test.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Power (W)</th>
<th>Reactive Power (Var)</th>
<th>R_NL / phase (Ω)</th>
<th>Xn (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Phase</td>
<td>413.300</td>
<td>0.689</td>
<td>50.550</td>
<td>490.000</td>
<td>346.381</td>
<td>344.618</td>
</tr>
<tr>
<td>Per Phases</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>238.200</td>
<td>0.662</td>
<td>20.170</td>
<td>157.050</td>
<td>359.873</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>238.900</td>
<td>0.717</td>
<td>21.040</td>
<td>169.650</td>
<td>333.008</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>238.800</td>
<td>0.688</td>
<td>9.336</td>
<td>163.950</td>
<td>347.345</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>238.633</td>
<td>0.689</td>
<td>16.849</td>
<td>163.550</td>
<td>346.381</td>
<td></td>
</tr>
</tbody>
</table>

**Locked-Rotor Test Results:** The calculated values of stator and rotor reactance and rotor resistance from the locked-rotor test.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Power (W)</th>
<th>Reactive Power (Var)</th>
<th>R_NL / phase (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Phase</td>
<td>92.128</td>
<td>1.019</td>
<td>96.040</td>
<td>134.150</td>
<td>52.212</td>
</tr>
<tr>
<td>Per Phases</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>53.320</td>
<td>1.018</td>
<td>32.680</td>
<td>44.360</td>
<td>52.357</td>
</tr>
<tr>
<td>b</td>
<td>53.340</td>
<td>1.036</td>
<td>32.480</td>
<td>45.700</td>
<td>51.511</td>
</tr>
<tr>
<td>c</td>
<td>52.910</td>
<td>1.002</td>
<td>30.880</td>
<td>44.090</td>
<td>52.789</td>
</tr>
<tr>
<td>Average</td>
<td>53.190</td>
<td>1.019</td>
<td>32.013</td>
<td>44.717</td>
<td>52.212</td>
</tr>
</tbody>
</table>
The calculated values of torque characteristics are given below in Table 22. It is used to measure in the SI units instead of per unit values. But PowerFactory calculations are in per units values. So these values are not used in PowerFactory. Matlab simulation tool is used to carry out the torque characteristics then convert the values in per unit in Matlab.

Table 22: Theoretical calculated values of torque characteristics

<table>
<thead>
<tr>
<th>Methods</th>
<th>V_Th (V)</th>
<th>Z_Th (Ω)</th>
<th>Torque (Nm)</th>
<th>Max Torque (N.m)</th>
<th>Starting Torque (N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chan &amp; Shi Test</td>
<td>228.0997</td>
<td>11.78 + j16.47</td>
<td>2.661</td>
<td>12.43</td>
<td>7.344</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>0.2077%</td>
<td>0.42 + j3.8%</td>
<td>1.7663%</td>
<td>2.3572%</td>
<td>5.4466%</td>
</tr>
</tbody>
</table>

8.1.2 PowerFactory Results

Table 23 & Table 24 show the average test results of Chan & Chi (2011) and IEEE Standard 112 (2004) electrical parameters of induction machine, which is implemented in PowerFactory at rated mechanical power and then PowerFactory’s automatic calculated values are highlighted in gray color.

Table 23: Basic Data of (Chan & Shi, 2011) Experimental results by PowerFactory

<table>
<thead>
<tr>
<th>Types</th>
<th>Symbols</th>
<th>Three-phase Induction Motor, Wye-Connected, Squirrel Cage</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Voltage</td>
<td>V_rated</td>
<td>415</td>
<td>V</td>
</tr>
<tr>
<td>Input Mode</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rated Apparent Power</td>
<td>S_rated</td>
<td>0.654055</td>
<td>kVA</td>
</tr>
<tr>
<td>Rated Mechanical Power</td>
<td>P_mech.</td>
<td>0.37</td>
<td>kW</td>
</tr>
<tr>
<td>Rated Power Factor</td>
<td>P_f</td>
<td>0.6531272</td>
<td></td>
</tr>
<tr>
<td>Efficiency at Nominal Operation</td>
<td>η</td>
<td>86.61432</td>
<td>%</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>F</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Nominal Speed</td>
<td>n_0</td>
<td>1410.664</td>
<td>rpm</td>
</tr>
<tr>
<td>Number of Poles Pairs</td>
<td>P</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Connection</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance (Zero Sequence)</td>
<td>R_{x,0}</td>
<td>0.0516</td>
<td>p.u</td>
</tr>
<tr>
<td>Reactance (Zero Sequence)</td>
<td>X_{x,0}</td>
<td>0.0681</td>
<td>p.u</td>
</tr>
</tbody>
</table>
Table 24: Load tab of the PowerFactory calculated values

<table>
<thead>
<tr>
<th>Types (Single Cage)</th>
<th>Symbols</th>
<th>Three-Phase Induction Motor, Wye-Connected, Squirrel Cage</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locked Rotor Current</td>
<td>It or LRA</td>
<td>4.83603</td>
<td>p.u</td>
</tr>
<tr>
<td>Locked Rotor Torque</td>
<td>T_{st}</td>
<td>2.744265</td>
<td>p.u</td>
</tr>
<tr>
<td>R/X Locked Rotor</td>
<td>R/X LQ</td>
<td>0.7324177</td>
<td></td>
</tr>
<tr>
<td>Torque at Stalling Point</td>
<td>T_{max}</td>
<td>3.386269</td>
<td>p.u</td>
</tr>
<tr>
<td>Slip at Stalling Point</td>
<td>R_{s}</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>Stator Resistance</td>
<td>X_{s}</td>
<td>0.0516</td>
<td>p.u</td>
</tr>
<tr>
<td>Stator Reactance</td>
<td>X_{m}</td>
<td>0.0681</td>
<td>p.u</td>
</tr>
<tr>
<td>Magnetizing Reactance</td>
<td>X_{m}</td>
<td>1.2977</td>
<td>p.u</td>
</tr>
</tbody>
</table>

Operating Cage/Rotor Data

| Rotor Resistance | R_{rA} | 0.0824 | p.u |
| Rotor Reactance | X_{rA} | 0.1020 | p.u |

8.2 Matlab Simulation

Table 25: Average electrical parameter calculated in Matlab in per unit values

<table>
<thead>
<tr>
<th>Average Electrical Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_1 (pu)</td>
</tr>
<tr>
<td>0.0516</td>
</tr>
</tbody>
</table>

8.2.1 Chan and Shi Parameter Test Matlab Calculation

```plaintext
clear all
clc % Clear All the Comments
R1=13.04; % Stator Resistance
X1=17.5709.*1i; % Stator Leakage Reactance
Xm=327.7353.*1i; % Magnetizing Reactance
X2=26.2253.*1i; % Rotor Leakage Reactance
R2=20.9552; % Rotor Resistance
V_ph=.415e3./sqrt(3); % Per-Phase Voltage

%---------------------------basic Calculation---------------------------
Motor_S=1410; % Motor Speed
Frequency=50; % Rated Frequency
Syn_S=2.*pi().*Frequency./2; % Synchronous speed in Rad/s
Syn_speed=Syn_S.*60./(2.*pi()); % Synchronous speed in rpm
Slip=(Syn_speed-Motor_S)./Syn_speed; % Slip of Motor

%---------------------------rated values---------------------------
```
s_rated=Slip; % Rated Slip
Zth_rated=((X2+R2./s_rated).*(Xm))./(X2+R2./s_rated+Xm); % Rated Thevenin Impedance
Zeq_rated=Zth_rated+R1+X1; % Rated Equivalent Impedance
Vth_rated=V_ph.*Zth_rated./(Zth_rated+R1+X1); % Rated Thevenin Voltage
I2_rated=Vth_rated./(X2+R2./s_rated); % Rated Rotor Current
Pag_rated=3.*(abs(I2_rated))^2.*R2./s_rated; % Rated Mechanical Power
tau_rated=Pag_rated/Syn_S; % Rated Torque
S_rated=3.*(V_ph)^2./Zeq_rated; % Rated Apparent Power
Srated=abs(S_rated); % Rated Absolute Apparent Power
pf_rated=real(S_rated)./abs(S_rated); % Rated Power Factor
eff=Pag_rated./real(S_rated); % Rated Efficiency
I=abs(V_ph/Zeq_rated); % Absolute Current

%--------------------------Per Unit Value Calculation--------------------------

V_base=240; % Base Voltage
S_base=Srated./3; % Base Apparent Power
Z_base=V_base^2./S_base; % Base Impedance
omega_s=Syn_S; % Synchronous Speed in Rad/s
s=1; % Unity Slip
R1pu=R1./Z_base; % Stator Resistance in Per Unit
X1pu=X1./Z_base; % Stator Leakage Reactance in Per Unit
Xmpu=Xm./Z_base; % Magnetizing Leakage Reactance in Per Unit
X2pu=X2./Z_base; % Rotor Leakage Reactance in Per Unit
R2pu=R2./Z_base; % Rotor Resistance in Per Unit
V_pu=V_ph./Z_base; % Voltage in Per Unit
omega_pu=omega_s./omega_s; % Synchronous Speed in Per Unit
tau_base=tau_rated/3 % Base Torque
hold on;
tau_max=0; % Set Maximum Torque to zero for iteration
tau_start=0; % Set Starting Torque to zero for iteration
for n=0:1000 % For loop number of iteration from 0 to 1000
  n=n+1; %
  s;
  n_ns=(1-s);
  omega=omega_s.*(1-s);
  Zth=((X2+R2./s).*(Xm))./(X2+R2./s+Xm); % Thevenin Impedance in rotor side
  Vth=V_ph.*Zth./(Zth+R1+X1); % Thevenin Voltage
  I2=Vth./(X2+R2./s); % Rotor current
  abs(I2);
  Pag=(abs(I2))^2.*R2./s; % Air-gap Power
  tau_ph=Pag./omega_s; % Mechanical torque
tau_pu=(tau_ph)./tau_base; % Torque in per unit

if n==1;
    tau_start=tau_pu; % If n is equal to 1 then display starting torque value
end % End of if condition

if tau_pu>tau_max;
    tau_max=tau_pu; % If torque is maximum then display maximum torque
end % End of if condition

plot(n_ns,tau_pu); % Plot the graph of torque in per unit vs speed
s=s-.001;
end

hold off;

Zthlr=((X2pu+R2pu./1).*(Xmpu))./(X2pu+R2pu./1+Xmpu); % Thevenin impedance in rotor side of circuit
Zlr=X1pu+R1pu+Zthlr; % Thevenin impedance
Ilr=abs(1./Zlr) % Display the locked rotor current
P_mech=Pag_rated % Display mechanical power
pf_rated % Display power factor
eff % Display efficiency
tau_start % Display starting torque
tau_max % Display maximum torque
Rs=R1pu % Display stator resistance in per unit
Xs=imag(X1pu) % Display stator leakage reactance in per unit
Xr=imag(X2pu) % Display rotor leakage reactance in per unit
Rr=R2pu % Display rotor resistance in per unit
Xmpu=imag(Xmpu) % Display magnetizing reactance in per unit

8.2.2 IEEE Standard 112 Matlab Calculation:

8.2.2.1 IEEE Standard 112 Parameter Test Matlab Calculation
clc
clear all % Clear all on each simulation

P_h=1; % Lets assume power is equal to 1
--------------------------Impedance test (Slip/reduced voltage)--------------------------
P_L=107.025; % Measured value of power from locked-rotor test
V_L=96.7339./sqrt(3); % Measured value of voltage from locked-rotor test
I_L=1.0712; % Measured value of current from locked-rotor test
--------------------------No-load test----------------------------------
\[ P_o = 52.092; \]  % Measured value of power from no-load test
\[ V_o = 417.7533 / \sqrt(3); \]  % Measured value of voltage from no-load test
\[ I_o = 0.7026; \]  % Measured value of current from no-load test

%-------------------------- (Slip/reduced voltage)--------------------------
\[ P_s = 7.6767; \]  % Measured value of power from reduced voltage test
\[ V_s = 51.27563 / \sqrt(3); \]  % Measured value of voltage from reduced voltage test
\[ I_s = 0.1293; \]  % Measured value of current from reduced voltage test
\[ R_1 = 13.04; \]  % Measure stator resistance from DC test (separate test)
\[ s = (1500-1411) / (1500); \]  % Calculated slip value
%-----------------------------locket rotor test(slip-method)-----------------
\[ m = 3; \]  % Number of Phase of motor
\[ Q_o = \sqrt((m.*V_o.*I_o)^2-P_o^2); \]  % Calculated reactive power at no-load test
\[ Q_L = \sqrt((m.*V_L.*I_L)^2-P_L^2); \]  % Calculated reactive power at locked-rotor test

%-----------------------------Guesses-------------------------------------
\[ X_1 = 1; \]  % Stator reactance is equal to 1 for Iteration
\[ X_M = 10; \]  % Magnetizing reactance assume to 10 for more iteration
\[ n = 1; \]  % First number of iteration
\[ \text{for } n = 1:10 \]  % For loop iteration
\[ n = n+1; \]  % Adding 1 buy each iteration
\[ X_2 = X_1 / 0.67; \]  % Rotor reactance calculation
\[ X_{Mnew} = m.*V_o^2 / (Q_o-(m.*I_o^2.*X_1)).*1/(1+X_1./X_M)^2; \]  % Magnetizing reactance calculation
\[ X_L = Q_L / (m.*I_L^2.*(1+(X_1./X_2)+X_1./X_M)).*((X_1./X_2)+X_1./X_M); \]  % Reactance calculation from locked rotor test
\[ X_1 = X_L; \]  % Stator reactance is equal to locked rotor reactance
\[ X_M = X_{Mnew}; \]  % End of for loop
\[ X_1; \]  % Number of iteration for stator reactance
\[ X_M; \]  % Number of iteration for magnetizing reactance
\[ X_2; \]  % Number of iteration for rotor reactance
\[ B_M = 1./X_M; \]  % Magnetizing susceptance
\[ X_{2L} = X_L / (X_1./X_2); \]  % Rotor reactance from locked-rotor test
\[ X_2 = X_{2L}; \]  % Rotor Impedance
\[ G_fe = P_h / (m.*V_o^2).*(1+X_1./X_M)^2; \]  % Core loss conductance
\[ R_fe = 1./G_fe; \]  % Core loss resistance
\[ V_1 = V_s; \]  % Stator resistance
\[ I_1 = I_s; \]  % Stator current
\[ \text{theta}_1 = \text{acos}(0.6687); \]  % Power factor
\[ V_2 = \text{sqrt}((V_1-I_1.*(R_1.*\text{cos(theta}_1)-X_1.*\text{sin(theta}_1))^2+(I_1.*(R_1.*\text{sin(theta}_1)+X_1.*\text{cos(theta}_1)))^2); \]  % Reduced voltage from slip test
\[ \text{theta}_2 = \text{atan}((-I_1.*(R_1.*\text{sin(theta}_1)-X_1.*\text{cos(theta}_1))./(V_1-I_1.*(R_1.*\text{cos(theta}_1)-X_1.*\text{sin(theta}_1)))); \]  % Phase angle calculation
\[ I_e = V_2 / X_M; \]  % Core current
\[ I_fe = V_2 / R_fe; \]  % Core loss current
\[ I_2 = \text{sqrt}(((I_1.*\text{cos(theta}_1)-I_e.*\text{sin(theta}_2)-I_fe.*\text{cos(theta}_2))^2+(-I_1.*\text{sin(theta}_1)+I_e.*\text{cos(theta}_2)+I_fe.*\text{sin(theta}_2))^2); \]  % Rotor Current calculation
\[ Z_2 = I_2^2 / X_2; \]  % Rotor Impedance
\[ R_2 = Z_2 / 2; \]  % Rotor Resistance
\[ R_1 = R_1; \]  % Display Stator resistance
\[ X_1 = \text{abs}(X_1.*1i); \]  % Display Stator reactance
\[ X_M = \text{abs}(X_M.*1i); \]  % Display magnetizing reactance
\[ X_2 = \text{abs}(X_2.*1i); \]  % Display rotor reactance
\[ R_2 = R_2; \]  % Display Rotor resistance
\[ V_{ph} = 415 e3 / \sqrt(3); \]  % Per phase voltage
%-----------------------------rated values--------------------------------
75

\[
\begin{align*}
\text{s}_{\text{rated}} &= 0.06; \quad \text{% Rated slip} \\
Z_{\text{th\_rated}} &= \left((X_2+R_2./\text{s}_{\text{rated}})\right)\cdot(X_m)/(X_2+R_2./\text{s}_{\text{rated}}+X_m); \quad \text{% Rated Thevenin impedance} \\
Z_{\text{eq\_rated}} &= Z_{\text{th\_rated}}+R_1+X_1; \quad \text{% Rated Equivalent impedance} \\
V_{\text{th\_rated}} &= V_{\text{ph}}\cdot Z_{\text{th\_rated}}/(Z_{\text{th\_rated}}+R_1+X_1); \quad \text{% Rated Thevenin voltage} \\
I_2_{\text{rated}} &= V_{\text{th\_rated}}/(X_2+R_2./\text{s}_{\text{rated}}); \quad \text{% Rated rotor current} \\
S_{\text{rated}} &= 3\cdot(\text{abs}(I_2_{\text{rated}}))^2\cdot R_2./\text{s}_{\text{rated}}; \quad \text{% Rated output power} \\
\text{pf\_rated} &= \text{real}(S_{\text{rated}})/\text{abs}(S_{\text{rated}}); \quad \text{% Rated absolute apparent power} \\
\text{eff} &= \text{Pag\_rated}/\text{real}(S_{\text{rated}}); \quad \text{% Rated efficiency} \\
\end{align*}
\]

### 8.2.2.2 Per Unit Calculation of IEEE Standard 112 Parameters

```matlab
clear all
clc

R1=13.04; \quad \text{% Stator Resistance} \\
X1=17.21.*1i; \quad \text{% Stator Leakage Reactance} \\
Xm=327.72.*1i; \quad \text{% Magnetizing Reactance} \\
X2=25.75.*1i; \quad \text{% Rotor Leakage Reactance} \\
R2=20.81; \quad \text{% Rotor Resistance} \\
V_{\text{ph}}=.415e3./sqrt(3); \quad \text{% Per-Phase Voltage} \\

%-----------------------------
% basic Calculation
%-----------------------------
Motor_S=1410; \quad \text{% Motor Speed} \\
Frequency=50; \quad \text{% Rated Frequency} \\
Syn_S=2.*pi().*Frequency./2; \quad \text{% Synchronous speed in Rad/s} \\
Syn_{\text{speed}}=Syn_S.*60./(2.*pi()); \quad \text{% Synchronous speed in rpm} \\
Slip=(Syn_{\text{speed}}-Motor_S)./Syn_{\text{speed}}; \quad \text{% Slip of Motor} \\

%-----------------------------
% rated values
%-----------------------------

s_{\text{rated}}=Slip; \quad \text{% Rated Slip} \\
Z_{\text{th\_rated}}=((X_2+R_2./s_{\text{rated}}).\cdot(X_m))/(X_2+R_2./s_{\text{rated}}+X_m); \quad \text{% Rated Thevenin Impedance} \\
Z_{\text{eq\_rated}}=Z_{\text{th\_rated}}+R_1+X_1; \quad \text{% Rated Equivalent impedance} \\
V_{\text{th\_rated}}=V_{\text{ph}}\cdot Z_{\text{th\_rated}}/(Z_{\text{th\_rated}}+R_1+X_1); \quad \text{% Rated Thevenin voltage} \\
I_2_{\text{rated}}=V_{\text{th\_rated}}/(X_2+R_2./s_{\text{rated}}); \quad \text{% Rated Rotor Current} \\
S_{\text{rated}}=3\cdot(\text{abs}(I_2_{\text{rated}}))^2\cdot R_2./s_{\text{rated}}; \quad \text{% Rated Mechanical Power} \\
\text{tau\_rated}=\text{Pag\_rated}/\text{Syn}_S; \quad \text{% Rated Torque} \\
\text{pf\_rated}=\text{real}(S_{\text{rated}})/\text{abs}(S_{\text{rated}}); \quad \text{% Rated Power Factor} \\
\text{eff}=\text{Pag\_rated}/\text{real}(S_{\text{rated}}); \quad \text{% Absolute Current} \\

%-----------------------------
% Per Unit Value Calculation
%-----------------------------

V_{\text{base}}=240; \quad \text{% Base Voltage} \\
S_{\text{base}}=S_{\text{rated}}./3; \quad \text{% Base Apparent Power} \\
Z_{\text{base}}=V_{\text{base}}^2./S_{\text{base}}; \quad \text{% Base Impedance} \\
\omega_{\text{syn}}=\text{Syn}_S; \quad \text{% Synchronous Speed in Rad/s} \\
s=1; \quad \text{% Unity Slip} \\
R1pu=R1./Z_{\text{base}}; \quad \text{% Stator Resistance in Per Unit} \\
X1pu=X1./Z_{\text{base}}; \quad \text{% Stator Leakage Reactance in Per Unit} \\
Xmpu=Xm./Z_{\text{base}}; \quad \text{% Magnetizing Reactance in Per Unit} \\
X2pu=X2./Z_{\text{base}}; \quad \text{% Rotor Leakage Reactance in Per Unit} \\
R2pu=R2./Z_{\text{base}}; \quad \text{% Rotor Resistance in Per Unit} \\
V_{\text{pu}}=V_{\text{ph}}./Z_{\text{base}}; \quad \text{% Voltage in Per Unit} \\
\omega_{\text{pu}}=\omega_{\text{syn}}./\omega_{\text{syn}}; \quad \text{% Synchronous Speed in Per Unit} \\

\text{tau\_base}=\text{tau\_rated}/3; \quad \text{% Base Torque} \\
\text{tau\_max}=0; \quad \text{% Set Maximum Torque to zero for iteration} \\
\text{tau\_start}=0; \quad \text{% Set Starting Torque to zero for iteration} \\
for n=0:1000 \quad \text{% Number of iteration from 0 to 1000}
```
n=n+1; %
s;
n_ns=(1-s); % Speed
omega=omega_s.*(1-s);
Zth=((X2+R2./s).*Xm)./(X2+R2./s+Xm); % Thevinen Impedance in rotor side
Vth=V_ph.*Zth./(Zth+R1+X1); % Thevinen voltage
I2=Vth./(X2+R2./s); % Rotor current
abs(I2); % Absolute value of rotor current
Pag=(abs(I2))^2.*R2./s; % Air-gap Power
tau_ph=Pag./omega_s; % Mechanical torque
tau_pu=(tau_ph)./tau_base; % Torque in per unit

if n==1; % If condition when n is equal to 1
    tau_start=tau_pu; % If n is equal to 1 then display starting torque value
end % End of if condition

if tau_pu>tau_max; % If condition when torque is greater than other values
    tau_max=tau_pu; % If torque is maximum then display maximum torque
end % End of if condition
plot(n_ns,tau_pu); % Plot the graph of torque in per unit vs speed
s=s-.001;

end

hold off;

Zthlr=((X2pu+R2pu./1).*Xmpu)./(X2pu+R2pu./1+Xmpu); % Thevinen impedance in rotor side of circuit
Ilr=abs(1./Ilr); % Display the locked rotor current
P_mech=Pag_rated % Display mechanical power
pf_rated % Display power factor
eff % Display efficiency
tau_start % Display starting torque
tau_max % Display maximum torque
Rs=R1pu % Display stator resistance in per unit
Xs=imag(X1pu) % Display stator leakage reactance in per unit
Xr=imag(X2pu) % Display rotor leakage reactance in per unit
Rr=R2pu % Display rotor resistance in per unit
Xmpu=imag(Xmpu) % Display magnetizing reactance in per unit