EFFECTS OF VOLTAGE SAG DURING STARTING OF AN INDUCTION MOTOR

MALALA ABUBAKAR ABUBAKAR

A project report submitted in partial fulfilment of the requirement for the award of the Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JANUARY 2016
I dedicate this work to my late father Malam Abubakar Muhammad Malala and my mother Malama Hauwa Abubakar Malala.
“In the name Allah, the most Gracious and the most Merciful”

All praise and thanks be to Allah, the Lord of the World, who spear my life to this time and witness the accomplishment of this project. May the peace and blessings of Allah be upon our beloved Prophet Muhammad (SAW), his family and his companions.

I would like to express my deepest appreciation to my supervisor Assoc. Prof. Dr. Kok Boon Ching for given me the opportunity to be supervised under him; his patient, his enthusiasm, his inspiration and his great effort for his guidance make this work reality. This report would not be accomplished without his advice, thoughtfulness and constructive criticism.

I also would like to thank all my family for their support, especially my mother, my wife Malama Hauwa Ali Maremi, my senior brother Malam Mohd Bappah Malala, my sisters and my children’s for their prayers, understanding and encouragement.

I would like to take this opportunity to thank the entire academic and non-academic staffs of EEP (UTHM) for their contributions especially, Prof. Hussein Ahmad, Assoc. Prof. Dr. Jiwa Bin Abdullah, Dr. Dur Muhammad Soomro, Dr. Mohd Aifaa Bin Mohd Ariff, Dr. Mohd Noor Bin Abdullah, Dr. Siti Zarina Binti Mohd Muji and Assoc. Prof. Dr. Tay Kim Gaik, of Mathematics Programme just to mention few.

I am grateful to the provost of my college Dr. Adamu Gimba Abbas, the registrar of the college Alh. Ahmed Muhd Dukku, my distinguish Director Arch. Usman Mukhtar Wali, Qs. Hamisu Garba Muhammed and all my colleagues in the office/ college for their advice, prayers and contributions.

I am indebted to my senior brothers Engineer Bello Gwarzo Abdullahi of Ardugal Engineering Ltd, and Alh. Muhammad kabir Alkali of Yasab Nig. Limited,
my friends Saleh Bello, Musa Zakariya (kano), Abubakar Musa, Adamu lamido and all friends and relations whose space will not be enough to includes all their names for their understandings, prayers and contributions during the course of this study

This acknowledgement will not be completed without mentioning the names of my senior colleagues and friends for their contribution, during the course of this research, like Dr. Lilik Jamilatul Awalin (Uni. KL), Dr. Bala Ishiyaku, Dr. Adamu Isa Harir, Dr. Mohammed Maikudi Usman (Uni. Malaya), Norrolhuda Sanif (Noi), Mr. Azmi Sidek, and Mr. Garba Hamza.
ABSTRACT

Power quality (PQ) has become one of the important issues to be focused with the increasing number of sensitive equipment in industrial distribution system. Voltage sag during large motor starting has become the most common PQ problem as induction motor carries about 60 percent of the number of equipment used in the industries and is one of the prevalent source of voltage sag problem. This project aims to study the effect of voltage sag during starting of large induction motors by using three different starting methods i.e. direct online, star-delta and autotransformer. An 11kV induction motor of kiln main drive utilised in a cement factory has been modelled and tested using various motor ratings. The effect of voltage sag during the starting of the motor is observed using different starting methods and the findings are then been compared to ascertain the best starting method of the under test induction motor with least voltage sag problem. Based on the obtained simulation results run on Power System Computer-Aided Design (PSCAD) software, all starting methods shown the linear characteristic on different motor ratings with direct online method produced most significant voltage sag depth while star-delta method gave the least significant voltage sag depth. Thus, the later method is recommended as the best methods of starting based on the NEMA MG-1 standard for variations in voltage and frequency, along with the voltage unbalance by IEEE std. 1159-1995. However, system reliability can be maintained by compensating the reactive power to a certain level using static VAR compensation technique. This technique has been chosen as the mitigation method because it uses semiconductor devices such as thyristor for faster switching of connecting capacitor bank and reactors according to the system requirement with low harmonics interference.
ABSTRAK

Kualiti kuasa (PQ) telah menjadi salah satu isu penting yang perlu difokuskan dengan peningkatan bilangan peralatan sensitif dalam sistem pengagihan industri. Sag voltan semasa menghidupkan motor berkadaran tinggi telah menjadi masalah kualiti kuasa yang lumrah kerana motor aruhan menyumbang kira-kira 60 peratus daripada bilangan peralatan yang digunakan dalam industri dan ia merupakan sumber dominan kepada masalah sag voltan. Projek ini bertujuan untuk mengkaji kesan sag voltan semasa menghidupkan motor aruhan berkadaran tinggi dengan menggunakan tiga kaedah yang berbeza iaitu, pemasangan terus dalam talian, wye-delta dan alatubah auto. Motor aruhan berkadaran 11kV yang digunakan dalam kilang simen pada pemacu utama relau telah dimodelkan dan diuji pada motor yang berkadaran pelbagai. Kesan sag voltan semasa menghidupkan motor telah diperhati dengan menggunakan kaedah menghidupkan motor yang berbeza dan hasil kajian kemudiannya dibandingkan untuk menentukan cara terbaik bagi menghidupkan motor aruhan yang diuji dengan masalah sag voltan yang minimum. Berdasarkan keputusan simulasi yang diperolehi menggunakan perisian Reka bentuk Sistem Kuasa Berbantukan-Komputer (PSCAD), semua kaedah menghidupkan motor menunjukkan ciri-ciri linear pada kadar motor yang berbeza dengan pemasangan terus dalam talian menghasilkan kedalaman sag voltan yang paling ketara sementara wye-delta memberikan kedalaman sag voltan yang paling minimum. Oleh itu, kaedah wye-delta telah disarankan sebagai kaedah terbaik berlandaskan piawaian NEMA MG-1 untuk variasi dalam voltan dan frekuensi dan piawaian IEEE std. 1159-1995 bagi ketidakseimbangan voltan. Walau bagaimanapun, kebolehpencayaan sistem dapat dikekalkan dengan mengimbangi kuasa reaktif kepada suatu tahap tertentu menggunakan kaedah pengimbangan VAR statik. Kaedah pengurangan ini telah dipilih kerana ia menggunakan peranti semikonduktor seperti “thyristor” yang
membolehkan pensuisan pantas dilakukan pada bank pemuat dan reactor sebagaimana yang diperlukan oleh sistem dengan gangguan harmonik yang rendah.
CONTENTS

TITLE i
DECLARATION ii
DEDICATION iii
ACKNOWLEDGEMENT iv
ABSTRACT vi
ABSTRAK vii
TABLE OF CONTENTS ix
LIST OF TABLES xii
LIST OF FIGURES xiii
LIST OF SYMBOLS AND ABBREVIATIONS xv
LIST OF APPENDICES xvii

CHAPTER 1 INTRODUCTION 1

1.1 Project Background 1
1.2 Problem Statements 2
1.3 Project Aim and Objectives 3
1.4 Project Scopes 3

CHAPTER 2 LITERATURE REVIEW 4

2.1 Introduction 4
2.2 Induction Motor 4
   2.2.1 Motor Power 6
   2.2.2 Motor Torque 7
2.2.3 Starting Characteristic of Induction Motor 9
2.2.4 Running Characteristic of Induction Motor 10
2.2.5 Efficiency of Induction Motor 11
2.2.6 Power factor of Induction Motor 11
2.2.7 Starting Methods of Induction Motor 12
  2.2.7.1 Direct On-line Starter 12
  2.2.7.2 Star-Delta Starter 14
  2.2.7.3 Autotransformer Starter 15
2.3 Voltage Sag 15
  2.3.1 Causes of Voltage sag 17
  2.3.2 Factors Affecting Voltage Sag 17
  2.3.3 Characteristics of Voltage Sag 18
    2.3.3.1 Voltage Sag Magnitude 18
    2.3.3.2 Voltage Sag Duration 19
    2.3.3.3 Phase Angle 19
2.4 Previous Work Study 19
  2.4.1 Impacts of Voltage Sags on IMs 19
    2.4.1.1 Negative Torque Spike 20
    2.4.1.2 Low Voltage Condition 20
    2.4.1.3 High Voltage Condition 21
    2.4.1.4 Effects of Voltage Imbalance 22
  2.4.2 Effects of Voltage Recovery on IMs 22
  2.4.3 Effects of Protection Setting on Motor Performance 23
  2.4.4 Review of some Mitigation Techniques and Proposed Method to be adopted 23
2.5 Summary 30

CHAPTER 3 METHODOLOGY 31
3.1 Introduction 31
3.2 Project Procedure

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction 35
4.2 Direct On-line Starting 35
4.3 Star-Delta Starting 41
4.4 Autotransformer Starting 45
4.5 Comparison between the three Methods of Starting 50
4.6 Mitigation Techniques 52

CHAPTER 5 CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions 55
5.2 Recommendations 56

REFERENCES 58

APPENDICES A – B 63 – 69
LIST OF TABLES

2.1 Voltage versus Current Imbalance on a 100 HP Induction Motor 22
3.1 Transformer Specification 33
3.2 Motor Parameters 34
4.1 Magnitude and duration of voltage sag for DOL using different rating of IM 36
4.2 Speed/Torque and Power readings for direct on-line starting 40
4.3 Magnitude and duration of voltage sag for star-delta starting using different rating of IM 42
4.4 Speed/Torque and Power readings (values) for star-delta starting 44
4.5 Magnitude and duration of voltage sag for auto transformer using different rating of IM 46
4.6 Speed/Torque and Power readings (values) for auto transformer different rating of IM 49
4.7 Percentage Comparison of Voltage sag depth for the three method of starting against Motor rating 51
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Equivalent circuit of an induction motor showing the referred values of rotor parameters</td>
<td>5</td>
</tr>
<tr>
<td>2.2</td>
<td>Slip Torque characteristics</td>
<td>8</td>
</tr>
<tr>
<td>2.3</td>
<td>Induction motor starting curve</td>
<td>9</td>
</tr>
<tr>
<td>2.4</td>
<td>Induction motor power factor and efficiency</td>
<td>12</td>
</tr>
<tr>
<td>2.5</td>
<td>Inrush current in direct on-line starting</td>
<td>13</td>
</tr>
<tr>
<td>2.6</td>
<td>Voltage sag in star-delta starting</td>
<td>14</td>
</tr>
<tr>
<td>2.7</td>
<td>Inrush current in auto transformer starting</td>
<td>15</td>
</tr>
<tr>
<td>2.8</td>
<td>Voltage Sag expressed as % of nominal voltage</td>
<td>16</td>
</tr>
<tr>
<td>2.9</td>
<td>Equivalent circuits for induction motor starting</td>
<td>16</td>
</tr>
<tr>
<td>2.10</td>
<td>Voltage sag duration and depth</td>
<td>17</td>
</tr>
<tr>
<td>2.11</td>
<td>Impact of voltage sags on an induction motor</td>
<td>20</td>
</tr>
<tr>
<td>2.12</td>
<td>Combine TSC and TCR configuration</td>
<td>25</td>
</tr>
<tr>
<td>2.13</td>
<td>Simplified block representation of the SVC and power system</td>
<td>26</td>
</tr>
<tr>
<td>2.14</td>
<td>Equivalent circuit of SVC</td>
<td>26</td>
</tr>
<tr>
<td>2.16</td>
<td>Model of SVC</td>
<td>28</td>
</tr>
<tr>
<td>2.17</td>
<td>Connection of VSC to the terminal of the motor</td>
<td>30</td>
</tr>
<tr>
<td>3.1</td>
<td>Project flow chart</td>
<td>32</td>
</tr>
<tr>
<td>4.1</td>
<td>Voltage sag during direct on-line starting</td>
<td>36</td>
</tr>
<tr>
<td>4.2</td>
<td>Variation of voltage sag and transient current during direct on-line starting for different motor rating</td>
<td>37</td>
</tr>
<tr>
<td>4.3</td>
<td>Variation of voltage sag and duration during direct on-line starting</td>
<td>38</td>
</tr>
<tr>
<td>4.4</td>
<td>Waveforms of speed, torque during direct on-line starting</td>
<td>39</td>
</tr>
<tr>
<td>4.5</td>
<td>Real and Reactive power during direct on-line starting</td>
<td>39</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.6</td>
<td>Variation of speed/ Torque during direct on-line starting for different motor rating</td>
<td>40</td>
</tr>
<tr>
<td>4.7</td>
<td>Voltage sag during star-delta methods of starting</td>
<td>41</td>
</tr>
<tr>
<td>4.8</td>
<td>Variation of voltage sag and transient current during star-delta starting for different motor rating</td>
<td>42</td>
</tr>
<tr>
<td>4.9</td>
<td>Variation of voltage sag and duration during star-delta starting for different motor rating</td>
<td>43</td>
</tr>
<tr>
<td>4.10</td>
<td>Variation of speed, torque during star-delta starting</td>
<td>43</td>
</tr>
<tr>
<td>4.11</td>
<td>Real and Reactive power during star-delta starting</td>
<td>44</td>
</tr>
<tr>
<td>4.12</td>
<td>Waveforms of speed/ Torque during star-delta starting for different motor rating</td>
<td>45</td>
</tr>
<tr>
<td>4.13</td>
<td>Voltage sag during auto transformer starting</td>
<td>46</td>
</tr>
<tr>
<td>4.14</td>
<td>Variation of voltage sag and transient current during auto transformer starting for different motor rating</td>
<td>47</td>
</tr>
<tr>
<td>4.15</td>
<td>Variation of voltage sag and duration during auto transformer starting for different motor rating</td>
<td>47</td>
</tr>
<tr>
<td>4.16</td>
<td>Voltage sag in three phase and rms view for auto transformer</td>
<td>48</td>
</tr>
<tr>
<td>4.17</td>
<td>Transient rise of electrical and mechanical torque at the point of switching for auto transformer starting</td>
<td>48</td>
</tr>
<tr>
<td>4.18</td>
<td>Transient rise of real and reactive Power at the point of switching for auto transformer starting</td>
<td>49</td>
</tr>
<tr>
<td>4.19</td>
<td>Speed, electrical and mechanical torque for auto transformer starting</td>
<td>50</td>
</tr>
<tr>
<td>4.20</td>
<td>Percentage Comparison of different methods of three methods of starting</td>
<td>52</td>
</tr>
<tr>
<td>4.21</td>
<td>Voltage sag effect without SVC connected to the system</td>
<td>53</td>
</tr>
<tr>
<td>4.22</td>
<td>Voltage sag effect SVC connected to the system</td>
<td>53</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS AND ABBREVIATIONS

E<sub>2</sub> - Induce Electromotive force
F - Frequency
I<sub>r</sub> - Rotor Current
I<sub>s</sub> - Stator Current
P<sub>in</sub> - Power delivered
P<sub>m</sub> - Mechanical Power
P<sub>c</sub> - Copper losses
P<sub>w</sub> - Power losses (windage)
Q - Reactive Power
R<sub>1</sub> - Stator Resistance
R<sub>2</sub> - Rotor Resistance
R<sup>′</sup>2 - Rotor Resistance referred to primary
S - Slip
T - Torque
Φ - Angle
T<sub>e</sub> - Electrical Torque
T<sub>m</sub> - Mechanical Torque
V<sub>1</sub> - Stator voltage
V<sub>b</sub> - Base line to line voltage
V<sub>s</sub> - Voltage source
V<sub>ref</sub> - Reference voltage
W - Angular velocity
X<sub>1</sub> - Stator reactance
X<sub>2</sub> - Rotor reactance
X<sub>2</sub> - Rotor reactance referred to primary
Z<sub>eq</sub> - Equivalent Impedance
$Z_m$ - Motor Impedance
$Z_s$ - Source Impedance
AC - Alternating Current
DC - Direct Current
DOL - Direct On-Line
DVR - Dynamic Voltage Restorer
FLC - Full Load Current
FLT - Full Load Torque
LRC - Locked Rotor Current
LRT - Locked Rotor Torque
PSCAD - Power System Computer Aided Design
RMS - Root Mean Square
TCR - Thyristor Controlled Reactor
TSC - Thyristor Switched Capacitor
SVC - Static VAR Compensator
<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Project Planning for Master Project 1 and 2</td>
<td>63</td>
</tr>
<tr>
<td>B</td>
<td>Schematic Diagram of Simulation Models</td>
<td>65</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Project Background

Induction motors (IM) as the heart of modern industries, is the most common electrical equipment used in every industry, it is considered as an industrial workhorse for electromechanical conversion for over decades. Although the machines are considered relatively reliable and robust due to their simple design and well-developed manufacturing technologies, failures do occur and may severely disrupt industrial processes and even lead to disastrous accidents. Therefore, protections, safety, efficiency, and performance improvements in these systems have been of paramount importance for economic reasons [1].

Electric power systems have today become polluted in industrialised world with unwanted variations in voltage and current. Power quality are primarily issues due to continually increasing sources of disturbances that occur in interconnected power grids, which contain large numbers of power sources, transmission lines, transformers and loads, such systems are exposed to environmental disturbances like lightning strikes [2]. As the numbers of sensitive equipment are increasing in the distribution systems, the voltage quality will becomes more and more important.

The most common power quality (PQ) problem in industrial distribution systems are the voltage disturbances, which mainly encompasses the voltage sags, swells, harmonics, transients, unbalances, and flickers, [3]. These disturbances can cause the malfunction of voltage-sensitive loads in factories and buildings [4]-[5].
However, the outcome of many power quality surveys were concluded that more than 90% of voltage related events are the voltage sags, [6]-[7].

Based on the above power quality issues, this research will focus on the effects of voltage sag during starting of an induction motor. According to IEEE regulation [8], voltage sag is a momentary decrease in the rms ac voltage (10%–90% of the nominal voltage) at the power frequency of duration from 0.5 cycles to a few seconds. Voltage sag is normally caused by short-circuit faults, such as a single-line-to-ground fault in a power system and by the start-up of motors of large ratings, causing enormous financial production losses.

The effect produced by this disturbance over industrial customers is variable depending on the magnitude and duration of the sag. Therefore, preventing of the sensitive loads from the voltage sags is a very important issue [9].

1.2 Problem Statements

Power Quality (PQ) has recently become an important concern to consumers, especially those dealing with electric drives, electronics and microprocessor-based industrial equipment as they require high-quality of electric power supply. Among the PQ problems, voltage sags constitutes most frequent and major prime factor that affect the performances of an induction motors [9]. Many researches [10-11] have shown that voltage sags due to switching ‘‘ON’’ or ‘‘OFF’’ of large induction motors will affect plant operations causing adjacent large induction motors to trip, either by under voltage or over current relays. When voltage drops as a result of switching of large motors, high current is drawn by the IM in order to maintain the power output which result in temperature rise and this put mechanical stress on the stator winding, that will result in winding fatigue which lead to stator insulation failure, as these prolong the relays will see this as a fault and automatically continue tripping the motor.

Voltages sags cause by switching of large motors affects the normal plant’s operation, at the instant supply voltage is restored, the motor's back-EMF is out of phase with the normal supply voltage. In order to align rotor currents, the motor has to decelerate, which results in negative torque transients that can reach up to 20 times the rated torque of the motor [12]. This amount of negative torque will eventually result in mechanical (rotor shaft) and electrical damage (motor windings).
The torque magnitude is directly proportional to speed and square of the applied voltage to the motor. The normal supply produced positive sequence torque while the backward rotating field (negative sequence currents) produced a negative torque. In view of the above, the resultant torque produced by the machine will be decreased hence the speed of the motor reduces as such, as the problem persist, the motor will stall.

1.3 Project Aim and Objectives

The aim of this study is to find out the magnitude and the duration of voltage sags during starting of an induction motor using different starting methods, and compare the outcomes to suggest the best method of starting the motor under review (11KV IM) with less voltage sag problem and propose a simple and sustainable method of mitigation. To achieve the above aim, the following objectives have been formulated:

(i) To measure the magnitude and duration of voltage sag during starting of induction motor of different ratings and proposed the best starting methods.
(ii) To use static VAR compensation mitigation techniques to minimise the effect of voltage sags during starting of an induction motor.

1.4 Project Scopes

(i) The study of this project will be on voltage sags cause by the induction motor during starting which result in tripping of the adjacent motors (a case study of three phase 11 KV, kiln main drive of a Cement Factory), using PSCAD modelling and simulation software.
(ii) The study will dwell on 11KV IM of different rating as compare with the rating of the voltage source (Transformer) using three methods of starting (i.e. Direct On line, Star-Delta and Auto-transformer methods of starting).
(iii) The simulation is intended for induction motor stand-alone test.
(iv) The static VAR compensation technique is chosen to be mitigation method.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The review of the literature is considered as a systematic and critical review of most important published scholarly literature on a particular topic.

This chapter is divided into five sub-chapters. Sub-section 2.2 gives brief introduction of induction motor as it is the most common electrical drives used in industries because of its ruggedness, simplicity and ease of maintenance. This sub-section is emphasised on squirrel cage type induction motor that covers the common starting methods with its related characteristic curves. Sub-section 2.3 reviews on voltage sag which is defined as a reduction of voltage for short duration of half cycles to one minute. The review will include the causes of voltage sag and its technical characteristics. Sub-section 2.4 discusses the effects of voltage sag on induction motor while sub-section 2.5 highlights the consequence of voltage recovery on induction motor. Sub-section 2.6 deliberates some reviews of mitigation techniques and proposed method to be adopted in this project.

2.2 Induction Motor

Induction motors are generally used in both industrial and domestic applications. The principle operation of an induction motor is due to the induced electric current in the rotor circuit by a varying magnetic field in the stator windings. The rotor current produces its own magnetic field, which then interacts with the stator field to
produce particular torque and rotation. Two common types of induction motor are squirrel cage and wound rotor (slip ring). The former type is the simplest, efficient and reliable to be operated in constant speed application with least maintenance as there is no commutator or slip-rings. Its rotor consists of permeable metal containing embedded strips of magnetic material. The latter type is used for a constant speed service that requiring higher starting torque than is obtainable with a squirrel cage type [13]. Wound rotor motors are generally started with secondary resistance in the rotor circuit. The external resistance gives the motor a characteristic that results in a large drop in rpm for a fairly small change in load and thus, the overall efficiency at this speed is low. Figure 2.1 shows the equivalent circuit of an induction motor.

Figure 2.1: Equivalent circuit of an induction motor showing the referred values of rotor parameters

The referred values are calculated by multiplying the value of $K^2$, where $K$ is the effective stator and rotor turns ratio. The equivalent circuit shown in Figure 2.1 has removed the dependence on slip for determining the secondary voltage and frequency. The circuit is simplified by eliminating the ideal transformer and referring the rotor's resistance and reactance to the primary (denoted by ′). From the equivalent circuit, the motor current can be calculated as [14]:

$$I_s = \frac{V_1}{Z_{eq}}$$ (2.1)
where, $I_s$ is stator current, $V_1$ is the input voltage and $Z_{eq}$ is the equivalent stator impedance, $R_2'$ is the rotor reactance referred to primary and $s$ is the slip value. The value of $Z_{eq}$ is as shown in Equation (2.2).

$$Z_{eq} = R_{eq} + \frac{R_2'}{s} + jX_{eq}$$  \hspace{1cm} (2.2)

From this equation, it can be seen that as the rotor speeds up (slip reduces), the circuit impedance will be increases and the stator current will be decreased.

### 2.2.1 Motor Power

As a simplification, if the core losses $R_c$ is neglected and giving ($I_s = I_2'$), the power ($P_{in}$) delivered to the motor per phase is given by:

$$P_{in} = I_s^2 (R_1 + \frac{R_2'}{s})$$  \hspace{1cm} (2.3)

The power loss dissipated by the windings is given as:

$$P_w = I_s^2 (R_1 + R_2)$$  \hspace{1cm} (2.4)

The difference between the power supplied to the motor and losses in the windings is the power ($P_m$) delivered to the connected load.

$$P_m = P_{in} - P_w = I_s^2 \left( \frac{1-s}{s} \right) R_2'$$  \hspace{1cm} (2.5)

For three-phase application, the delivered power is defined as:

$$P_{m3p} = 3 I_s^2 \left( \frac{1-s}{s} \right) R_2'$$  \hspace{1cm} (2.6)
where $P_m$ is the mechanical power develops, $P_{in}$ is the input power and $P_w$ is the power losses.

### 2.2.2 Motor Torque

The mechanical power of an induction motor is expressed as the motor torque ($T$) multiply with the angular velocity ($\omega$). Thus, the simple equation for torque ($T$) can be derived as:

\[
T = \frac{P_{m3\phi}}{w}
\]  

\[
w = \frac{2\pi n_r}{60} = \frac{2\pi}{60} (1-n)n_s
\]  

where $T$ is the torque in Nm and $w$ is the angular velocity in rad/s. In three-phase, the torque is represented as follows:

\[
T = 3I_s^2 \left(\frac{1-s}{s}\right)R_s^2 = Is^2 \frac{90}{\pi n_s} \frac{R_s^2}{(1-n)n_s}
\]  

To simplify the analysis, the magnetising current and iron losses are ignored (i.e. $R_e = jX_m = 0$). From the simplified equivalent circuit, the magnitude of the stator current $I_s$ is given as:

\[
|I_s| = \frac{|V_s|}{\sqrt{\left(R_1 + \frac{R_s^2}{s}\right)^2 + (X_1 + X_2)^2}}
\]  

and substituting into the torque equation gives:
\[ T = \frac{90}{\pi t_s} \frac{|V_i|^2}{R_i + \frac{R_2}{s} + (X_1 + X_2')^2} \]  

(2.11)

where, \( R_1 \), \( X_1 \) and \( X_2' \) are the stator resistance, stator reactance and rotor reactance referred to primary, respectively.

Therefore, from Equation (2.11), it can be seen that the torque is directly proportional to the square of the terminal voltage and inversely proportional to the slip. Figure 2.2 shows the variation of slip with torque and the rotor resistance. The increase of slip will decrease the torque, and vice versa [14].

![Slip against Torque](image)

Figure 2.2: Slip Torque characteristics

At full voltage, the starting current of an induction motor is depends on voltage and speed [15].
2.2.3 Starting Characteristics of Induction Motor

Induction motor is normally started from locked rotor condition and gradually accelerated to full speed. When connected to full load voltage, the induction motor will draw certain amount of inrush current known as the Locked Rotor Current (LRC) and produces torque, known as the Locked Rotor Torque (LRT) which is a function of motor terminal voltage and motor design. Both of the parameters are vary with rotor speed if the supply is constant.

The starting torque of an induction motor with fixed voltage will drop very slow known as Pull Up Torque as the motor accelerates and it will only begin to fall significantly once the motor has reached its maximum torque (Breakdown or Pull Out Torque) at around 80% of full speed and dramatically drop to zero at synchronous speed. The actual curves for induction motors will vary according to the rotor design [14]. A motor with a high starting current (i.e., 85% FLC) will generally produce a low starting torque, while a motor with a low starting current will generally produce a high starting torque [13] as shown in Figure 2.3.

Figure 2.3: Starting curve of induction motor
### 2.2.4 Running Characteristics of Induction Motor

When the motor is running, it operates at low slip, at a speed determined by the number of stator poles. The frequency of the current flowing in the rotor is low. Typically, the value of slip at the full load condition for a standard cage induction motor is less than 5% [14]. The losses of an induction motor comprise of copper loss, iron loss, windage loss and frictional loss. The iron, windage, and frictional losses are all load independent, while the copper loss is proportional to the square of the stator current which is expressed as:

\[ P_c = 3I_s^2R^2 \]  \hspace{1cm} (2.12)

and the rotor current is,

\[ I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \]  \hspace{1cm} (2.13)

Substitute the value of \( I_2 \) into Equation (2.13), the rotor copper losses \( P_c \) becomes,

\[ P_c = 3R_2\left(\frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}\right)^2 \]  \hspace{1cm} (2.14)

or

\[ P_c = \frac{3R_2s^2E_2^2}{R_2^2 + (sX_2)^2} \]  \hspace{1cm} (2.15)

The ratio of \( P_2 : P_c : P_m = 1 : s : (1 - s) \)

where \( P_2 \) is the rotor input, \( P_c \) is the rotor copper loss, and \( P_m \) is the developed mechanical power.

\[ \frac{P_c}{P_m} = \frac{s}{1 - s} \]  \hspace{1cm} (2.16)
Substitute the value of $P_c$ into Equation (2.16) yields,

$$ P_m = \frac{1}{s} \times \frac{(1-s)3R_s s^2 E_2^2}{R_s^2 + (sX_s)^2} $$

(2.17)

or,

$$ P_m = \frac{(1-s)3R_s sE_2^2}{R_s^2 + (sX_s)^2} $$

(2.18)

The developed mechanical power $P_m = T\omega$. Therefore, the mechanical power is direct proportional to the torque produced at the load.

### 2.2.5 Efficiency of Induction Motor

The efficiency of a typical induction motor is in the average of around 75% at 100% FLT. Efficiency is decreased a few percent at 50% FLT, and decreased a few more percent at 25% FLT. Efficiency can varies from less than 60% for small low speed motors to greater than 92% for large high speed motors [13].

Efficiency is defined as the ratio of the output power to the input power,

$$ Efficiency(\eta) = \frac{output}{input} = \frac{P_m}{P_2} = \frac{P_{out}}{P_m} $$

(2.19)

### 2.2.6 Power factor of Induction Motor

Induction motors present a lagging (inductive) power factor to the power line. The power factor in large fully loaded high speed motors can be as favourable as 90%. At 3/4 full load, the largest high speed motor power factor can be 92%. The power factor for small low speed motors can be as low as 50%. During starting, the power factor can be in the range of 10% to 25%, rising as the rotor achieves speed [14].

Figure 2.4 shows the variation of efficiency and power factor of an induction motor with loading. Induction motors are typically oversized to guarantee that their mechanical load can be started and driven under all operating conditions. An
unloaded motor is analogous to a transformer with no resistive load on the secondary. Little resistance is reflected from the secondary (rotor) to the primary (stator). Thus, the power line experiences a reactive load, as low as 10% PF. As the rotor is loaded, an increasing resistive component is reflected from rotor to stator, increasing the power factor.

![Figure 2.4: Induction motor power factor and efficiency](image)

### 2.2.7 Starting Methods of Induction Motor

There are many starting methods of three-phase induction motors, some of the common methods are as follows:

(i) Direct On-line Starter
(ii) Star-Delta Starter
(iii) Autotransformer Starter

#### 2.2.7.1 Direct On-line Starter

Induction motors can be started using Direct On-line (DOL), which means that the rated voltage is supplied to the stator. In squirrel cage, the rotor bars are short circuited via two end rings. Neglecting the stator impedance, the starting current in the stator windings is [16]:

![Figure 2.4: Induction motor power factor and efficiency](image)
\[(I_s)_{st} = \frac{E_r}{\sqrt{(R_2)^2 + (X_2)^2}}\]  

(2.20)

where,

\[(I_s)_{st} = (I_2)_{st} = (I_2)_{st} / a = \text{Starting current in the motor (stator)}\]
\[a = T_s / T_r = \text{Effective turns ratio between stator and rotor windings}\]
\[E_s = E_r = aE_r = \text{Input voltage per phase to the motor (stator)}\]
\[E_r = \text{Induced emf per phase in the rotor winding}\]
\[R_s = a^2R_s = \text{Rotor resistance in terms of stator winding}\]
\[X_2 = a^2X_2 = \text{Rotor reactance at standstill in terms of stator winding}\]

It can be noted that the starting current is relatively high, about 4-8 times the current at full load, depending on the rating of IM used. The starting torque is \((T_s)_{st} \propto [(I_s)_{st}]^2\) indicating that as the starting current increases, the starting torque also increases. The starting torque is likely to be 0.75 to 2 times the full load torque. In order to avoid excessive voltage drops in the supply line due to high starting currents, the DOL starter is used only for motors with a rating of less than 5KW[17].

Figure 2.5: Inrush current in Direct On-line starting method [18]
By applying Ohm's Law,

$$ V = I \times Z $$

(2.21)

where $V$ is the Voltage, $I$ is the Current, and $Z$ is the Impedance. The Kirchoff's Voltage Law stated that the sum of voltages around a closed loop must equal to zero, which gives the result of consequence of high current in motor starting, resulting in the voltage drop (i.e. voltage sags). The voltage sag occurs because the impedance of the motor initially (when the rotor is stationary) acts as a short circuit [18].

### 2.2.7.2 Star-Delta Starter

The star delta starting is a very common type of starter and extensively used as compared to the other types of the starters. In this type of starting method, the motor is started as a star connection and changed to delta connection when the motor start running. So, the starting current using star-delta starter is reduced by 33.3%. As for starting torque being proportional to the square of the current in each of the stator windings, thus, it is also reduced by $(1/\sqrt{3})^2$. As the ratio of the two currents is $(1/\sqrt{3})$, same as that (ratio) of the voltages applied to each winding. So, the starting torque is reduced by 33.3%, which is a disadvantage of the use of this starter [17]. Figure: 2.6 shows the voltage sag in Star-Delta starting which occurs as the result of transition from Star connection to Delta connection [18].

![Figure 2.6: Voltage sag in Star-Delta starting method](image-url)
2.2.7.3 Autotransformer Starter

The auto transformer starter is more expensive and more complicated in operation. Similar to Star-Delta starter, the starting current is limited by using a three-phase autotransformer. The autotransformer starter is suitable for both star and delta connected motors, and the starting current and torque can be adjusted to a desired value by taking the correct tapping from the auto transformer. Figure 2.7 depicted the occurrence of inrush current in autotransformer starting method.

![Inrush current in auto transformer starting method](image)

Figure 2.7: Inrush current in auto transformer starting method [18]

2.3 Voltage Sag

According to reference [8], voltage sag is defined as a decrement between 0.1 and 0.9 pu in rms voltage at the power frequency for durations of 0.5 cycle to 1 min. The amplitude of voltage sag is the value of the remaining voltage during the sag. The IEC terminology for voltage sag is dip. The IEC defines voltage dip as a sudden reduction of the voltage at a point in the electrical system, followed by voltage recovery after a short period of time, from half a cycle to a few seconds. The amplitude of voltage sag is defined as the difference between the voltage during the voltage sag and the nominal voltage of the system expressed as a percentage of the nominal voltage ($V_n$) [19]. Figure 2.8 shows the common voltage waveform with voltage sag influence.
Voltage sag is the most common disturbance and is one of the most significant aspect of power quality [19]. Figure 2.9 illustrates the equivalent circuit for an induction motor in a typical industrial power system.

The voltage at the point of common coupling (PCC) is given by the equation:

$$V_{sag} = \frac{Z_M}{Z_s + Z_M}E$$  \hspace{1cm} (2.22)

where $Z_M$ is the impedance of the motor under study and $Z_s$ is the source impedance. This calculation provides approximation result of voltage sag [18].
Figure 2.10 shows that the sag starts when the voltage decreases to less than the threshold voltage $V_{th}$ (0.9 pu) at time $T_1$ and it lasts at $T_2$ at which the voltage recovers to a value over the threshold value. Hence, the duration of the voltage sag is $(T_2 - T_1)$ and the magnitude of the voltage sag is $V_{sag}$ [10].

![Figure 2.10: Voltage sag duration and depth](image)

2.3.1 Causes Voltage Sag

Voltage sag can be classified into man-made and natural causes. The man-made causes (i.e. as a result of human activities on the power network) includes switching operations or starting of large motors, power system faults (short circuit), sudden load changes, etc. The natural causes include bad weather, pollution, animals and birds, etc. [20]. Therefore, two main causes of voltage sags are the short circuit faults in the internal supply scheme of the customer's installation, or faults on other branches of the supply network (in the utility equipment) and the sudden increase of the load such as starting of large motor loads or switching operations.

2.3.2 Factors Affecting Voltage Sag

(i) Type of fault: Type of fault in the power system is the first factor which affects sag characteristic. Voltage sags can be either balanced or unbalanced,
depending on the causes or type of fault. If the individual phase voltages are equal, the sag is balanced, whereas if the phase voltage is different, unbalanced voltage sag will be happened [21]-[22].

(ii) Location of fault: Along with the type, the locations of faults in the system have a great impact on the magnitude as well as the phase-angle jump of the sag, [21]-[22].

(iii) X/R ratio of the lines: With change in the X/R ratio of the line there is change in the X/R ratio of fault to source impedance which will affect the magnitude as well as phase-angle jump, [21]-[22].

(iv) Point on wave of sag initiation: The point on wave of sag initiation is the phase angle of the fundamental voltage wave at which the voltage sag starts. This angle corresponds to the angle at which the short circuit fault occurs, [21]-[22].

2.3.3 Characteristics of Voltage Sag

Voltage sag is defined as a decrease in rms voltage at the power frequency for durations of 0.5 cycles to 1 minute. This definition specifies two important parameters for voltage sag, the rms voltage magnitude and duration. The parameters used to characterise voltage sag are magnitude, duration and phase angle, [21] and [23].

2.3.3.1 Voltage Sag Magnitude

The magnitude of voltage sag can be determined in a number of ways. The most common approach to obtain the sag magnitude is to use rms voltage. Hence the magnitude of the sag is considered as the residual voltage or remaining voltage during the event. In the case of a three-phase system, voltage sag can also be characterised by the minimum rms voltage during the sag. The sag could be symmetrical or unsymmetrical depending on the affect the phases of the system, [24].
2.3.3.2 Voltage Sag Duration

The duration of voltage sag is mainly determined by the fault–clearing time. The duration of voltage sag is the amount of time during which the voltage magnitude is below threshold is typically chosen as 90% of the nominal voltage magnitude. For measurements in the three-phases systems the three phase rms voltages have to be considered to determine duration of the sag. The voltage sag starts when at least one of the rms voltages drops below the sag-starting threshold. The sag ends when all three voltages have recovered above the sag-ending threshold [24] and [25].

2.3.3.3 Phase Angle

The phase angle of measured sag is obtained as the phase-angle of the voltage during the sag which must be compared with the phase angle of the voltage before the sag. The phase angle is only concern in power electronics converters in which using phase angle information for their firing instants may be affected. Thus, this is not considered in this project [26] and [27].

2.4 Previous Work Study

2.4.1 Impacts of Voltage Sags on Induction Motors

Induction motors represent the most typical loads in power system applications. They consume about 60% of the electrical energy generated in industrialised countries. Figure 2.11 shows the impact of voltage sag on induction motor.
2.4.1.1 Negative Torque Spike

Consider an induction motor operating under steady state conditions and supply voltage is removed and reapplied several cycles’ later (short interruption). At the instant supply voltage is restored, the motor's back-EMF is out of phase with the supply voltage. In order to align rotor currents, the motor has to decelerate, which results in negative torque transients that can reach up to 20 times the rated torque of the motor [28]. This amount of negative torque will eventually result in mechanical (rotor shaft) and electrical damage if allowed to continue (motor windings).

2.4.1.2 Low Voltage Condition

Motor operation below the stamped nameplate voltage rating reduces its efficiency, shortens life expectancy, or worse, and causes premature failure. To drive a fixed mechanical load, a motor will draw a specific amount of power from the source. This amount of power has a direct correlation to the voltage and current drawn. Thus, when supply voltage gets low, the current must increase to maintain the level of power required to drive the load. An increase in current is a danger to the motor only if that current exceeds the nameplate current rating of the motor. When the
current exceeds the nameplate rating, heat begins to build up in the motor. Without timely correction, excessive heat will eventually damage the motor.

\[
I_1^2 t + \frac{R_{r2}}{R_{r1}} I_2^2 t \propto \text{Temp} \tag{2.23}
\]

\[R_{r2} = \text{negativesequence}\]
\[R_{r1} = \text{positivesequence}\]

The connected load is a major factor in determining how much of a decrease in supply voltage a motor can handle. For a motor that carries a light load, if the voltage decreases, the current will increase in roughly the same proportion that the voltage decreases. As an example, a 10% voltage decrease would cause a 10% load current increase. This would not damage the motor, if the current stays below the nameplate value. If the same motor was driving a heavy load, there is already a high current draw. When there is a reduction in voltage, the load current will rise to a new value, which may exceed the full-load rated current. Low voltage applied at the motor terminal can lead to overheating, shortened life, reduced starting ability, and reduced pull-up and pull-out torque [29].

### 2.4.1.3 High Voltage Condition

High voltage on a motor tends to push the magnetic portion of the motor into saturation. The concept of saturation is similar to the operation of a 60-hertz transformer operated on a 50-hertz system. The transformer must be derated by 1/6 or else the peak flux in the core will be too high. Saturation will cause the motor to draw excessive current in an effort to magnetise the iron beyond the point where magnetising is practical. Motors can tolerate a certain increase in voltage above the nameplate rating [30].

However, extremes above the design voltage will cause the current to go up with a corresponding increase in heating and a shortening of motor life. It is very important to stay as close as possible to the nameplate voltage rating of motors. Although motor manufacturers provide a tolerance curve for the motor supply
voltage, the best performance will be achieved when nameplate rated voltage is applied to the motor [28].

2.4.1.4 Effects of Voltage Imbalance

When line voltages applied to an induction motor are not equal, as in the case of Unsymmetrical voltage sags, unbalance currents in the stator windings will result. A small percentage voltage unbalance will result in a much larger percentage current unbalance. Three-phase motors supplied with unbalanced voltage will draw an unbalanced current approximately 6-10 times as unbalanced as the voltage. This current unbalance in 3-phase motors can cause overheating and premature damage to motors.

Although short duration sags will have little heating effect, continuous exposure to this type of condition will degrade the motor insulation and significantly reduce service life [31]. Imbalance of voltage and current are calculated in accordance with the IEEE definition of the maximum difference in magnitude between phases divided by the average of the 3-phase voltages expressed as a percentage as shown in Table 2.1.

Table 2.1: Voltage versus Current Imbalance on a 100 HP Induction Motor [31]

<table>
<thead>
<tr>
<th>V ( V_{\text{Imbalance}} )</th>
<th>I ( I_{\text{Imbalance}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>7%</td>
</tr>
<tr>
<td>2%</td>
<td>14%</td>
</tr>
<tr>
<td>3%</td>
<td>21%</td>
</tr>
<tr>
<td>4%</td>
<td>28%</td>
</tr>
</tbody>
</table>

2.4.2 Effects of Voltage Recovery on IMs

Reapplication of out of phase voltage to a motor with a strong remaining rotor field may result in electromagnetic and shaft torque and current transients which may exceed the starting values by several times, and may be destructive. Depending upon the initial speed loss and the magnitude of the recovery voltage after fault clearance, the motors may accelerate, taking currents that may approach the starting currents of
the motors. These starting currents of accelerating motors, flowing together through the supply system impedance, may prevent a fast recovery of voltage. The stronger the electrical system in relation to the size of the accelerating motors, the greater is the power available for the motors to accelerate and recover [32] and [33].

2.4.3 Effects of Protection Settings on Motor Performance

Motor recovering process after voltage sags is dynamically similar to motor starting process and is accompanied by large inrush currents. Depending on motor protection settings, these currents can trigger over current protection of the motor resulting in the tripping of the motor. Mechanical protection also can trip the motor if the motor torque becomes incapable of driving the load or if the transient torques after voltage recovery are too high.

Most of IM protection settings are too conservative. This leaves room for adjusting these settings without causing any threat to the motor safety. Many of the unnecessary motor tripping incidents can be avoided by simple adjustment to the motor protection settings, [33] and [34].

2.4.4 Review of some Mitigation Techniques and proposed Method to be adopted

The rapid changes of electric power systems create a growing need for flexibility, reliability, fast response and accuracy in the fields of electric power generation, transmission, distribution and one of the most worrisome disturbances is the voltage sag. Researches have shown many solutions available for voltage sags mitigations, but also there are special problems or consideration to every solution. For example, taking actions in the transmission or distribution system is responsibility of the Utility Company and some of these solutions are not so easy to apply whether they are complex system or the great investment of money and time to make these changes.

Other options could be taken indoors of the plant to mitigate the effect of voltage sag, one of the attractive solutions is the use of UPS, but the range of power that this device can handle is about 1MVA, so the installation of this equipment is
not feasible due to the amount of power consumed by the motor loads 26MVA or more [6].

The Dynamic Voltage Restorer (DVR) is also an attractive solution. It could handle voltage sags of 50% depth and its rated maximum power around 50MVA [4], but the high costs related to this equipment make it too expensive.

Other way in which voltage sag effects could be minimised consist on increasing or improving the immunity of the equipment, in this case contactors. One way is to use battery fed DC contactors and installing batteries and chargers, which also will require extra space to manage and maintain the batteries leading to additional expenses.

Another quite interesting methods of reactive power compensation is the used of static VAR compensations. The concept of VAR compensation is defined as the management of reactive power to improve the performance of AC power systems. The problem of reactive power compensation is observed from two aspects, load compensation and voltage support. In the loading point of view, compensation the objectives are to increase the value of the system power factor, to balance the real power drawn from the AC supply, compensate voltage regulation and to eliminate harmonics produced by fluctuating nonlinear industrial loads [35, 36].

This project is aimed to demonstrate the used of SVC in compensating the effect of voltage sag produced during the starting of large induction motor, despite the fact that it is the most expensive but reliable methods of voltage sag mitigation. It is applicable with the wide range of voltage from medium to high voltages and even extra high voltages. The software used in this project has the built-in model of SVC. In this method calculation of capacitors bank values as well as the changing some values of the control system has been carried out. It is found that maximum benefit from compensating equipment’s can be achieved when they are connected to the individual load side [35]. This is practically and economically possible only by using small rated capacitors to the most essential loads. The static VAR compensators (SVC) combines the shunt reactor (TCR) and the shunt capacitor (TSC) with thyristor of high voltage and current rating in obtaining fast and accurate control of reactive power flow [37].
REFERENCES


[38] Roy, R. B. Design of Microcontroller Based Static VAR Compensator.
