# DETERMINATION OF OPTIMIZED SOFT STARTER FIRING ANGLE TO MITIGATE HIGH INRUSH CURRENT DURING MOTOR STARTING USING PSCAD

by

**FARAH HANAN BINTI AHMAD**
**(1732222323)**

A dissertation submitted in partial fulfillment of the requirements for the degree of
Master of Science (Electrical Power Engineering)

**School of Electrical System Engineering**
**UNIVERSITI MALAYSIA PERLIS**
2018

## UNIVERSITI MALAYSIA PERLIS

## DECLARATION OF DISSERTATION

| | | |
|---|---|---|
| Author's Full Name | : | FARAH HANAN BINTI AHMAD |
| Title | : | DETERMINATION OF OPTIMIZED SOFT STARTER FIRING ANGLE TO MITIGATE HIGH INRUSH CURRENT DURING MOTOR STARTING USING PSCAD |
| Date of Birth | : | 17 APRIL 1993 |
| Academic Session | : | 2017/2018 |

I hereby declare that this dissertation becomes the property of Universiti Malaysia Perlis (UniMAP) and to be placed at the library of UniMAP. This dissertation is classified as:

| | | |
|---|---|---|
| ☐ | **CONFIDENTIAL** | (Contains confidential information under the Official Secret Act 1997)* |
| ☐ | **RESTRICTED** | (Contains restricted information as specified by the organization where research was done)* |
| ☑ | **OPEN ACCESS** | I agree that my dissertation to be published as online open access (Full Text) |

I, the author, give permission to reproduce this dissertation in whole or in part for the purpose of research or academic exchange only (except during the period of 10 years, if so requested above)

Certified by:

| | |
|---|---|
| **SIGNATURE** | **SIGNATURE OF SUPERVISOR** |
| 930417-03-5702 | DR. MUHAMMAD MOKHZAINI |
| **(NEW IC NO. /PASSPORT NO.)** | **NAME OF SUPERVISOR** |
| Date: 18 May 2018 | Date: 18 May 2018 |

**NOTES** : * If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization with the period and reasons for confidentiality or restriction. Replace thesis with dissertation (MSc by Mixed Mode) or with report (coursework)

# ACKNOWLEDGMENT

With deepest appreciation and gratitude, I would like to thank my dedicated supervisor, Dr. Muhammad Mokhzaini Bin Azizan for his continuous commitment and giving full support throughout the whole journey of this master's project. I also acknowledge the great co-operation provided by him in finishing this project and for his valuable guidance during the study.

I would also like to thank to the School of Electrical System Engineering for providing me the chance to carry out this project. Thousand thanks to lectures, staff and laboratory technician in helping me a lot to finish this project and allowing me to use the equipments in the laboratory. Thanks to Dr. Hana Abdull Halim who provides me with her ideas in finishing this project.

No words can express my highest gratitude to my beloved family members and colleagues for their support when I am almost giving up. Special thanks to my beloved father, Encik Ahmad Bin Mohd Adam and my mother, Puan Azizah Binti Mohd Daud for their moral and financial support to finish this project. It is because of their affection and motivation that I am able to gain this success. Without them I could not have accomplished my goals. Overall, I would like to thank Almighty for the endless blessing to me.

# TABLE OF CONTENTS

# LIST OF TABLES

## LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | Alternating Current |
| API | American Petroleum Institute |
| DC | Direct Current |
| DOL | Direct Online |
| EMTP | Electromagnetic Transients Program |
| FLT | Full Load Torque |
| HP | Horse Power |
| IEC | International Electro-technical Commission |
| IEEE | Institute of Electrical and Electronic Engineers |
| NEMA | National Electrical Manufacturers Association |
| PLL | Phase Locked Loop |
| PSCAD | Power System Computer Aided Design |
| PWM | Pulse Width Modulation |
| SCR | Silicon Controlled Rectifier |
| TNB | Tenaga Nasional Berhad |
| VSD | Variable Speed Drive |
| VVVF | Variable Voltage Variable Frequency |

## LIST OF SYMBOLS

| | |
|---|---|
| Hz | Hertz |
| $\eta$ | Efficiency |
| $n_r$ | Speed of rotation |
| $n_s$ | Synchronous speed |
| $R_1$ | Resistance stator winding |
| $R_2$ | Phase rotor resistance |
| $s$ | Slip |
| **V** | Voltage |
| $V_1$ | Input phase voltage |
| $X_1$ | Stator leakage reactance |
| $X_2$ | Phase rotor reactance |
| $X_m$ | Magnetizing reactance |
| **Ω** | Ohm |

# Penentuan Prestasi Sudut Isyarat Pemula Rendah (soft starter) untuk Mengurangkan Arus Permulaan Tinggi Semasa Permulaan Motor Menggunakan PSCAD

## ABSTRAK

Permulaan motor induksi adalah satu proses yang mencipta banyak masalah yang mencabar untuk motor dan operasi sistem kuasa. Motor induksi boleh rosak, ciri boleh diubah dan prestasi motor boleh menjadi lebih teruk. Motor induksi menarik arus permulaan yang tinggi dan menghasilkan beban yang tinggi semasa permulaan arus. Arus permulaan yang tinggi menyebabkan masalah seperti voltan menurun yang berlaku dalam sistem kuasa elektrik yang berkaitan dengan motor. Pemula motor yang berbeza yang terdapat di pasaran Malaysia dibincangkan dan dianalisa termasuk pemula elektromekanikal konvensional dan pemacu elektronik kuasa. Perbandingan antara pemula mendapati bahawa pemula lembut adalah yang paling berkesan kerana konfigurasi itu hanya melibatkan beberapa alat pengalir kuasa yang mengawal aliran semasa dari sumber kuasa ke motor. Suis adalah dalam bentuk *thyristor*. Hasil semasa boleh dikawal dengan mengubah sudut penembakan. Perisian PSCAD / EMTDC digunakan untuk pelaksanaan model dan menjalankan kajian simulasi. Pada permulaan, sumber kuasa disambung secara langsung kepada motor induksi dan litar disimulasikan untuk menganalisis arus masuk. Analisis diulang dengan menggunakan rangkaian *star delta* dan pemula lembut. Untuk pemula lembut, *thyristor* bertindak sebagai pintu untuk mengawal voltan yang digunakan untuk motor. Sudut penembakan berbeza-beza sehingga arus tinggi dikurangkan. Penyelidikan ini akhirnya membuat kesimpulan bahawa pemula lembut adalah paling sesuai untuk digunakan untuk mengurangkan arus pemulaan tinggi.

## Determination of Optimized Soft Starter Firing Angle to Mitigate High Inrush Current During Motor Starting Using PSCAD

## ABSTRACT

Starting of an induction motor is a process that creates many challenging problems for the motor and operations of the power system. The induction motor can be damaged, characteristic can be changed and performance of the motor can be worsen. An induction motor draws a high starting current and develops a high torque during the start-up. Inrush current often causes problem such as voltage dips and sags that occur in electrical power system associated with motor. The different motors starters available in Malaysia market are being discussed and analyzed. It includes both conventional electromechanical starters and power electronic drives. A comparison between the starters found that soft starter is the most convincing because the configuration ~~just~~ involves some power conductor device that control the current flow from power source to the motor. The switch is in the form of thyristor and being connected back-to-back. The current output can be controlled by varying the firing angle. This changing of firing angle is managed by a firing angle control circuit. PSCAD/EMTDC software is used for model implementation and in carrying out extensive simulation studies. Firstly, the power source was directly connected to the induction motor and the circuit is simulated to analyze the inrush current. The analysis of the starter is repeated by using star delta starter and soft starter. For soft starter, the thyristor acts as a gate to control the voltage applied to the motor. The firing angle was varied until the high current was mitigated. This research was finally concluded that soft starter circuit is designed to be used to mitigate inrush current.

# CHAPTER 1: INTRODUCTION

## 1.1 Background of the Project

Inrush current can be described as the highest current value drawn by electrical appliances immediately after the devices are being turned on. The starting current may reach about 5 to 7 times higher than normal full-load current and continues for a few cycles of the input waveform. According to Youxin, Y., Zezhong, et al.,(2007), the high starting current causes power voltage to drop and influences the normal operation of other equipment connected in the same power line. The starting current line could lead to severe damage and harm to the motor such as overheating.

To overcome the problem, various motor starters were being introduced. The motor drivers are classified into two types which are power electronic drives and conventional starters. The powers electronics drives are being categorized into soft-starter, frequency inverter and matrix converter while conventional starters are Direct-Online starter, Star-Delta starter, and Auto-transformer starter. Power electronic drives are concluded to be more reliable because it consists of only several power semiconductor switches and controller. Soft starter is widely used in industries because of its advantages which are simple structure, cheap price, easy maintenance and lower investment.

This research is focusing on developing the power electronic driver starter using soft starter by varying the firing angle to provide a low inrush current during the start-up of three-phase induction. This method will be compared with other starter which is Star-

Delta configuration to provide a low inrush current on the three-phase induction motor starter.

## 1.2 Problem Statements

There are many large induction motors are started directly online. However, when large motors are started using that method, they can cause some disturbance of voltage on the supply lines due to the large starting current surges. One of the disturbances is high inrush current. This current can influence sensitive loads by a voltage drop. Therefore, it is recommended to take measures to limit this inrush current. To limit the preliminary current surge, large induction motors are being started using lower voltage starter and then is reconnected when they run up to near rated speed. Motor can be started by using several electromechanical starters which are direct online, star-delta and autotransformer (Goh et al., 2009). However the existing methods still have some drawbacks such as high installation cost, low efficiency and can only be applied to certain types of motor. To overcome this problem, new method which is determination of soft starter firing angle have been done to mitigate the high inrush current. This control circuit operates by controlling the current flow through the circuit.

## 1.3 Objectives

In designing the soft-starter to mitigate motor high inrush current, several objectives are needed to be completed. The objectives of this project are:

1) To study the magnitude and duration of inrush current during the starting of three phase induction motor.

2) To propose mitigation method on inrush current through implementation of soft starter through firing angle adjustment.
3) To compare the magnitude current during the start-up and steady state of induction motor between direct online, star delta and soft starter.

## 1.4 Scope of the Research

This research focuses on applying the soft starter to mitigate the high inrush current during start-up of the induction motor. The soft starter varies the value of firing angle to find the best current value to be applied to the system. The motor starting motor is being conducted and analysed using the simulation system throughout PSCAD software. This research will be using three-phase wound rotor induction motor, 415V, and 50Hz frequency.

## 1.5 Thesis Outline

Chapter 1 discusses about the background of the research which is the high inrush current that occurs when starting-up the motor. Besides that, this chapter will discuss about the problem statements, objectives of research and the scope boundaries of the project.

Chapter 2 discusses about the literature review comprising the review of other’s project, existing project, application and implementation of the project. The software used for this project are also being discussed. There are also review of several starter methods that has been used, such as conventional motor starters and power electronics starter.

Chapter 3 describes the methodology of the research including the flowchart, procedure in achieving the objectives and circuit implementation of the starter used with Power System Computer Aided Design/ Electromagnetic Transients including DC (PSCAD/EMTDC) software. The design covers the selection of power electronic devices, firing control circuit and the parameter used for the source and induction motor.

Chapter 4 describes about the result including data collected shown using table and graph of data analysis. The simulation results of the direct online, star delta and soft starter for controlling inrush current is taken. The result of current, voltage and speed will be compared using the theory.

Lastly, chapter 5 concludes the highlight of the accomplishment of the research objectives based on the result obtained. The recommendations of the future enhancement are also being mention in this chapter.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Introduction

Chapter 2 is the reviews of the previous work developed by other researchers that are related to this project in order to have a better understanding to be implemented. Literature review mainly discusses a few projects that used other methods that have the same objectives as the soft-starter firing angle performance to mitigate motor high inrush current. Application and implementation of the project are also being discussed throughout this chapter. The conventional starters and power electronic starters has been tested for its effectiveness and circuit diagram to find the most suitable starting method to be implemented in this project.

## 2.2 Overview of Induction Motor

Induction motors can be classified into several types which are squirrel-cage rotor and wound rotor. Squirrel cage induction motors are very famous in industrial and manufacturing process. This is because of its reliability, low cost and rugged construction (Srinivasan, J., K.Selvaraj, 2016). It also has a high efficiency up to 95%. The constructions of squirrel-cage rotor is made up of conducting bars laid into slots carved in the face of the rotor and shorten at either end by large shorting rings.

The stator of wound rotor induction motor is similar to squirrel cage but with shielded winding carried out through slip ring and brushes. This type of induction motor is not short-circuited, but connected in three phase configuration. Wound rotor is effective in the application due to having high starting torque and can deliver heavy speed control but squirrel-cage induction motor may result in high starting current in power system.

## 2.3 Equivalent Circuit of Induction Motor

Induction motor is usually being used in both industrial and domestic applications. The electric current in the rotor is being induced by changing magnetic field in the stator winding. The rotor current yields its own magnetic field, which interacts with the stator field to yield torque and rotation. The construction of an induction motor circuit is very similar to circuit of a transformer. This is because the voltages and currents in the rotor circuit of an induction motor are mainly the transformer operation. It is also known as the rotating transformer. Induction motor is acts as a transformer with rotating secondary. The primary transformer looks like stator winding of an induction motor and secondary is similar to rotor. The induction motor runs below the synchronous speed and slip which is denoted by $s$ which shown the difference between the synchronous speed and speed of rotation.

Figure 2.1 shows the equivalent circuit of induction motor. $V_1$ is input phase voltage, $R_1$ denotes the resistance of stator winding and $X_1$ denotes the stator leakage reactance. $Xm$ is the magnetising reactance requires to cross the air gap and $Rc$ denotes the core losses. $R_2$ is per phase rotor reactance and $X_2$ is per phase rotor reactance. The induction motor continuously run below the synchronous speed and the relative difference between the synchronous speed ($n_s$) and speed of rotation ($n_r$) is known as slip which is denoted by $s$. Slip can be expressed as either a fraction or percentage:

$$s = \frac{n_s - n_r}{n_s} \tag{2.1}$$

Where,

s = slip

$n_s$ = synchronous speed

$n_r$ = speed of rotation

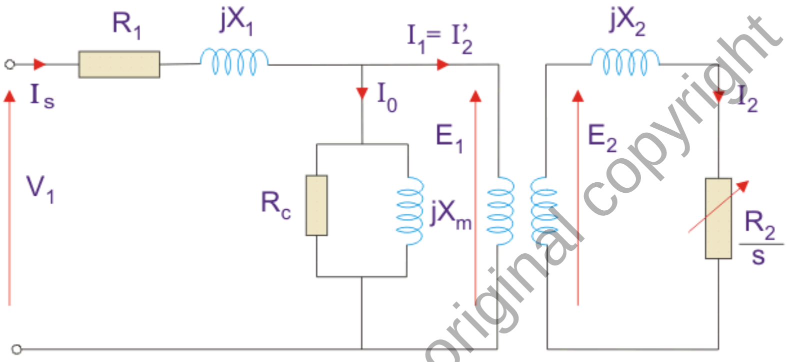

Figure 2.1: The equivalent circuit of an induction motor (M.Thirugnanasambandamoorthy et.al, 2011)

## 2.4 Motor Power

If the core losses $R_C$ is neglected and the value of ($I_1$=$I_2$'), the power delivered to the motor ($P_{in}$) per phase is given by:

$$P_{in} = I_1^2(\mathrm{R}_1 + \frac{R_2}{s}) \tag{2.2}$$

The power loss dissipated by the winding is given as:

$$P_W = I_1^2(\mathrm{R}_1 + \mathrm{R}_2) \tag{2.3}$$

The variance between the power delivered to the motor and losses in the windings is the power delivered to the connected load (*$P_m$*):

$$\mathrm{P_m} = P_{in} - P_W = I_1{}^2(\frac{1-s}{s})\,\mathrm{R_2} \tag{2.4}$$

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

$$P_{in(3\Phi)} = 3I_1{}^2(\frac{1-s}{s})\,\mathrm{R_2} \tag{2.5}$$

Where;

$P_m$= mechanical power develops

$P_{in}$= input power

$P_w$ = power losses

## 2.5 Running Characteristics of Induction Motor

Motor drives at a low slip and at a speed that was determined by the number of stator poles when it is being operated. The value of slip at the full-load condition for a standard cage induction motor is not more than 5% (J.Cathey,2010). The losses of an induction motor which are iron, windage and frictional are loads independent while copper loss is directly proportional to the square of the stator current as equation below:

$$P_c = 3I_1{}^2R^2 \tag{2.6}$$

Rotor current is:

$$I_2 = \frac{sE_2}{\sqrt{R_2{}^2 + (\mathrm{sX_2})^2}} \tag{2.7}$$

Substitute the value of $I_2$ into equation (2.6), the rotor copper losses $P_c$ becomes:

$$P_c = 3R_2\left(\frac{sE_2}{\sqrt{R_2{}^2 + (\mathrm{sX}_2)^2}}\right)^2 \tag{2.8}$$

Or

$$P_c = \frac{3R_2 s^2 E_2{}^2}{R_2{}^2 + (\mathrm{sX}_2)^2} \tag{2.9}$$

The ratio of $P_2$: $P_C$: $P_m$ = 1: $s$: (1-$s$)

Where;

$P_2$ = rotor input

$P_C$ = rotor copper loss

$P_m$ = developed mechanical power

$$\frac{P_c}{P_m} = \frac{s}{1-s} \tag{2.10}$$

Substitute the value of $P_c$ into equation (2.9) yields,

$$P_m = \frac{1}{s} \times \frac{(1-s)3R_2 s^2 E_2{}^2}{R_2{}^2 + (\mathrm{sX}_2)^2} \tag{2.11}$$

Or

$$P_m = \frac{(1-s)3R_2 s E_2{}^2}{R_2{}^2 + (\mathrm{sX}_2)^2} \tag{2.12}$$

The developed mechanical power $P_m = T_{\acute{\omega}}$. Therefore, the mechanical power is directly proportional to the torque produced at the load.

## 2.6 Efficiency of the Induction Motor

The effectiveness of the induction motor at the average of 75% of 100& full load torque (FLT). The efficiency can vary from less than 60% for small and low speed motors that is higherthan 92% for large high speed motor. Efficiency is defined as the ratio of the output power to the input power as below:

$$Efficiency(\eta) = \frac{output}{input} = \frac{P_m}{P_2} = \frac{P_{out}}{P_{in}} \tag{2.13}$$

## 2.7 Industry Standard of Motor Inrush Current

In industrial, there is several standard for motor that stipulate requirements of torque and inrush current. There are three key standards which are National Electrical Manufacturers Association (NEMA, 2009-2010), International Electro-technical Commission (IEC) and American Petroleum Institute (API, 2011). The induction motor performance standard of NEMA, IEC and API are summarized as in Table 2.1.

Table 2.1: Motor Performance (M.Thirugnanasambadamoothy et al. 2011)

| **Parameter** | **NEMA MG-1 (NEMA 2009-2010)** | **API 541 (API 2011)** | **IEC 60034 (IEC)** |
|---|---|---|---|
| Inrush Current | Not available for large motor | 450% Minimum to 650% Maximum | Not available |
| Starting torque/ pull-up torque | 60% Minimum | 60% Minimum | 30% Minimum |
| Breakdown torque | 175% Minimum<br>Motor of inrush less than 450% allowed to have 150% breakdown torque. | 175% Minimum<br>Motor of inrush less than 450% allowed to have 150% breakdown torque. | 160% for 15 seconds.<br>Motor of inrush less than 450% allowed to have 150% breakdown torque. |