การศึกษาผลกระทบของแรงดันตกชั่วขณะที่มีต่อมอเตอร์เหนี่ยวนำ

นายฟิกรี วัสกิโต้

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมไฟฟ้า ภาควิชาวิศวกรรมไฟฟ้า
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2554

A STUDY OF VOLTAGE SAG EFFECTS ON INDUCTION MOTORS

Mr. Fikri Waskito

Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Electrical Engineering
Department of Electrical Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2011

Thesis Title	A STUDY OF VOLTAGE SAG EFFECTS ON INDUCTION MOTORS
By	Mr. Fikri Waskito
Field of Study	Electrical Engineering
Thesis Advisor	Channarong Banmongkol, Ph.D

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

…………………………………… Dean of the Faculty of Engineering
(Associate Professor Boonsom Lerdhirunwong, Dr. Ing)

THESIS COMMITTEE

…………………………………… Chairman
(Assistant Professor Naebboon Hoonchareon, Ph.D)

…………………………………… Thesis Advisor
(Channarong Banmongkol, Ph.D)

…………………………………… Examiner
(Assistant Professor Thavatchai Tayjasanant, Ph.D)

…………………………………… External Examiner
(Chakphed Madtharad, Ph.D)

ฟิกรี วัสกิโต้ : การศึกษาผลกระทบของแรงดันตกชั่วขณะที่มีต่อมอเตอร์เหนี่ยวนำ. (A STUDY OF VOLTAGE SAG EFFECTS ON INDUCTION MOTORS) อ.ที่ปรึกษาวิทยานิพนธ์หลัก : อ.ดร.ชาญณรงค์ บาลมงคล, 57 หน้า.

แรงดันตกชั่วขณะเป็นปัญหาทางด้านคุณภาพไฟฟ้าชนิดหนึ่งที่พบได้ในระบบไฟฟ้า ซึ่งสามารถระบุลักษณะเฉพาะได้จากขนาดแรงดันที่คงเหลือ ระยะเวลาที่เกิดแรงดันตกและการเลื่อนเฟส อุปกรณ์ในงานอุตสาหกรรมบางอย่างโดยเฉพาะมอเตอร์เหนี่ยวนำมีความไวเป็นอย่างมากต่อแรงดันตกชั่วขณะ วิทยานิพนธ์นี้นำเสนอการศึกษาอิทธิพลของแรงดันตกชั่วขณะทั้งแบบสมมาตรและไม่สมมาตรที่มีต่อพฤติกรรมของมอเตอร์เหนี่ยวนำ โดยใช้การทดลองและการจำลองด้วยโปรแกรม EMTP-ATP เพื่อสังเกตุการเปลี่ยนแปลงของกระแส ความเร็วและแรงบิดในช่วงที่เกิดแรงดันตกชั่วขณะที่แหล่งจ่าย นอกจากนี้แรงดันตกชั่วขณะยังมีผลกระทบต่อคอนแทกเตอร์ซึ่งควบคุมการทำงานของมอเตอร์ จึงทำการทดสอบความไวต่อแรงดันตกชั่วขณะของคอล์ยของคอนแทกเตอร์ และใช้การจำลองด้วยคอมพิวเตอร์เพื่อศึกษาการตอบสนองของคอนแทกเตอร์เมื่อเกิดแรงดันตกชั่วขณะ

ภาควิชา ....วิศวกรรมไฟฟ้า..... ลายมือชื่อนิสิต...
สาขาวิชา.........วิศวกรรมไฟฟ้า..... ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ....
ปีการศึกษา ....2554....................

527 07219 21 : MAJOR ELECTRICAL ENGINEERING

KEYWORDS : VOLTAGE-SAGS / INDUCTION MOTOR / AC CONTACTOR / SAG TYPE / EMTP-ATP

FIKRI WASKITO: A STUDY OF VOLTAGE SAG EFFECTS ON INDUCTION MOTORS. ADVISOR : CHANNARONG BANMONGKOL, Ph.D., 57 pp.

Voltage sags are a common power quality problem occurring in power systems. They are usually characterized by remaining voltage, duration, and phase jump. Several industrial equipment, especially induction motors, are highly sensitive to voltage sags. This thesis studies the effects of unsymmetrical and symmetrical voltages sags on behavior of an induction motor. Both experiment and computer simulation using EMTP-ATP are conducted to observe variations of current, speed and torque of the induction motor during voltage sags of its supply. Voltage sags affect not only motor supply but also contactors that control the operation of motors. Thus, the sensitivity of an ac coil contactor to voltage sags is investigated by a test. Computer simulation is also carried out to study the response of contactor to voltage sags.

Department : Electrical Engineering Student's Signature ....

Field of Study : Electrical Engineering Advisor's Signature ....

Academic Year : 2011

Acknowledgements

I would like to to express my greatest gratitude to my thesis supervisor, Channarong Banmongkol, Ph.D, for all his careful guidance, patience, and considerable support during my study at Chulalongkorn University. This thesis would not have been possible without his great supervision.

I am thankful to Chulalongkorn University, especially to all of member and staff of High Voltage Laboratory and M. Son Gewertz Laboratory in helping me on the experiment. I am also indebted to Channarong Banmongkol, Ph.D, Assistant Professor Komson Petcharaks, Assistant Professor Kulyos Audomvongseree, Surachai Chaitusaney, Ph.D, Professor David Banjerdpongchai, and Assistant Professor Suchin Arunsawatwong for providing me the fundamental background involving the field of Power Systems. The knowledge that I gained from their lectures is particularly useful not only for the work in this thesis but also for my future research.

I also greatly appreciate the considerable effort of all the committee members including Channarong Banmongkol, Ph.D, Assistant Professor Naebboon Hoonchareon, Ph.D, Assistant Professor Thavatchai Tayjasanant, Ph.D, and Chakphed Madtharad, Ph.D who have spent time in reading the manuscript of the thesis and attending the thesis defence. Their useful comments and constructive advices are absolutely invaluable. My thanks also go to everyone at Chulalongkorn University, especially students of High Voltage Laboratory and Power System Laboratory, for their great friendship and enthusiastic help.

I gratefully acknowledge the full financial support from the ASEAN University Network/Southeast Asia Engineering Education Development Network (AUN/SEED-Net) for my Master's program in Thailand. My sincere thanks are also extended to the International School of Engineering (ISE), Chulalongkorn University for their care and help during my study.

Finally, I would like to dedicate this thesis to all members in my family for their endless love and support.

Contents

List of Tables

List of Figures

Figure Page

CHAPTER I

INTRODUCTION

1.1 Introduction

A voltage sag can be defined as a short duration decrease of the rms voltage. This voltage event can be considered as a sag when the magnitude of rms voltage remains between 10 % and 90 % of the nominal voltage and the event duration between 0.5 cycles to 1 minute [1]. In similar definition, we can also define a voltage sag as a sudden reduction of the voltage a particular point of an electricity supply system below a specified threshold then followed by its recovery after brief interval [2]. Recently, a short interruption where remaining voltage is almost zero can also be considered as a particular case of voltage sags [3]. An example of voltage sag can be seen on Figure 1.1.

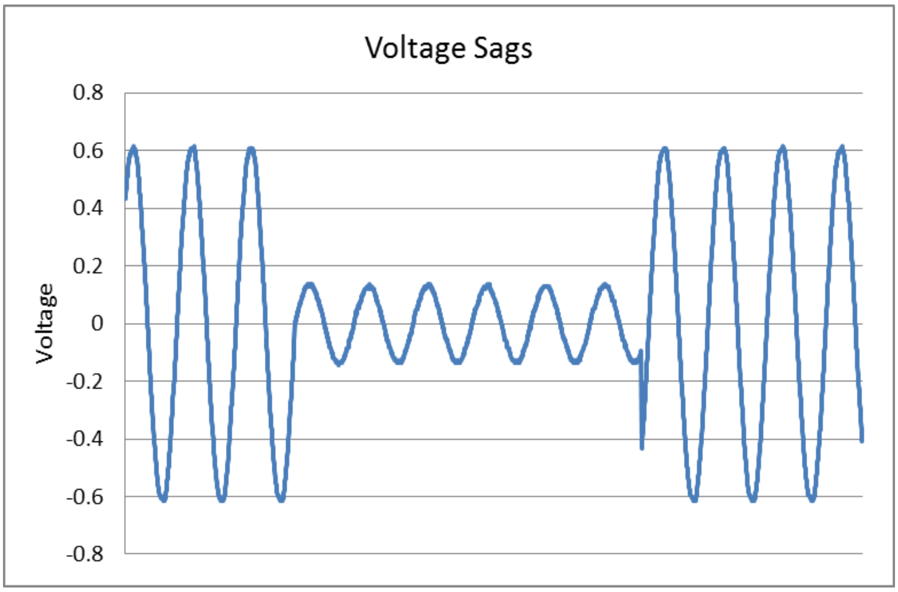


Figure 1.1: A voltage sag event.

Voltage sags is the most common power quality problem occurring in power system. This phenomenon is usually characterized by remaining voltage, the duration, and the phase jump. Even the effects of voltage sags are less dangerous than voltage interruptions, they happen more frequently. Because of their significant effect to sensitive equipment, it can be as important as voltage interruption [4]. There is a diversity of the causes of voltage sags, which make it difficult to prevent them [5]. But most of the causes of voltage sags are short circuit [6].

The sensitivity of equipment to voltage sag may vary because of its characteristic. This different characteristic may result in different response of equipment to voltage sag. Assessment is needed to investigate this kind of respond.

Testing in laboratory is probably the simplest and the most efficient way for assessment [7]. The other ways for the assessment are monitoring and simulation. Monitoring will take long time to wait a real case of voltage sag on a system. Voltage sags can be simulated using several types of tools based on a time-domain solution to obtain high accuracy of the main characteristics of voltage sags [8]. Even the most complex and most realistic model cannot include all influence.

The induction motor is one of equipment that affected by voltage sag. The effects of voltage sag on the induction machine can be seen on speed loss and current and torque peaks that appear in the fault and recovery voltage instants [9, 10]. After the fault is removed the system voltage may recover to a value higher than its pre-fault value. This is due to loss of load, and the accompanying voltage drop, upon removal of feeding lines during the fault clearing process. It is also confirmed that voltage sags can also affect power of induction motor and also possibility of stall [11].

AC contactors also sensitively affected by voltage sag. AC coil contactors usually used as electromechanical AC switches in several different kinds of electrical systems. They are used both for powering and process control. Despite a simple design they are often quite sensitive to voltage dips.

1.2 Literature Review

There are several power quality issues which until today were normally not included in motor protection studies. However, they should be taken into consideration due to their increasing influence. Other actual power quality problems have been considered for many years now, such as voltage imbalance, undervoltages, and interruptions [1].

This type of problems is intensified today because power requirements of sensitive equipment, and voltage–frequency pollution have increased drastically during recent years. The actual trend is anticipated to be maintained in the near future. Besides, the system should be kept operating until the last extreme situation, since any system dropout would have very high economic consequences.

Induction motor has a unique behavior due to voltage sags. When a temporary interruption takes place, with time duration between 3 s and 1 minute, the whole production process will be disrupted. Keeping the motor running is useless because most of the sensitive equipment will drop out. The induction motor should be disconnected, and the restart process should begin at the supply recovery, taking into account the reduction and control of the hot-load pickup phenomenon.

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. 3-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 these type of condition will degrade the motor insulation and significantly reduce service life [12].

Keeping the motor connected to the supply during voltage sags and short interruptions, rather than disconnecting and re-starting it, is advantageous from the system's stability point of view. It is necessary to avoid the electromagnetic contactor drop out during transients, for which several measures have been presented. This scheme improves the system ride-through ability due to the reduction of the re-acceleration inrush, however, a quasistartup phenomenon will be produced, which can be equally or more severe than the normal motor startup [13].

This research can be done experimentally or analytically, by using dynamic load models mainly designed for stability analysis, but they are rather complicated, requiring precise system data and high level software such as EMTP.

From previous research, it can be concluded that short interruptions or extremely deep voltage sags represent the worst case for the motor thermal stress as well as for the circuit and neighboring sensitive loads. The main reason for difficult re-acceleration is the hot-load pickup.

Measured and observed effects in the tests can cause possible damages in the mechanical structure of the machine, such as damages in bearings. Isolation will be possibly damaged the increase of current in the windings, which produces heating. Voltage sags can also loss of useful life, as resulting from the mentioned effects.

Previous research also shows that mechanical damages were noticed after performing a large amount of tests. These damages were evidenced as, for example, audible vibrations in the machine.

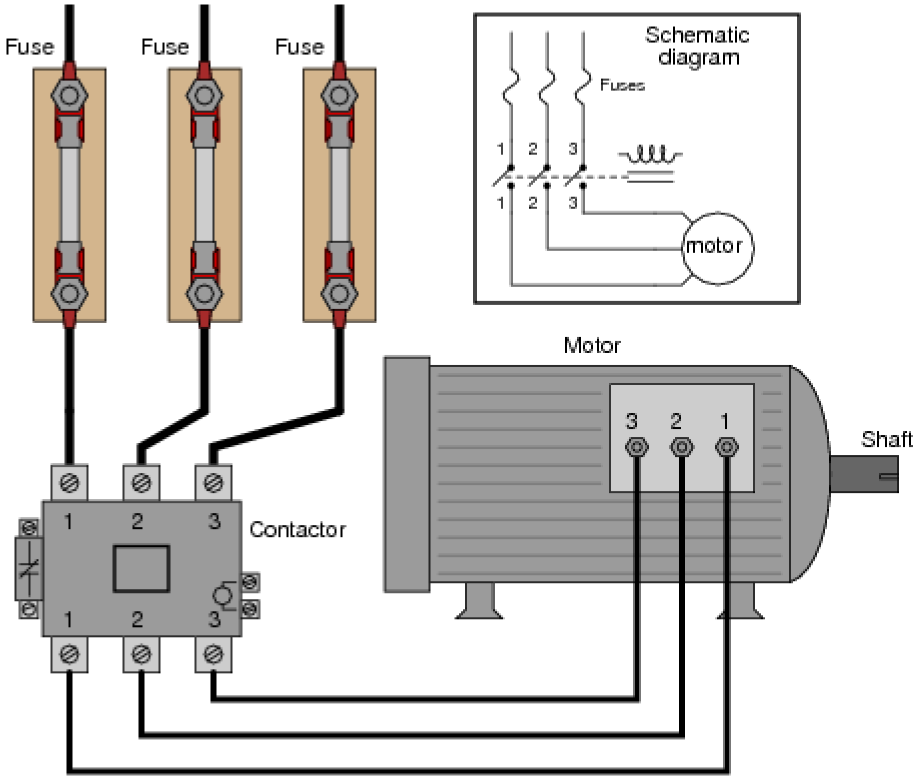


Figure 1.2: Connection of contactor and induction motor.

On the other hand, the effect of voltage sags to electrical contactors should also be considered. As we know that when we talk about induction motor, it should consider power part and control part of the motor. Power part of the motor is the induction motor and the control part includes contactors. Electrical contactors are sensitive equipment due to their weakness to withstand voltage transients, disconnecting the induction motor which otherwise would be able to ridethrough most of the usual events [13].

Several reports have shown the capability of electromagnetic contactors to withstand short interruptions and voltage sags, which is approximately 65 to 75% voltage magnitude during one to two cycles. It has been reported that both the "point-in-wave" where a sag occurs and the corresponding "point-in-wave" where the voltage recovers have a large effect on the contactor response. In order toavoid the electromagnetic contactor dropout during transients, several measures have been presented, such as mechanical latch, dc coil, dc coil and storage capacitor, etc. Most of these additions delay the contactor dropout by up to 0.5 s, with the recommendation not to extend this delay further for safety reasons [13].

Another thing is that the out-of-phase reconnection produces peak current and specific energy of the same order of those produced in the startup process. Most of the voltage sags do not prevent motor re-acceleration, thus the contactor and undervoltage protection should be properly coordinated [14].

1.3 Objectives

The objectives of this thesis are to study the voltage sag effect on induction motor and AC contactors to understand their responses during voltage sags using lab testing and simulation.

1.4 Scope of Thesis

The study is confined to an investigation of characteristic of induction motor and AC contactor due to voltage sag. Both simulation and testing procedure will be done. The simulation will be done using EMTP-ATP and testing will be done using voltage sag generator which has manufactured on laboratory.

1.5 Thesis Outline

The contents of the thesis are organized as follows:

Chapter II generally presents the related theory that is used in this thesis. Types of voltage sags, importance of “point in wave”, EMTP-ATP, and standard in voltage sags testing will be explained in this chapter.

Chapter III explains the method of the experiment in laboratory. This chapter will present the specifications, configurations, and methods that are used in experiment. The result and of simulation will be explained as well.

Chapter IV explains the method of the simulation using EMTP-ATP. This chapter will present the specifications, configurations, and methods that are used in simulation. The result will be analyzed and also compared to previous experiment.

Chapter V gives the conclusions of the thesis.

CHAPTER II

RELATED THEORY

2.1 Characteristic of Voltage Sags

There are various types of faults that can affect voltage sags in electrical power system: three-phase faults, single phase-faults, phase-to-phase faults, and two-phase-to-ground faults. This voltage is not equal to the voltage at the equipment terminals. Normally, equipment is located on a lower voltage level than the voltage level where the fault occurs.

The voltage characteristic at the equipment terminals not only depend on the voltage at source but also on the winding connection of the transformers between source and the equipment terminals. Three-phase load is normally connected in delta but sometimes star-connection is also used [6].

Voltage sags are usually caused by weather and utility equipment problems. This problem normally lead to system faults on the transmission or distribution system. For example, a fault on a parallel feeder circuit will result in a voltage drop at the substation bus that affects all of the other feeders until the fault is cleared. This problem would also apply for a fault somewhere on the transmission system. Most of the faults on the utility transmission and distribution system are single-line-to-ground faults [4].

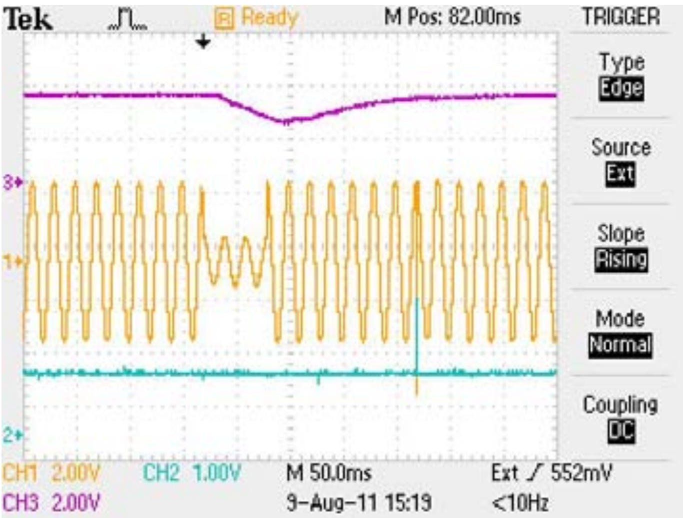


Figure 2.1 Voltage sag event and the effect to motor current.

The switching of heavy loads or the starting of large motors usually also affect voltage sags. For example, an induction motor can draw six to ten times of its full load current during starting. If the current magnitude is relatively larger than the available fault current at that point in the system, the voltage sag can become significant [4].

The types of voltage sag are generally based on the individual voltages (both magnitude and angle) for each of the three phases during sags. Usually, three-phase voltage sags are categorized by either the ABC classification or the symmetrical components classification. However, voltage sag type according to the ABC classification is frequently used due to its simplicity as it is based on a simplified network model.

The classification is based on incomplete assumptions and cannot be used to obtain the characteristics of measured sags. The symmetrical component classification is more general and gives a direct link with measured voltages but is harder to understand and a translation to the ABC classification may be suitable for many applications. In addition, the ABC classification was developed to analyze the propagation of sag or dip from transmission to distribution levels, when a disturbance propagates through a transformer.

2.1.1 Factors that Affect Voltage Sag Type

Voltage sag occurs in equipment terminals. This voltage sags type can be affected by:

2.1.1.1 Fault type

Voltage sags are primarily caused by system faults. Each fault type has a different effect to the voltages at the fault point, which subsequently defined the voltage sag types.

- Single-Line-to-Ground Fault
- Line-to-Line Fault
- Double-Line-to-Ground Fault
- Three Phase Fault

2.1.1.2 Transformer Winding Connection

Transformer winding connections are classified into three types to explain the transfer of three-phase unbalanced voltage sags, as well as the change in voltage sag type, from one voltage level to another.

- Type 1 – Transformers that do not change anything to the voltages. The primary voltages (per unit) are equal to the secondary per unit voltages. The only transformer configuration that falls under this type is the WYE Grounded-wye grounded (Ynyn).

- Type 2 – Transformers that remove the zero-sequence voltage. Basically, the secondary voltage (pu) is equal to the primary voltage (pu) minus the zero-sequence component. The DELTA-delta (Dd), DELTA-zigzag (Dz) and the WYE-wye (with both windings ungrounded or with only one star point grounded) belong to this type.
- Type 3 – Transformers that changes line and phase voltages. DELTA-wye (Dy), WYE-delta (Yd) and the WYE-zigzag (Yz) fit under this type.

2.1.1.3 Load Connection

- Wye-connected load
- Delta-connected load

2.1.2 Voltage Sag Types - ABC Classification

There are seven basic voltage sag types according to the ABC classification. These are shown (equation and phasor forms) in the figure below considering phase A as the reference.

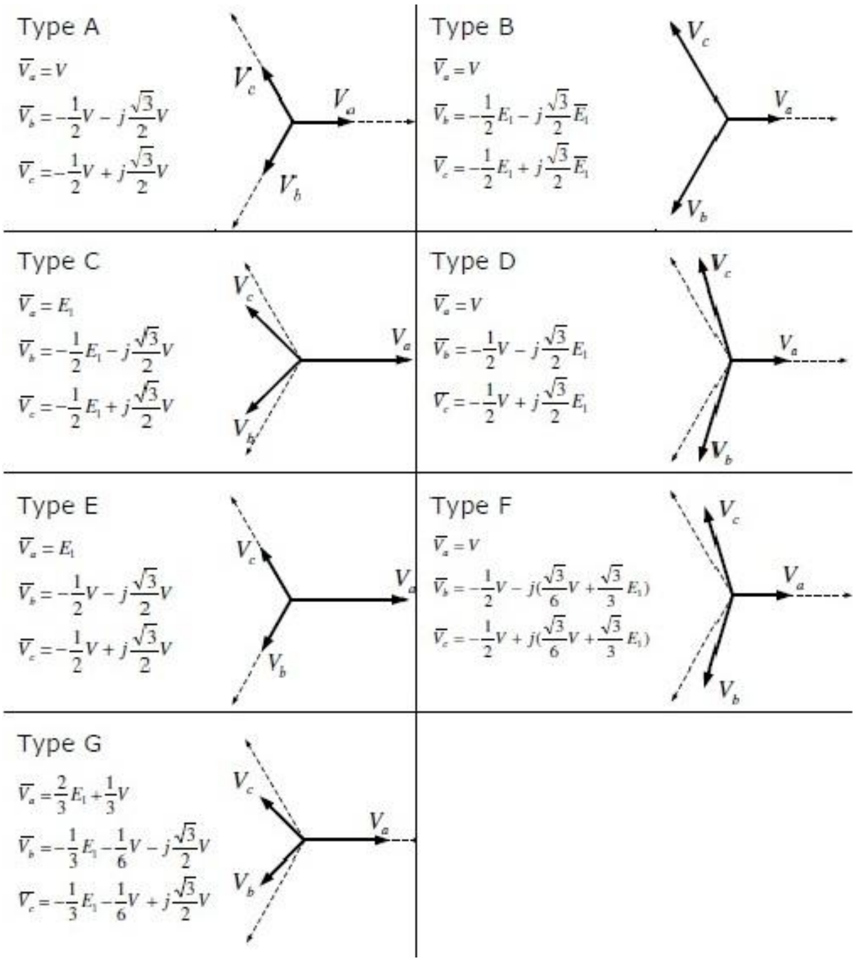


Figure 2.2 Voltage sag type [6].

From the figure 2.2 above, we can observe that:

- Voltage Sag Type A results to all three voltages down by the same amount.
- Type B has the faulted phase voltage reduced.
- Type C sag causes the two affected phase voltages to change along the imaginary axis only (both in magnitude and angle).
- For type D, the two affected phase voltages change in the real axis only with an accompanying drop in magnitude in the remaining phase.
- Type E results to reduced voltage magnitude in the two affected phases.
- Type F is similar to Type D, except that the voltage change is along both real and imaginary axes.
- Voltage sag type G is similar to Type C but with the voltage change in both axes. In addition, the remaining phase also experiences a decrease in voltage.

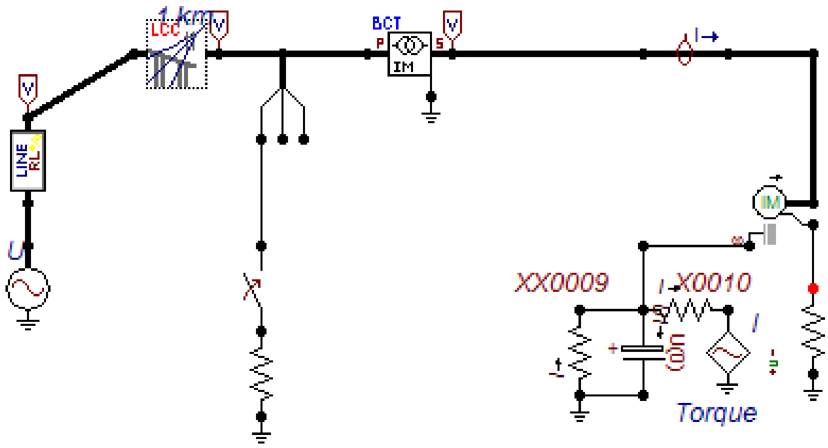
2.2 EMTP-ATP

Electromagnetic Transients Program (EMTP) is a software tools targeting a slice of the spectrum of design and operation problems presented by electrical power system, that of the so called "electromagnetic transients" and associated insulation issues.

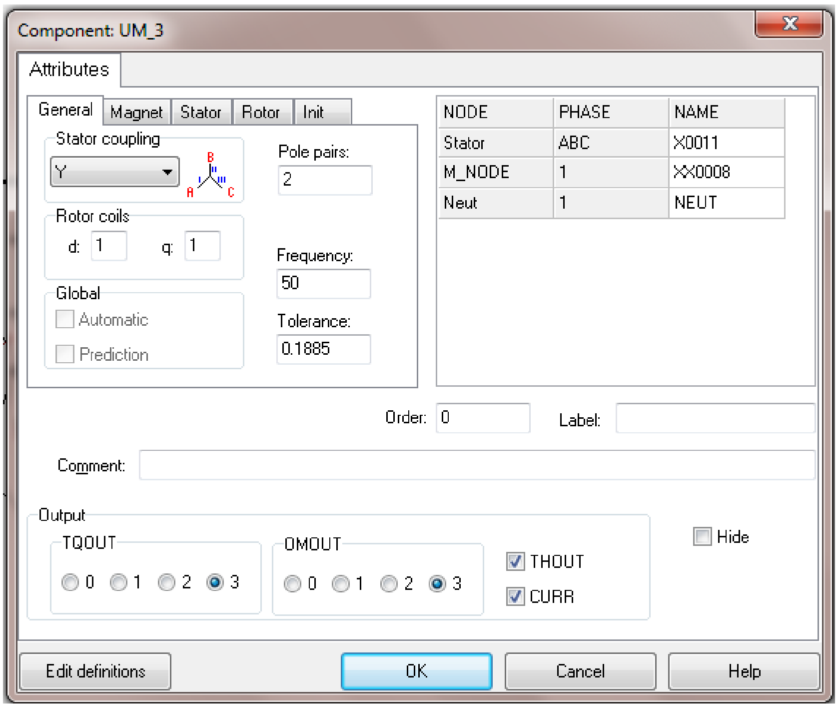
ATP is a universal program system for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature. With this digital program, complex networks and control systems of arbitrary structure can be simulated. ATP has extensive modeling capabilities and additional important features besides the computation of transients using.

ATPDraw is a graphical preprocessor to the ATP-EMTP on the MS Windows platform. In the program the user can build up an electric circuit, using the mouse, by selecting predefined components from an extensive palette. Based on the graphical drawing of the circuit, ATPDraw generates the ATP file in the appropriate format based on "what you see is what you get". All kinds of standard circuit editing facilities (copy/paste, grouping, rotate, export/import) are supported. Circuit node naming is administrated by ATPDraw and the user only needs to give name to "key" nodes.

We can easily set and determine the parameters of system using graphic interface of ATPDraw. The example of figure using EMTP-ATP program can be seen on Fig. 2.3. We can set AC source, distribution line, transformer, and load using graphic interface. We can also set parameters of each component by double-clicking the component.



(a)



(b)

Fig. 2.3. Configuration of system for simulation with EMTP-ATP
(a) System configuration (b) configuration tab

More than 65 standard components and 25 TACS objects are available, and in addition the user can create new objects based on MODELS or Data Base Modularization ash shown in Figure 2.4. ATPDraw has a standard Windows layout, supports multiple documents and offers a large Windows help file system, which explains the most basic rules. Other facilities in ATPDraw are: a built-in editor for ATP-file editing, support of Windows clipboard for bitmap/metafile, output of MetaFiles/Bitmaps files or PostScript files not limited to circuit window size, a new module for using Line/Cable Constant punch files directly in ATPDraw.

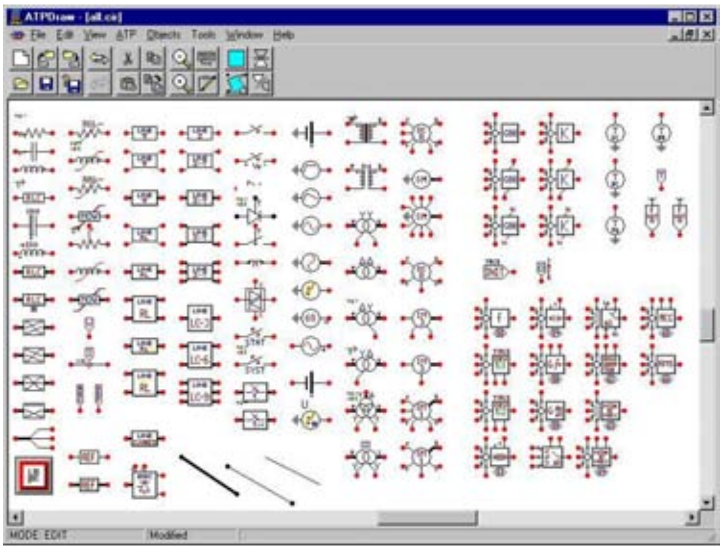


Figure 2.4: Components of ATPDraw simulation.

2.3 Standard in Voltage Testing

It is widely known that response of equipment to voltage sag may vary because of voltage sags' and equipment's characteristic. Some equipment may severely affected by voltage sag. There are some standards that limit the equipment's immunity to voltage sags.

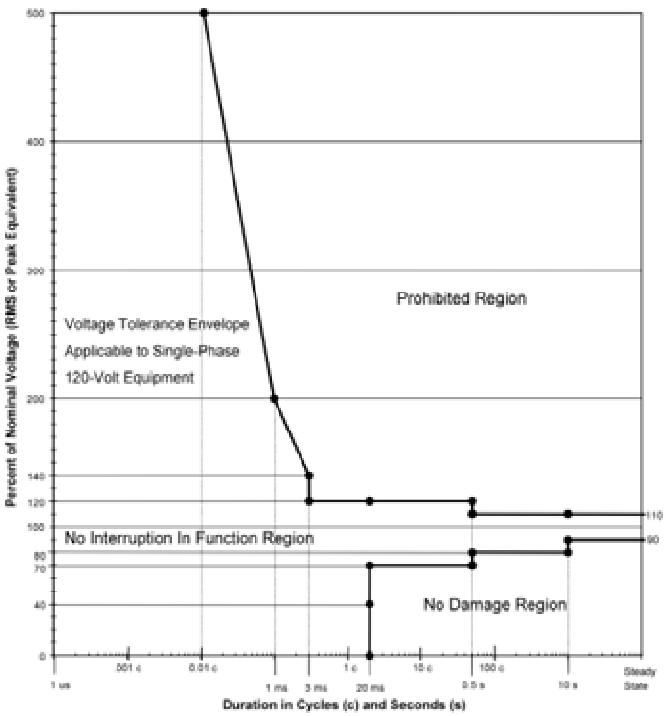


Fig. 2.5.ITI (CBEMA) curve

One of the standards is Information Technology Industry (ITI) curve that shown on Fig. 2.5. It is obvious that this curve standardize every equipment to be immune to this voltage sags event in duration and percent of nominal voltage. It means, when the voltage sag is still on voltage tolerance zone, the equipment should still work without trip. But when the voltage sag surpass the prohibited region, the equipment can be outage. This standard is widely known and used by electrical equipment's manufacturer to test their immunity.

In testing the equipment, the standard that mostly used is International Electrotechnical Commision (IEC) standard 61000-4-11, Testing and measurement techniques – Voltage dips, short interruptions, and voltage variations immunity test [2]. This standard give us guidance how we should test the equipment to know the sensitivity of equipment to voltage sag. The table of preferred test level and durations for voltage dips based on IEC standard 61000-4-11 can be seen on table 2.1.

Both the mentioned standard only consider duration and voltage level as the parameters of voltage sag. Djokic in [11] propose several factors that should also be considered to investigate the characteristic of equipment to voltage sag. It is obvious from his experiment that point on wave of sag affect the behavior of equipment to voltage sag, as shown on Fig. 2.6. This thesis will also investigate the effect of point on wave of sag to induction motor and AC contactors.

Table 2.1 Preferred test level and durations for voltage dips based on IEC 61000-4-11

Class[a]	Test level and durations for volage dips (t_s) (50Hz/60Hz)				
Class 1	Case-by-case according to the equipment requirements				
Class 2	0% during ½ cycle	0% during 1 cycle	70% during 25/30[c] cycles		
Class 3	0% during ½ cycle	0% during 1 cycle	40% during 10/12[c] cycles	70% during 25/30[c] cycles	80% during 250/300[c] cycles
Class X[b]	x	x	X	X	X

a. Classes as per IEC 61000-2-4

b. To be defined by product committee. For equipment connected directly or indirectly to the public network, the levels must not be less severe than Class 2.

c. "25/30 cycles" means "25 cycles for 50Hz test" and "30 cycles for 60Hz test"

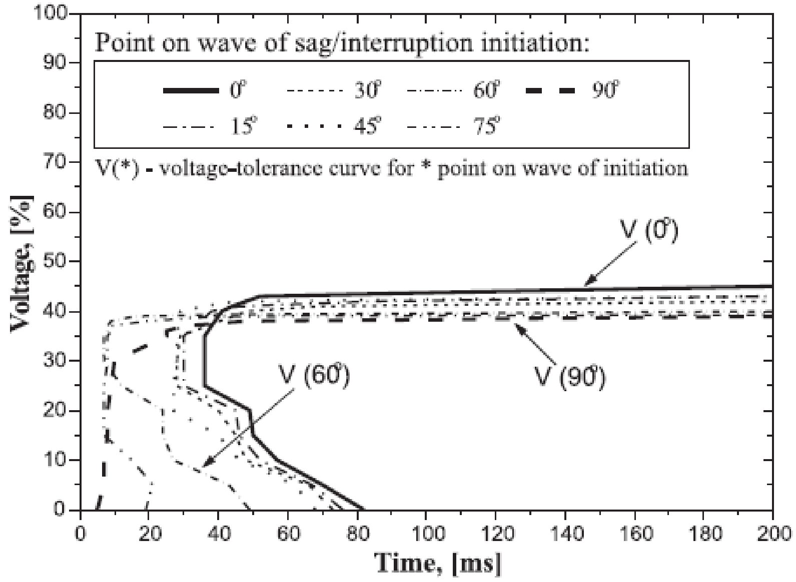


Fig. 2.6 .Effects of point on wave of sag to outage [13]

CHAPTER III

VOLTAGE SAG EXPERIMENTS

An investigation of effects of voltage sag on an induction motor using computer simulation is faster than using experiments. The accuracy of simulation results, however, depends on models and parameters of system and equipment. To confirm models and parameters, the simulation results should be compared with experimental ones. This chapter explains about laboratory experiments which are included in this thesis. Because of equipment limitation, only voltage sag of type B can be experimented in laboratory. Effects of voltage sag of type B on an induction motor were investigated and the results were compared to the simulation.

3.1 Methode of Experiment

The experiment is done in laboratory based on the table 2.1 of preferred test level and durations for voltage dips based on IEC 61000-4-11. After doing the experiment, the expected outcome is making curve similar to CBEMA curve, called sensitivity curve. From experiment, we can get the result look like on Figure 3.1 to be implemented in further result. The experiment is done three times to make sure the accuracy of the result.

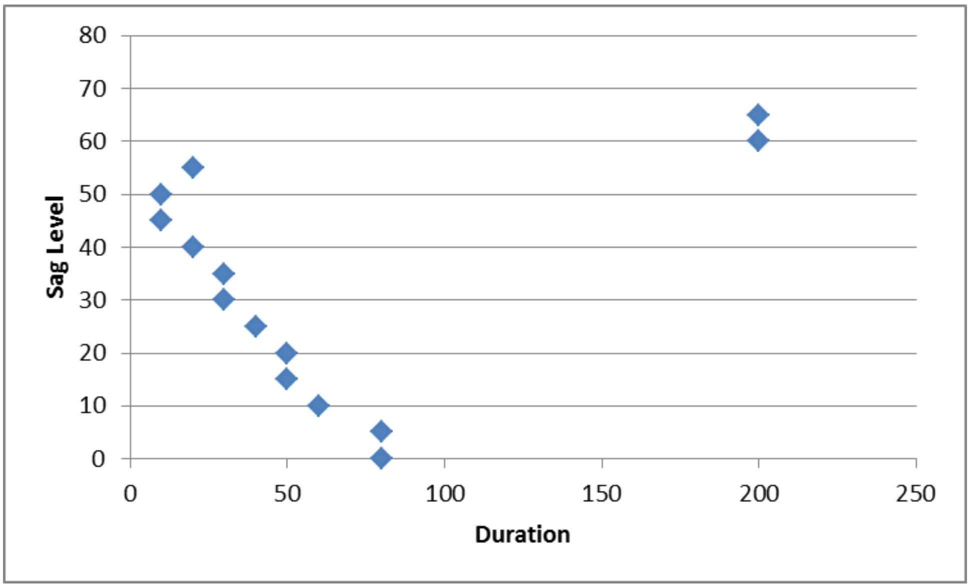


Figure 3.1 Result of Experiment

3.2 Specification of Experiment Tools

The response of induction motor to voltage sag was tested through an experiment using a three-phase squirrel cage induction motor. Its ratings are 50 Hz, 400 V star connected, 1.07 A, 0.37 kW, 1400 rpm. A pendulum machine (0-8 Nm, 0-6000 rpm) was used as a load of the induction motor. In this experiment, a self-designed three-phase voltage sag generator is used. It consists of two parts; main unit and control unit. The main unit is shown in Figure 3.1. Its main function is to switch between normal-voltage and sag-voltage sources at the times specified by the control unit. Therefore, the main unit has three inputs; i.e. normal voltage source, sag voltage source and control signal. The sag voltage source is an auto transformer which can adjust sag level manually. Figure 3.2 shows the control unit. The user can set sag starting time or phase angle, sag duration and period via panel board. The control unit also sends a signal as an external trigger to an oscilloscope for recording waveforms. Because it is still under development, the control unit can manage voltage sag only one phase of voltage. This means that the sag generator can only generate voltage sag of type B. One phase of input voltages was connected to the induction motor via voltage sag generator for producing a voltage sag of type B. The general configuration of this experiment can be seen on Figure 3.3 and Figure 3.4. Phase voltage, torque and speed of the induction motor during a sag event were recorded using a digital oscilloscope (Tektronix TDS2024B) shown in Figure 3.5. A variety of sag duration, sag level, and starting angle phase of voltage is applied to the induction motor for studying impacts of voltage sag on the operation of induction motor.

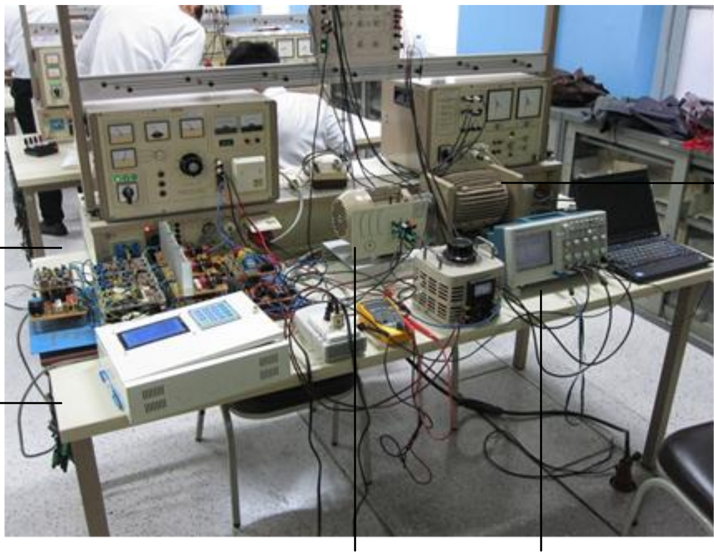


Figure 3.2 General configuration of experiment (photo).

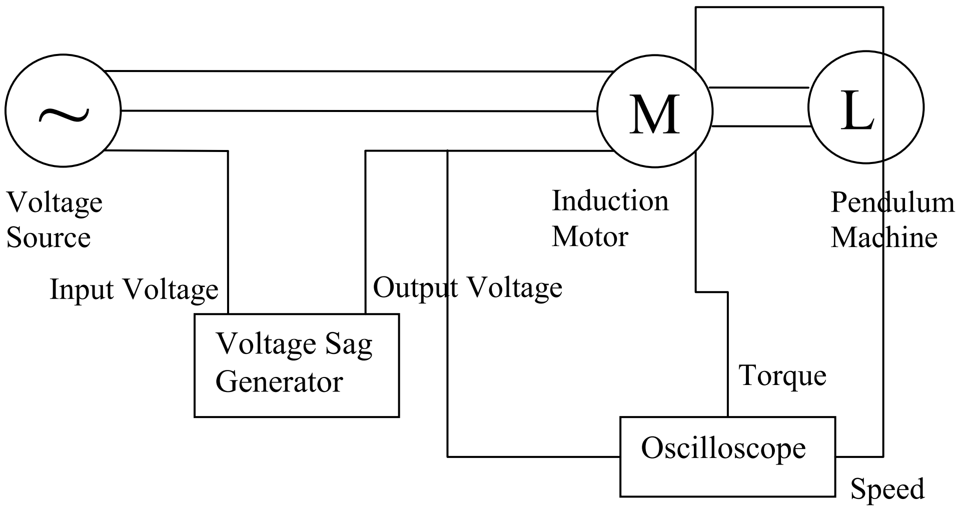


Figure 3.3 General configuration of experiment (diagram).

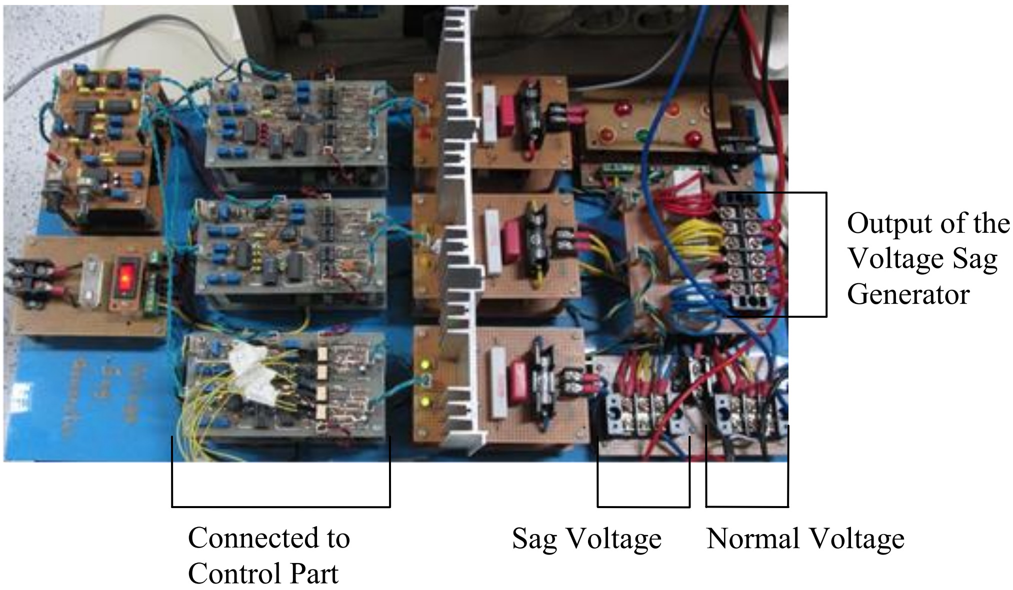


Figure 3.4 Main part of voltage sag generator.

Figure 3.5 Control part of voltage sag generator.

Figure 3.6 Observation of voltage sag using oscilloscope.

The operation of an induction motor can be affected directly by a voltage sag of power supply of the motor. It can be also affected indirectly by a voltage sag of power supply of magnetic contactors in its control parts. The response of a motor contactor to voltage sag was tested through an experiment using a contactor shown in Figure 3.6. Its rated coil voltage is 208-220 V 50 Hz with voltage tolerance of 0.85 – 1.1 times rated coil voltage.

Figure 3.7 Magnetic contactor.

3.3 Experimental Result of Induction Motor

This experiment will apply voltage sag of type B with different sag levels, durations, and starting phase angles. The changes of shaft torque and speed of motor during each voltage sag event were observed using a digital oscilloscope. An example of captured waveforms is shown in Figure 3.7. Channels 1 (middle), 2 (lower) and 3 (upper) display voltage sag, speed and torque of motor, respectively. As seen on the example, the results of all channels can be measured and captured simultaneously. Torque is dropped when a sag event is happened and recovered in a moment after the event. While motor speed has a very slow response, it hardly changes during sag event.

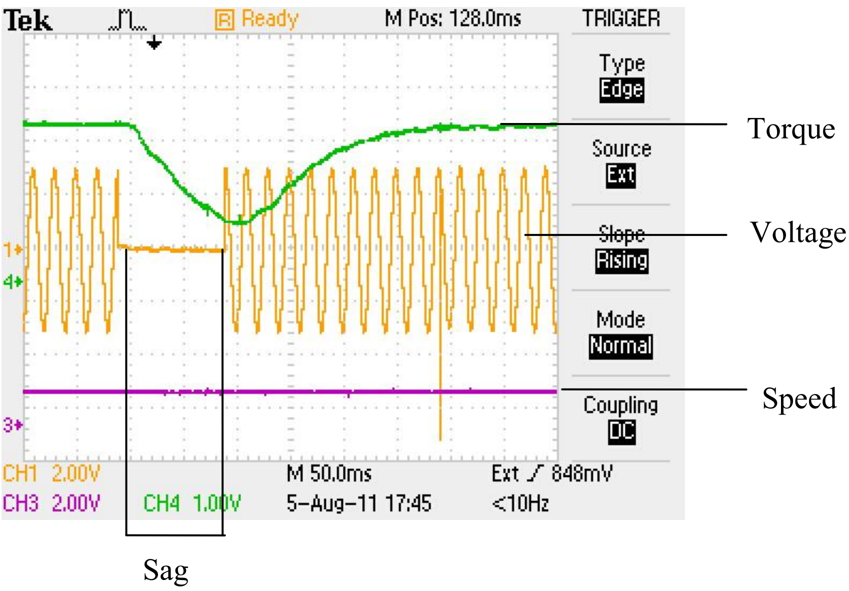


Figure 3.8 Effect of voltage sag to induction motor in oscilloscope.

3.3.1 Voltage Sag Level

Common experiment when testing equipment to voltage sag is varying sag level. In this thesis, the experiment of variation of voltage sag level was done with loaded induction motor. Each voltage sag level was done three times for confirmation. This section shows the data when different sag levels were applied to the induction motor for 100 ms (5 cycles). Figure 3.8 shows the changes of torque with different voltage sag levels. It should be noted that voltage sag started at a different time for each waveform. Table 3.1 shows the variation of torque with voltage sag level. It is obviously seen from data that voltage sag of type B has an effect on torque of the motor. The torque decreases with increasing sag level. This reduction goes with different oscillations. Once the voltage recovers to the normal level, the torque also recovers slowly to the normal torque. On the other hand, it is found that while the torque changes obviously with sag level, there is little change in the speed of motor. These results agree with those observed in a previous research [16] that voltage sag of type B has only an effect on torque of the motor but its speed is not affected by this type of voltage sag.

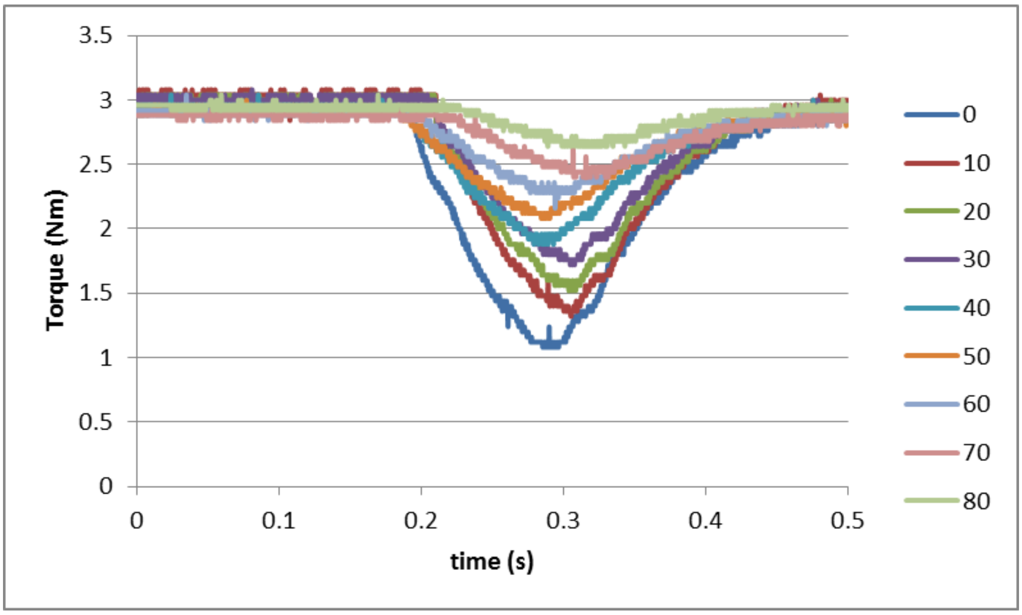


Figure 3.9 Change of torque due to variation of voltage sags of 5 ms.

Table 3.1 Condition of motor during variation of sag levels for 5 ms.

Sag Level	% Loss Torque
0%	63.37
10%	51.56
20%	48.89
30%	46.1
40%	43.32
50%	39.72
60%	32.65
70%	26.5
80%	17.87

3.2.2 Duration of Voltage Sag

Duration of voltage sag is also an important thing that should be considered in voltage sag testing. When the different duration of voltage sag is applied to the motor, the significant difference is also shown by torque. Figure 3.9 shows the difference of torque behavior due to duration changing of voltage sag of 0%.

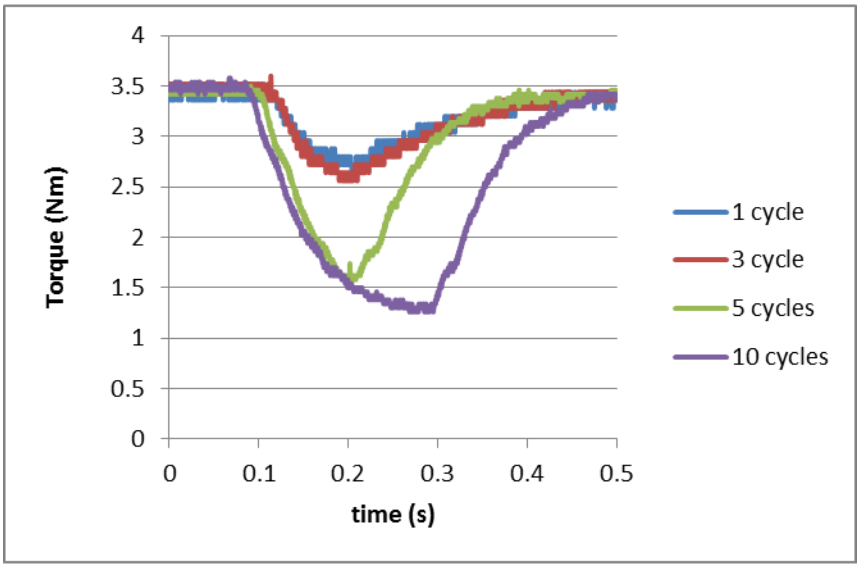


Figure 3.10 Change of torque due to variation of voltage sag duration in 0% sag level.

3.2.3 Phase Angle

Different phase angle of voltage sag starting does not cause significant differences on all value in induction motor as can be seen on Fig. 3.11. The green curve is the torque, the yellow curve is voltage, and purple curve is the current.

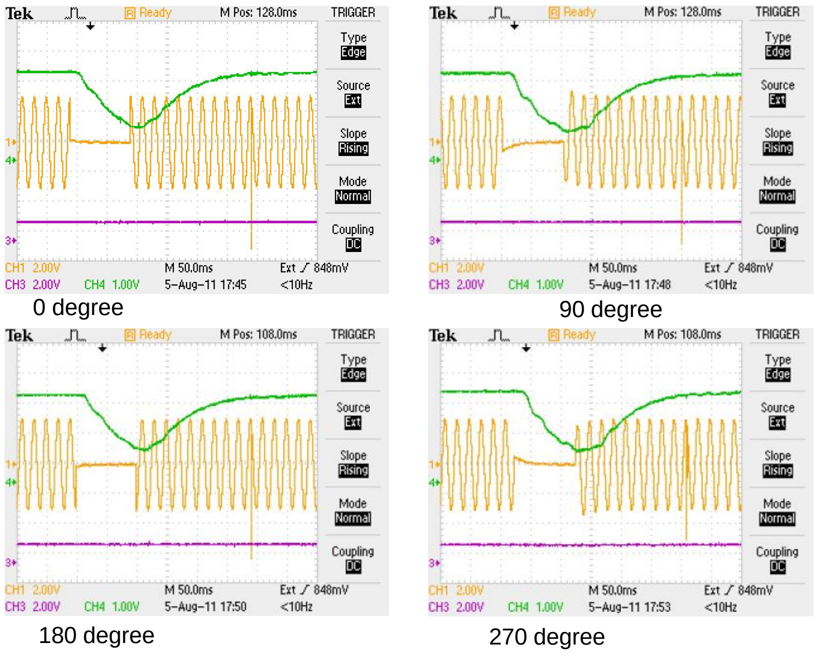


Figure 3.11 Explanation of voltage-tolerance curves

3.3 Magnetic Contactor

The results of contactor testing are presented in the form of voltage-tolerance curves as explained in Fig. 3.12.

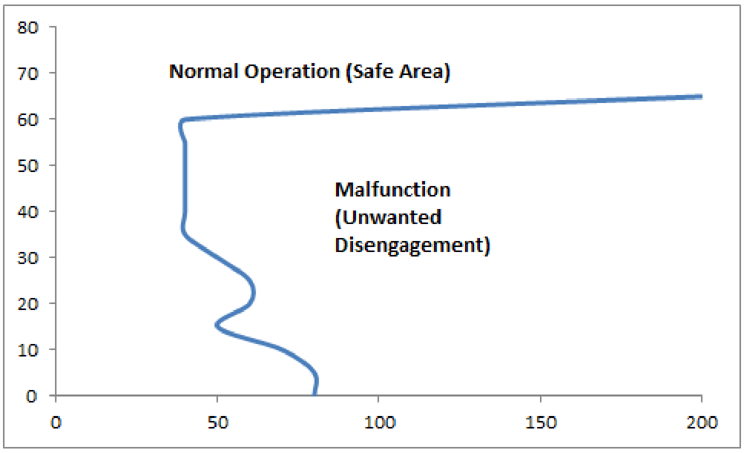


Figure 3.12 Explanation of voltage-tolerance curves

When sag level and duration occur above the curve area, it means that the contactor still work on normal operation. If the sag level and duration occur above the curve line, it means that there is malfunction on the contactor.

The example of data taken from the experiment is shown on table 3.2. This table shows the result of experiment to the contactor when voltage sags is initiated on 0 degree. The “o” mark shows a condition where contactor is still working properly during the sag. The “x” mark shows a condition where there is unwanted disengagement during the sag. From this table, a curve showing voltage tolerance of the contactor can be made.

Table 3.2 Effects of voltage sags to contactor on 0 degree initiation

duration (ms)	Voltage sags (%)												
	0	5	10	15	20	25	30	35	40	45	50	55	60
10	o	o	o	o	o	o	o	o	o	x	x	o	o
20	o	o	o	o	o	o	o	o	x	x	x	x	o
30	o	o	o	o	o	o	x	x	x	x	x	x	o
40	o	o	o	o	o	x	x	x	x			x	o
50	o	o	o	x	x	x	x	x					o
60	o	o	x	x	x	x							o
70	o	o	x	x	x								o
80	x	x	x										
90	x	x											
100	x	x											
110													
120													

From table 3.2, we can create curve by moving the table to curve like Fig. 3. 13.

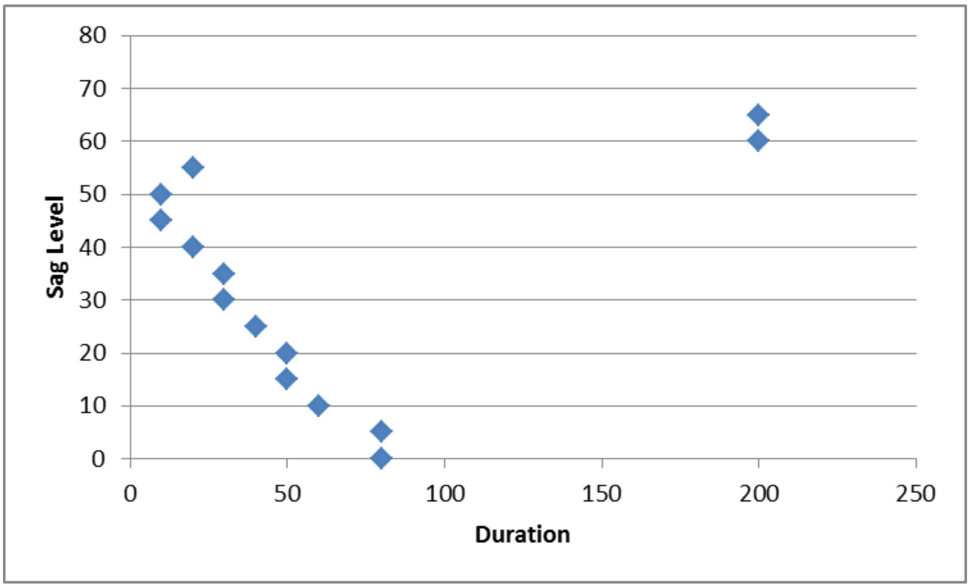


Figure 3.13 Effects of voltage sags to contactor on 0 degree initiation

The detailed test results for contactor Mitsubishi S-N 10 are shown in Fig. 3.14. Fig.3.14 clearly shows the influence of the point on wave of sag initiation on contactor's sensitivity.

It is obviously seen from the figure that different starting phase angle make significant differences to the voltage-tolerance curves. It means, different starting phase angle will affect the working behavior of contactor severely.

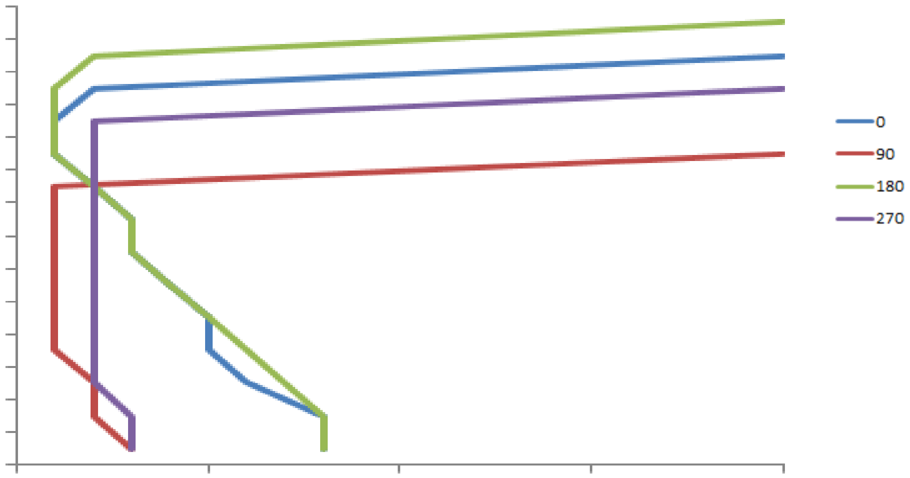


Figure 3.14 Sensivity of magnetic contactor to voltage sags.

CHAPTER IV

VOLTAGE SAG SIMULATION

4.1 Method of Simulation

The method to simulate effects of voltage sag to induction motor will be explained in this chapter. The voltage sag will be generated using voltage sources that connected parallel each phase. Using this simple method, various type of voltage sag can be generated.

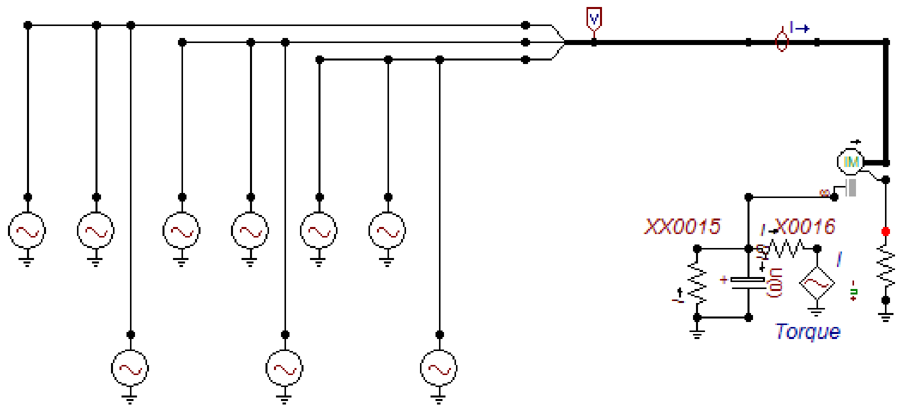


Figure 4.1: Simulation of Voltage Sags to Induction Motor.

After applying various types of voltage sags to induction motor, the different response to each type will be investigated.

4.2 Specification of Simulation Parameter

4.2.1 Induction Motor

The objection of this simulation is to simulate effects of different types of voltage sags to an induction motor. This simulation will be compared to actual experiment using three-phase squirrel cage induction motor ELWE (230/400V, 2.0/1.07 A, 0.37kW, 1,400 rpm, 50 Hz, star connected) connected to pendulum machine (0 to 8 Nm, 0 to 6,000 rpm) as the load.

The simulation will use standard induction motor model using induction motor type UM 3.

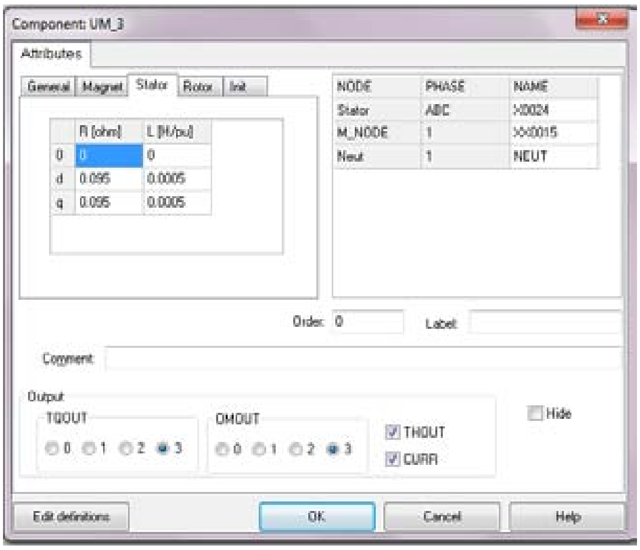


Figure 4.2: Parameters of Induction Motor UM3.

Parameters of this induction motor mode can be calculated using this equivalent circuit:

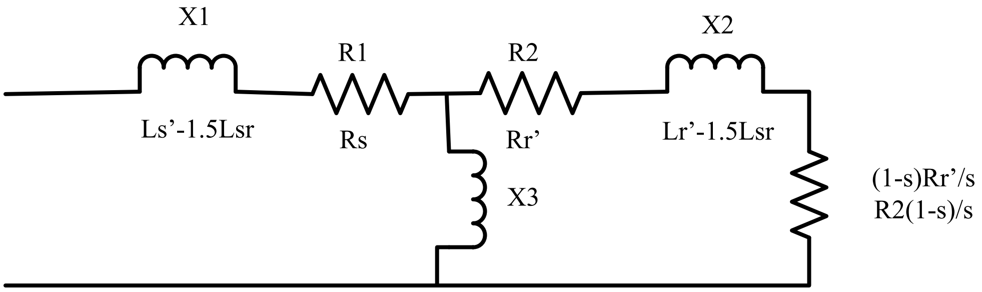


Figure 4.3: Equivalent Circuit of Induction Motor

It is assumed that the nominal voltage V, power P, slip s, efficiency η, power factor $cos\varphi$ and the locked rotor current I_s are known. The power is the "useful" electrical power, that is, the power consumed in the load resistance $R_2(1-s)/s$ of the equivalent circuit. The efficiency η is the electrical efficiency, i.e. the "useful" electrical power divided by the total power taken by the motor.

Note, one has to assume something about X_1, because there are too many unknowns compared with the number of equations. The unknowns are X_1, X_2, X_3, R_1, R_2. Equations can be written for power, efficiency, power factor, and the locked rotor current.

The resistance R_1 is solved first. When the useful power per phase is $P/3$, the losses in R_2 are $(P/3)*s/(1-s)$. The losses in R_1 are equal to I^2R_1. The total power taken by the motor per phase is thus

$$UIcos\varphi = I^2R_1 + \frac{(P/3)}{(1-s)}$$

Where U is the phase to neutral voltage and I is the absolute value of the nominal current. Because $P/3$ is equal to the power taken by the motor times efficiency, $P/3 = \eta\, U\, I\, cos\varphi$, the resistance R_1 is equal to

$$R_1 = \left(\frac{U\cos\varphi}{I}\right)\left(\frac{1-\eta}{1-s}\right)$$

$$R_1 = \left(\frac{230\times 0.67}{1.13}\right)\left(\frac{1-0.8}{1-0.076}\right)$$

$$R_1 = 25.2014\ Ohm$$

The solution of the other impedances is a bit more complicated. Let us first define the "apparent impedance" $R_a + j\,X_a$ as $i = U/(R_a + j\,X_a)$ where i is the nominal complex current of the motor. Because the voltage, power, and another component are known for the motor, the numerical values of the current i and the apparent impedance can be calculated. Equations for the resistance R_a and reactance X_a of the apparent impedance can be derived using the equivalent circuit of the motor, as

$$R_a = R_1 + \frac{R{X_3}^2}{[R^2 + (X_2 + X_3)^2]}\ where\ R = \frac{R_2}{s}$$

$$X_a = X_1 + \frac{[R^2X_3 + X_2X_3(X_2 + X_3)]}{[R^2 + (X_2 + X_3)^2]}$$

Next, R_2 is solved from equations above. After some simplifications and assuming $X_1 = X_2$, an equation is obtained for R, as

$$R(X_3 + X_2 - X_a) = (X_2 + X_3)(R_a - R_1)\ where\ R = \frac{R_2}{s}$$

R is solved from those equation, which gives an equation for X_3, as

$${X_3}^2 = \frac{(R_a - R_1)^2(X_2 + X_3)}{(X_2 + X_3 - X_a) + (X_2 + X_3)(X_2 + X_3 - X_a)}$$

After these calculations, R_1 is known, and the resistance R_2 and the reactances X_1, X_2, X_3 can be expressed as a function of X_2+X_3, which is still unknown. The sum X_2+X_3 must be solved iteratively from the equation for the locked rotor current. This completes the solution of the impedances.

After iteration, the solutions are :

R_2 = 23.8522 Ohm,

X_1= X_2= 5.67493 Ohm = 0.018064 H

X_3= 277.351 Ohm = 0.882834 H

The result of this calculation can be filled in the UM3 of ATPDraw, where R_1 as R_d and R_q of stator, R_2 as R_1 and R_2 of rotor, the reactances $X_1 = X_2$ as L_d and L_q of stator and L_1 and L_2 of rotor, and X_3 as LMUD and LMUQ of magnetization.

4.2.2 Contactor

The contactor can be simulated using R-L-C circuit on EMTP-ATP. The contactor itself is tested using R-L-C meter. Each component of R-L-C can be drawn in ATPDraw as can be seen of figure 4.4 and the result can be seen.

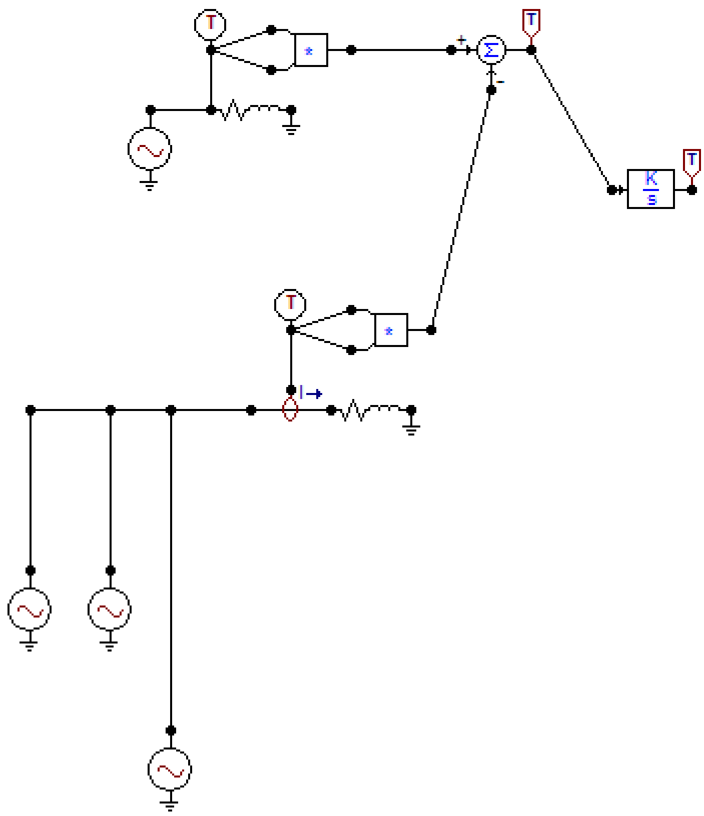


Figure 4.4: Simulating Effects of Voltage Sag on Contactor

The S-N10 contactor is tested using the R-L-C meter and the result of testing can be seen on Table 4.1. The parameter used is the series pair of 50Hz frequency.

Table 4.1 Result of contactor testing using R-L-C meter

Frequency 1 kHz	
L_{series} 1.54435 H	$L_{parallel}$ 1.56232 H
R_{series} 870.147 Ohm	$R_{parallel}$ 1.09650 kOhm
Frequency 50 Hz	
L_{series} 1.59696 H	$L_{parallel}$ 3.76437H
R_{series} 584.961 Ohm	$R_{parallel}$ 1.01540 kOhm

4.3 Result of Simulation

4.3.1 Induction Motor

The main objective of this thesis is to investigate effect of types of voltage sags to induction motor. In this part, the voltage sags will be applied to induction motor. Different types of voltage sag should be produced to model different kinds of faults in power systems. Voltage sag type can be determined by different types of transformer connections in power grid [17]. As mention in chapter II that Voltage sag are divided in to seven groups as type A, B, C, D, E, F and G.

4.3.1.1 Comparison with Experiment

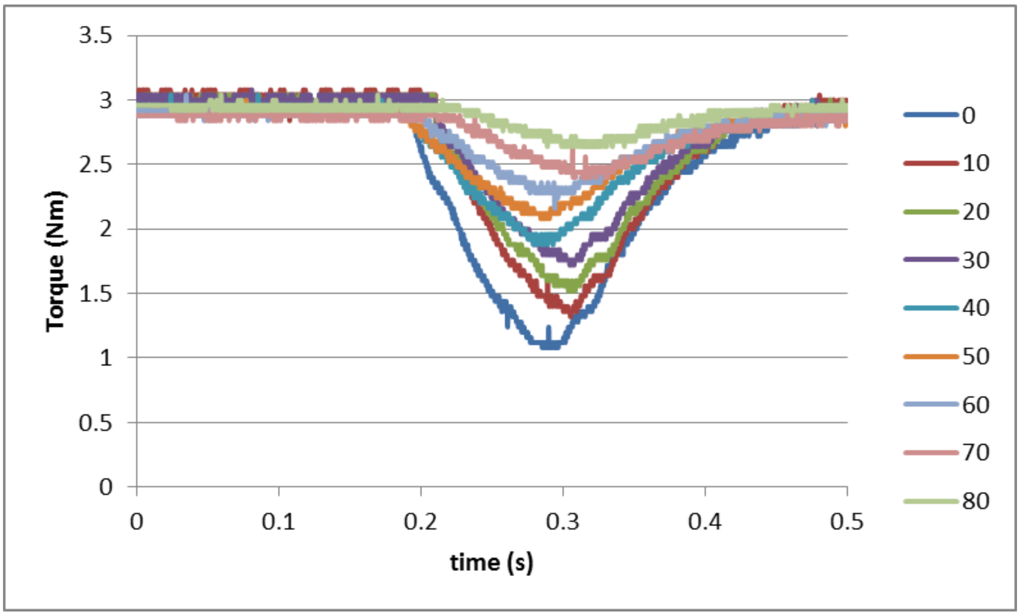


Figure 4.5 Change of Torque on Changing Sag Level Type B

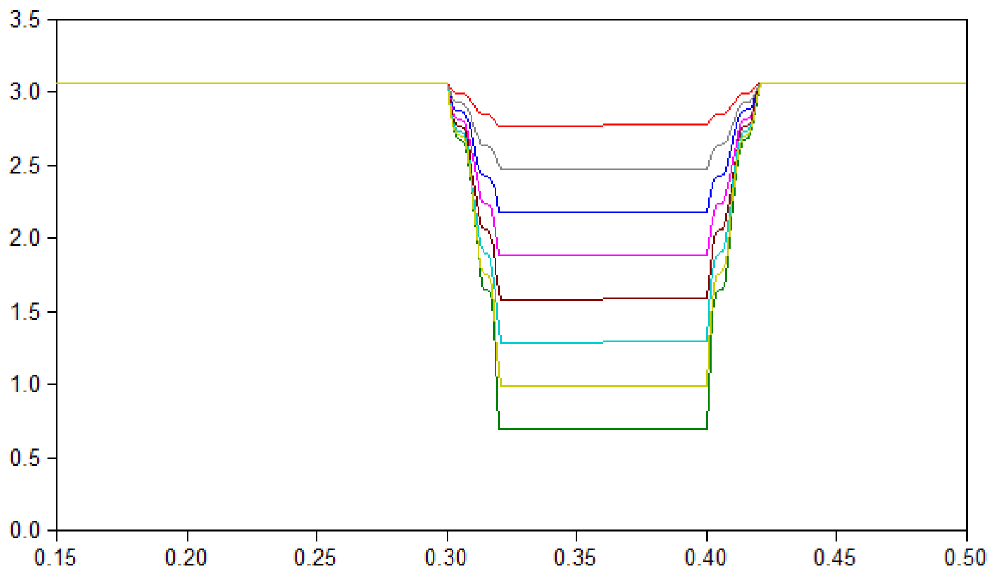


Figure 4.6 Change of Torque on Changing Sag Level Type B

As stated on Chapter III that we can only generate voltage sags type B due to the equipment's limitation. The result of voltage sags type B is notably seen on the change of torque due to sags. We can see from figure 4.5 and figure 4.6 that it has similar behavior between experiment and simulation. So we can conclude that the result of simulation is similar with the experiment.

4.3.1.2 Result of Type A

Sag type A is balanced. All phasors drop the same amount in magnitude. They can be defined by

$$\overline{V_a} = hV$$

$$\overline{V_b} = -\frac{1}{2}hV - j\frac{3}{2}hV$$

$$\overline{V_c} = -\frac{1}{2}hV + j\frac{3}{2}hV$$

where h is the sag magnitude or depth ($0 \leq h \leq 1$).

Selected result of this type is when the motor is applied with 10% voltage sags for 5 cycles. The speed of motor is shown on Figure 4.7. We can see that when sag occurs, the speed will swing between 1800 rpm to 1200 rpm. After the voltage sag ends, it will swing again and return to normal speed.

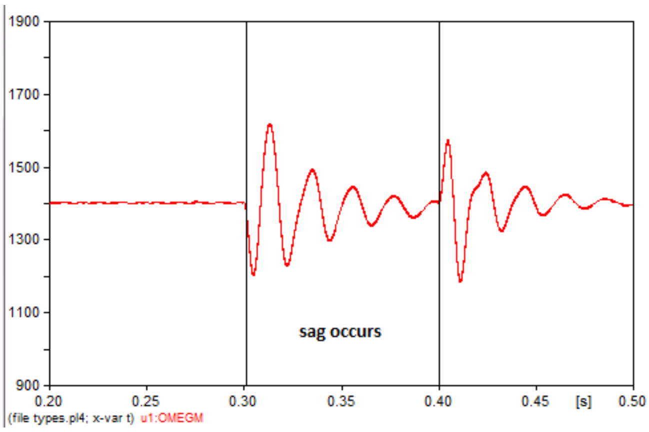


Figure 4.7: Motor speed on Voltage Sag Type A

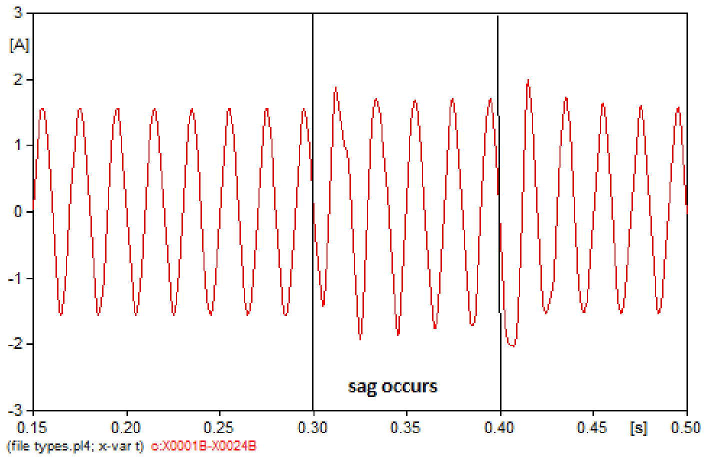


Figure 4.8 Phase b Current on Voltage Sag Type A

On figure 4.6, we can see that when sag occurs, the current will slightly increase for 10% after the sag occurs and ends. And on figure 4.8 we can observe that torque will also swing into maximum 4.7 Nm when sag occurs and it will stall into 2 Nm when sag ends.

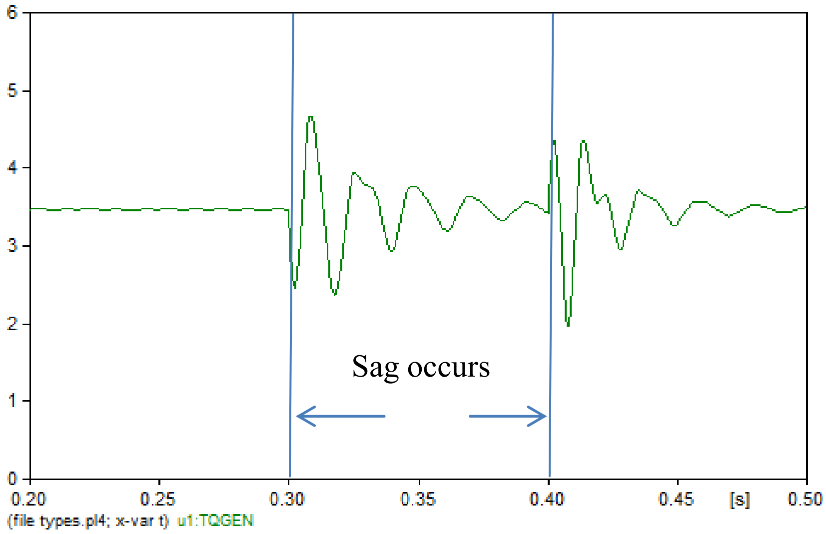


Figure 4.9 Torque of motor on Voltage Sag Type A

4.3.1.3 Result of Type B

For sag type B, only one phasor drops in magnitude. They can be defined by

$$\overline{V_a} = hV$$

$$\overline{V_b} = -\frac{1}{2}V - j\frac{3}{2}V$$

$$\overline{V_c} = -\frac{1}{2}V + j\frac{3}{2}V$$

where h is the sag magnitude or depth ($0 \leq h \leq 1$).

Selected result of this type is when the motor is applied with 10% voltage sags for 5 cycles. The speed of motor is shown on Figure 4.10. We can see that when sag occurs, the speed will slightly swing. After the voltage sag ends, it will swing again and return to normal speed.

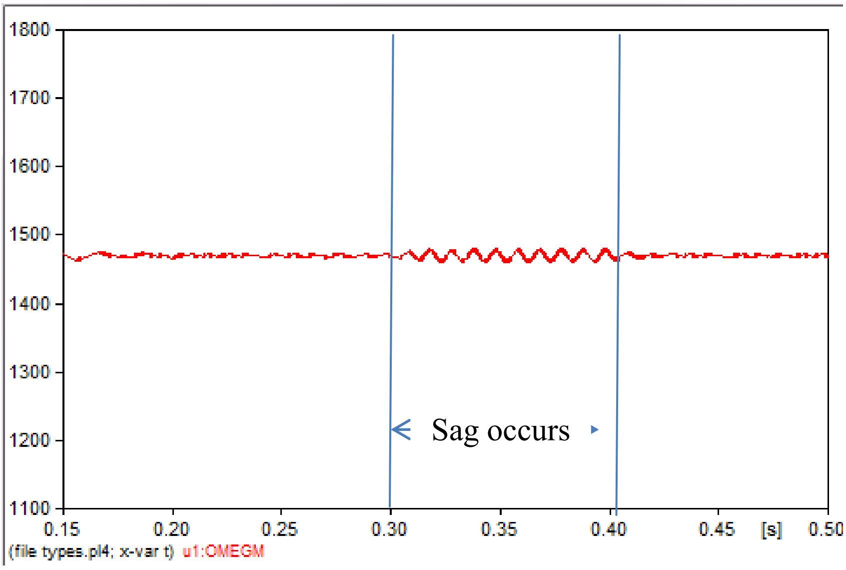


Figure 4.10: Motor speed on Voltage Sag Type B

On figure 4.11, we can see that when sag occurs, the current not show any particular changes. And on figure 4.12 we can observe that torque will slightly decrease into 2.8 Nm when sag occurs.

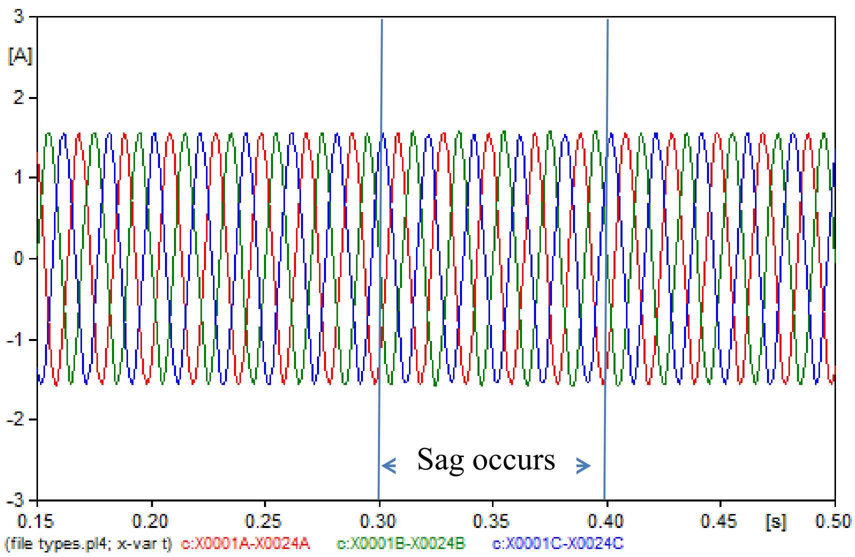


Figure 4.11 Current on Voltage Sag Type B

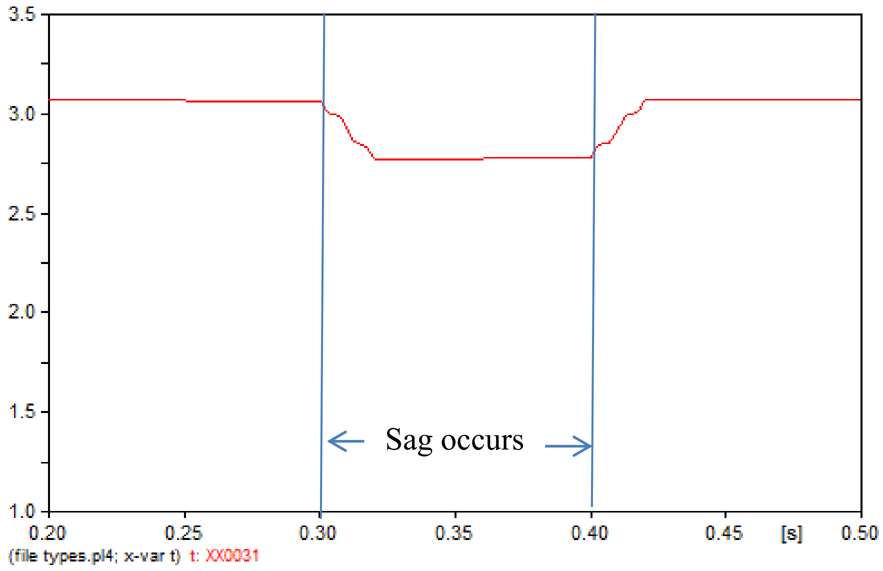


Figure 4.12 Torque of motor on Voltage Sag Type B

4.3.1.4 Result of Type C

For sag type C, Two phasors drop in magnitude and there are phase shift on this phase. This is one kind of unbalanced sags. They can be defined by

$$\overline{V_a} = V$$

$$\overline{V_b} = -\frac{1}{2}V - j\frac{3}{2}hV$$

$$\overline{V_c} = -\frac{1}{2}V + j\frac{3}{2}hV$$

where h is the sag magnitude or depth ($0 \le h \le 1$).

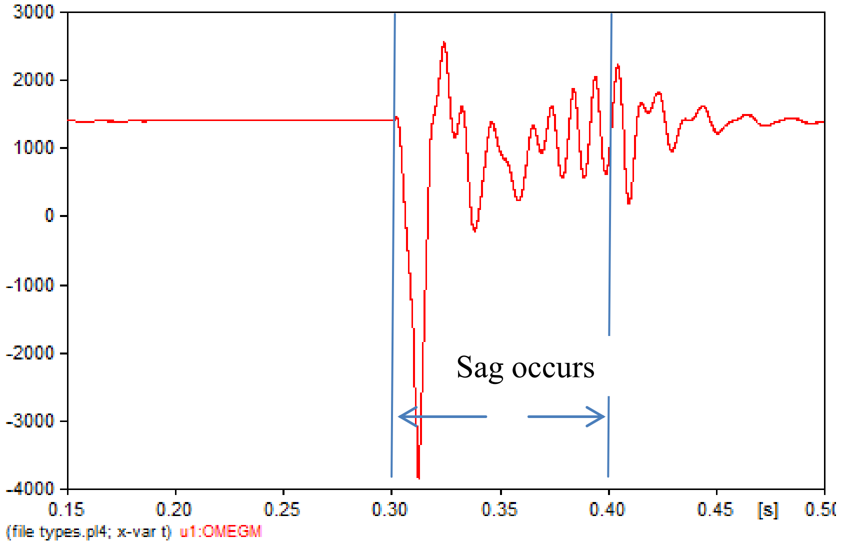


Figure 4.13: Motor speed on Voltage Sag Type C

Selected result of this type is when the motor is applied with 10% voltage sags for 5 cycles with 10 degrees of phase shift. The speed of motor is shown on Figure 4.13. We can see that when sag occurs, the speed will stall right after the sag occurs. After the voltage sag ends, it will swing again and return to normal speed.

On figure 4.14, we can see that when sag occurs, the current on one phase will increase for 370% after the sag occurs and return to normal condition after sag ends. And on figure 4.15 we can observe that torque will also swing into maximum 25.3 Nm when sag occurs and it will stall into -12.7 Nm when sag ends.

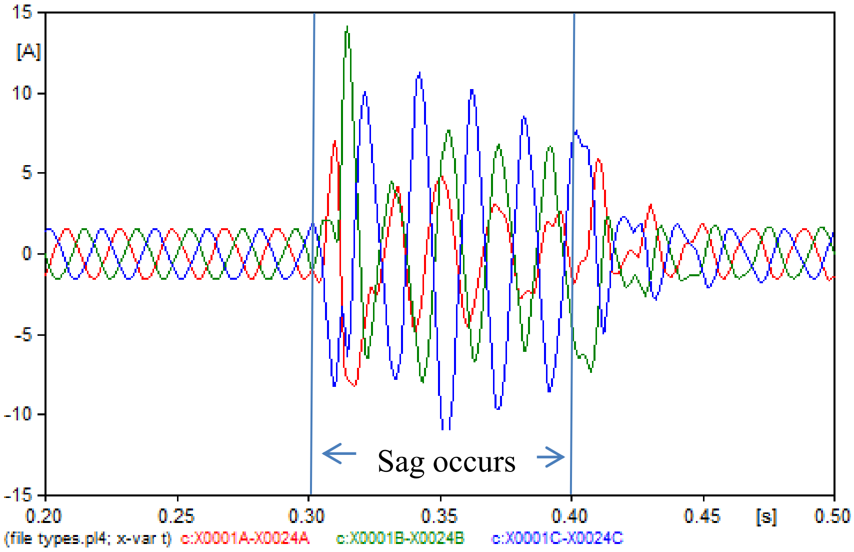


Figure 4.14 Current on Voltage Sag Type C

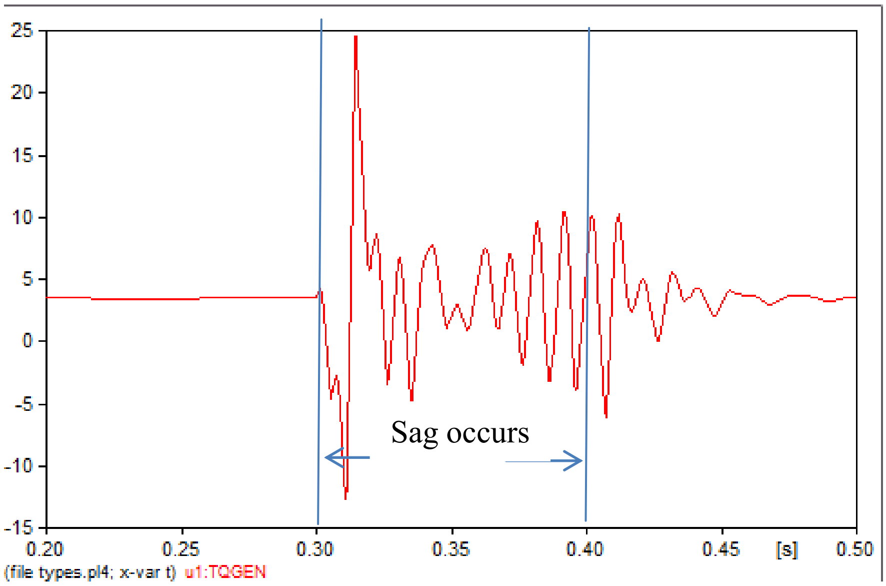


Figure 4.15 Torque of motor on Voltage Sag Type C

4.3.1.5 Result of Type D

For sag type D, three phasors drops in magnitude while two phasors will have phase shift. This is one kind of unbalanced sags. They can be defined by

$$\overline{V_a} = V$$

$$\overline{V_b} = -\frac{1}{2}hV - j\frac{3}{2}V$$

$$\overline{V_c} = -\frac{1}{2}hV + j\frac{3}{2}V$$

where h is the sag magnitude or depth ($0 \leq h \leq 1$).

Selected result of this type is when the motor is applied with 10% voltage sags for 5 cycles with 10 degrees of phase shift. The speed of motor is shown on Figure 4.16. We can see that when sag occurs, the speed will swing between 1625 rpm to 1126 rpm. After the voltage sag ends, it will swing again and return to normal speed.

On figure 4.17, we can see that when sag occurs, the current on one phase will decrease for about 37% and another two phases will increase for 27% when the sag occurs. And on figure 4.18 we can observe that torque will also swing into maximum 5.3 Nm when sag occurs and it will stall into 1.7 Nm when sag ends.

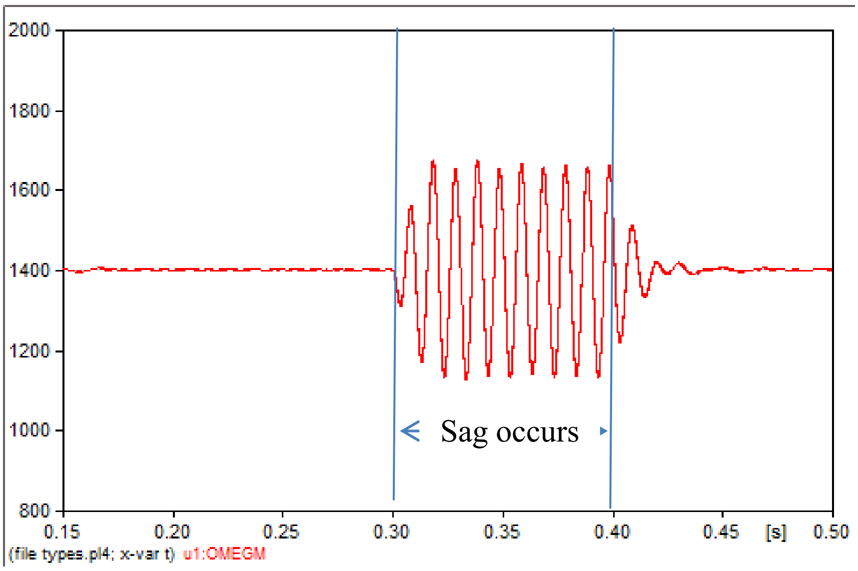


Figure 4.16: Motor speed on Voltage Sag Type D

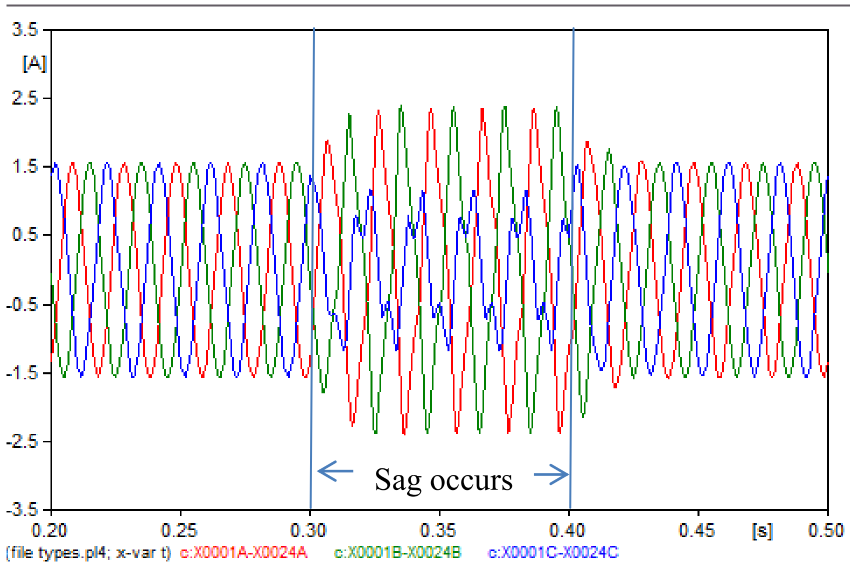


Figure 4.17 Current on Voltage Sag Type D

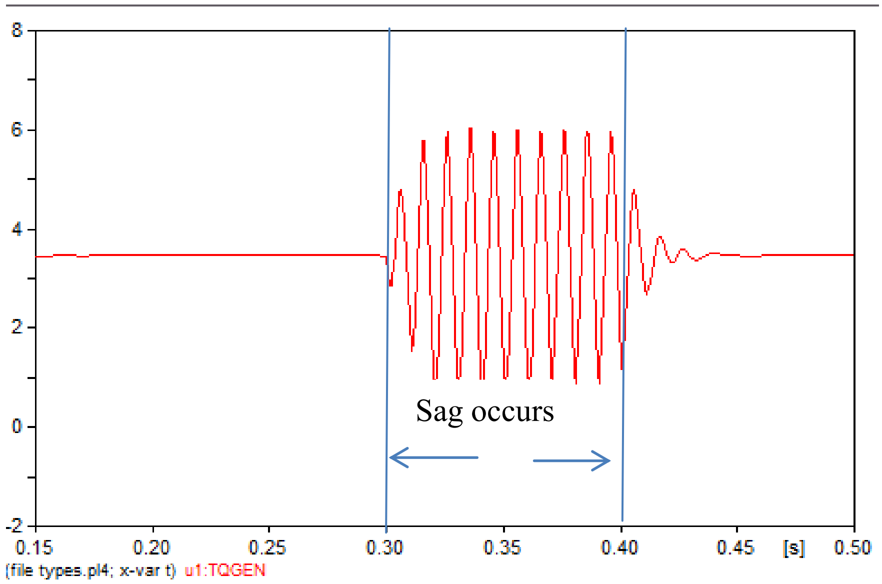


Figure 4.18 Torque of motor on Voltage Sag Type D

4.3.1.6 Result of Type E

For sag type E, Two phasors drop in magnitude. This is one kind of unbalanced sags. They can be defined by

$$\overline{V_a} = V$$

$$\overline{V_b} = -\frac{1}{2}hV - j\frac{\sqrt{3}}{2}hV$$

$$\overline{V_c} = -\frac{1}{2}hV + j\frac{\sqrt{3}}{2}hV$$

where h is the sag magnitude or depth ($0 \leq h \leq 1$).

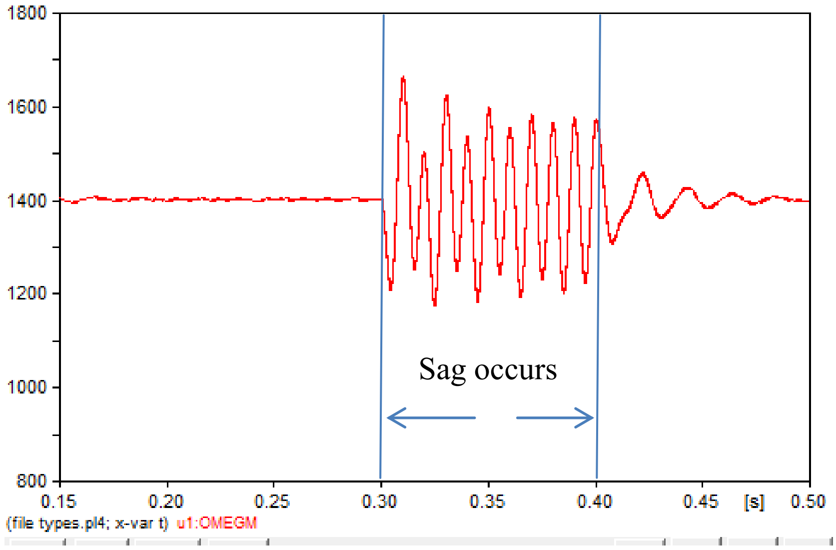


Figure 4.18: Motor speed on Voltage Sag Type E

Selected result of this type is when the motor is applied with 10% voltage sags for 5 cycles. The speed of motor is shown on Figure 4.19. We can see that when sag occurs, the speed will swing between 1700 rpm to 1200 rpm. After the voltage sag ends, it will swing again and return to normal speed.

On figure 4.20, we can see that when sag occurs, the current on one phase will increase for 23% after the sag occurs. And on figure 4.21 we can observe that torque will also swing into maximum 5.3 Nm when sag occurs and it will stall into 1.7 Nm when sag ends.

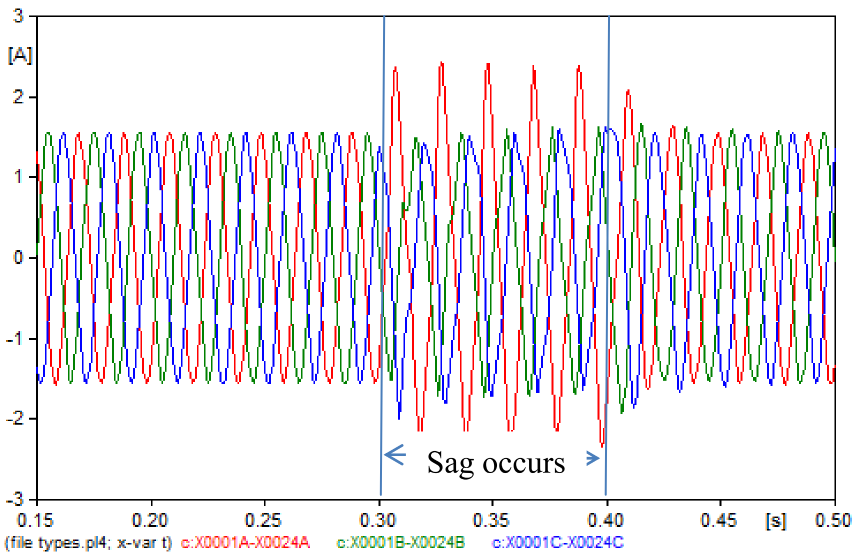


Figure 4.20 Current on Voltage Sag Type E

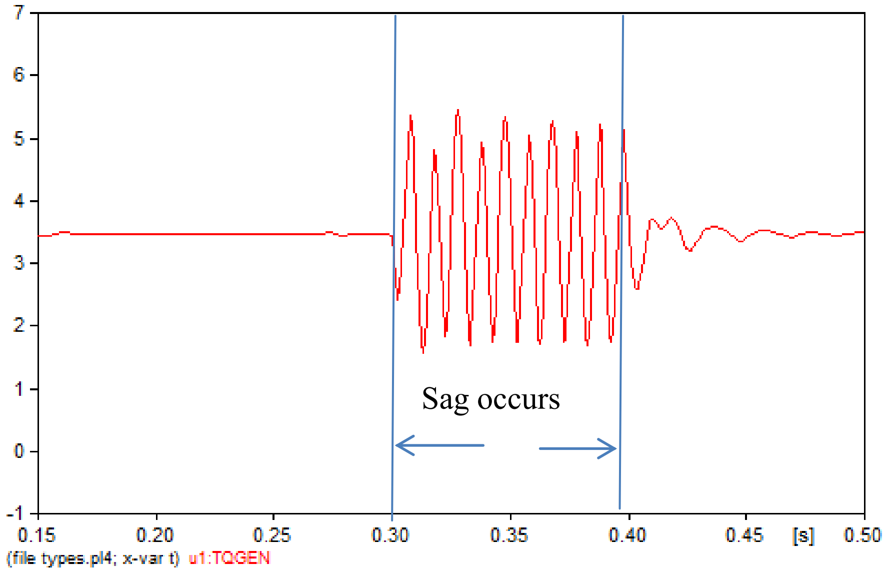


Figure 4.21 Torque of motor on Voltage Sag Type E

4.3.1.7 Result of Type F

For sag type F, three phasors drop in magnitude and two phasors will change the phase. This is one kind of unbalanced sags. They can be defined by

$$\overline{V_a} = V$$

$$\overline{V_b} = -\frac{1}{2}hV - j\frac{1}{\sqrt{12}}(2+h)V$$

$$\overline{V_c} = -\frac{1}{2}hV + j\frac{1}{\sqrt{12}}(2+h)V$$

where h is the sag magnitude or depth ($0 \le h \le 1$).

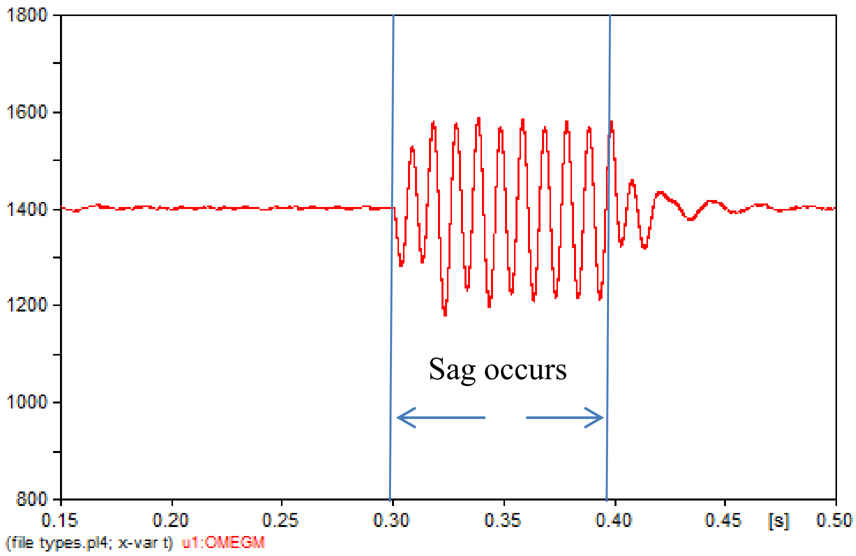


Figure 4.22: Motor speed on Voltage Sag Type F

Selected result of this type is when the motor is applied with 10% voltage sags for 5 cycles with 10 degrees of phase shift. The speed of motor is shown on Figure 4.22. We can see that when sag occurs, the speed will swing between 1596 rpm to 1145 rpm. After the voltage sag ends, it will swing again and return to normal speed.

On figure 4.23, we can see that when sag occurs, the current on one phase will decrease for about 31% and another two phases will increase for 43% when the sag occurs. And on figure 4.24 we can observe that torque will also swing into maximum 5.3 Nm when sag occurs and it will stall into 1.7 Nm when sag ends.

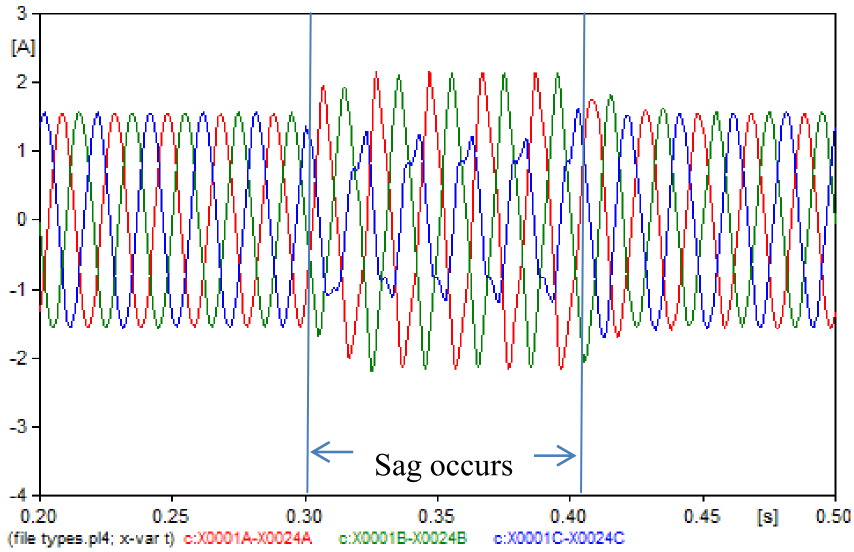


Figure 4.23 Current on Voltage Sag Type F

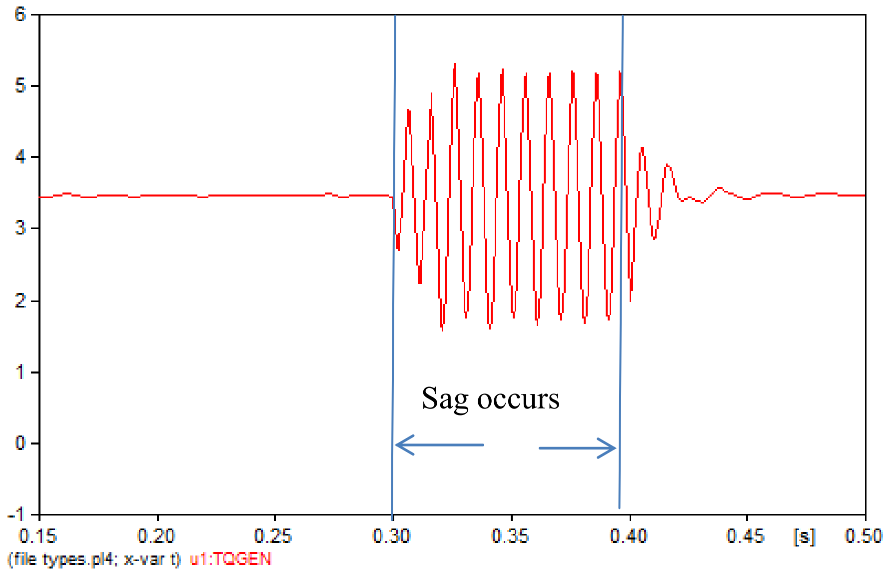


Figure 4.24 Torque of motor on Voltage Sag Type F

4.3.1.8 Result of Type G

For sag type G, three phasors drop in magnitude and two phasors will change the phase. This is one kind of unbalanced sags. They can be defined by

$$\overline{V_a} = \frac{1}{3}(2+h)V$$

$$\overline{V_b} = -\frac{1}{6}(2+h)V - j\frac{\sqrt{3}}{2}hV$$

$$\overline{V_c} = -\frac{1}{6}(2+h)V + j\frac{\sqrt{3}}{2}hV$$

where h is the sag magnitude or depth ($0 \leq h \leq 1$).

Selected result of this type is when the motor is applied with 10% voltage sags for 5 cycles with 10 degrees of phase shift. The speed of motor is shown on Figure 4.25. We can see that when sag occurs, the speed will stall right after the sag occurs. After the voltage sag ends, it will swing again and return to normal speed.

On figure 4.26, we can see that when sag occurs, the current on one phase will increase for 365% after the sag occurs and return to normal condition after sag ends. And on figure 4.27 we can observe that torque will also swing into maximum 24.3 Nm when sag occurs and it will stall into -11.7 Nm when sag ends.

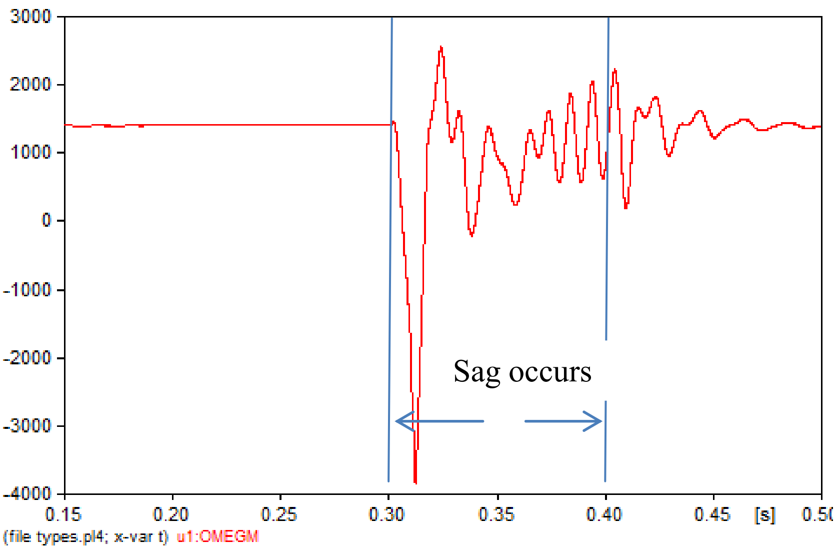


Figure 4.25: Motor speed on Voltage Sag Type G

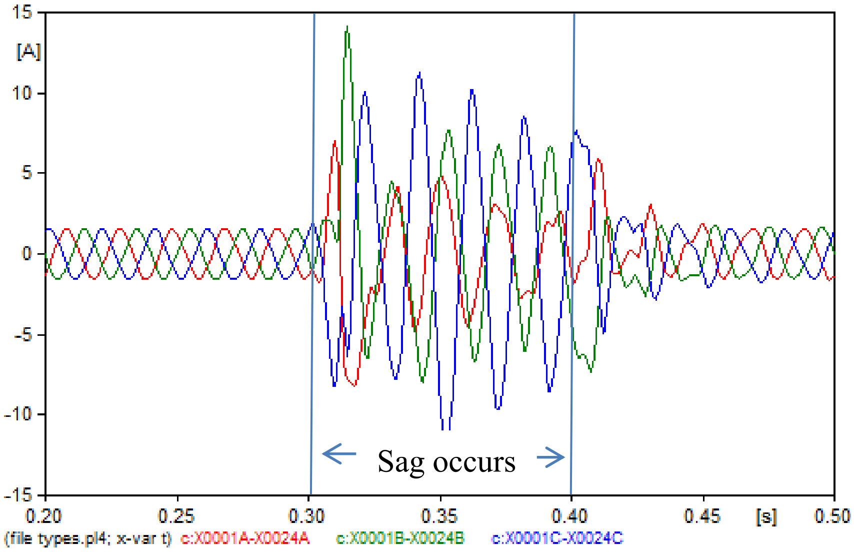


Figure 4.26 Current on Voltage Sag Type G

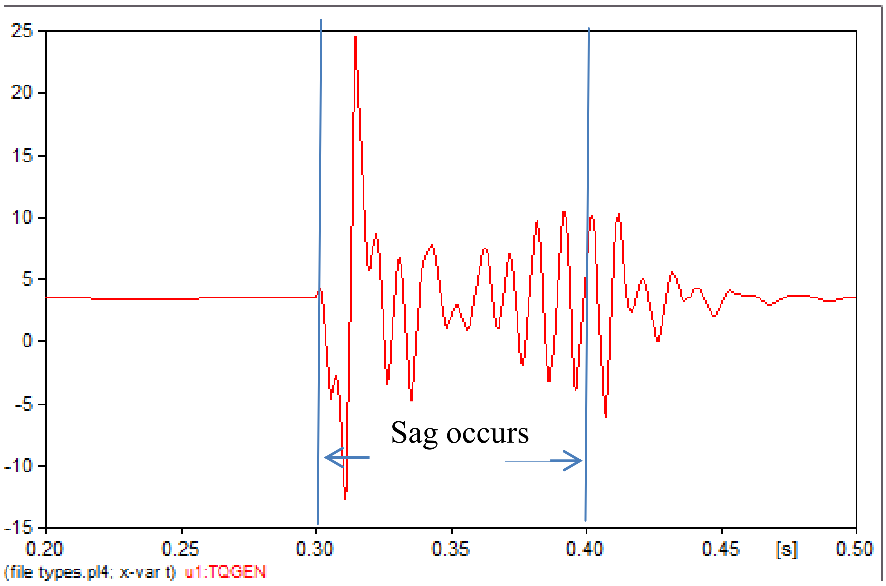


Figure 4.27 Torque of motor on Voltage Sag Type G

4.3.1.9 Analysis

To compare the severity of the different sags types, it is necessary to measure the distance between sag types under same condition. In this simulation, all of sag types are set on 10% level loss of sag for five cycles.

As the motor torque is directly proportional to the square of the applied voltage, therefore, as the supply voltage to the induction motor decreases, the motor torque will decrease drastically. The speed also decreases with a decrease in torque. Depending on the depth and the duration of the voltage sag, the motor speed may recover to its normal value as the voltage amplitude recovers. Otherwise, the motor speed may slow down and the torque exerted by the motor could not supply the load.

Comparison of effects of severity by voltage sags can be made by comparison of corresponding graphs. For example, sags type A seems to be more severe than sags type B as regards current peaks. The value needed to obtain a specific current peak in a sag type A is higher than in a sag type B.

We can also see that voltage sag type A which is symmetrical, and the single-phase voltage sags type B have different result. The transients of unsymmetrical sags are very different from the symmetrical ones. They are sensitive to the fault and recovery voltage instants. And among the unsymmetrical sags, type B produces lower current, torque peaks, and speed loss.

Most of the faults on the utility transmission and distribution systems are single line-to-ground faults. These kind of faults are the most common cause of voltage sags for industrial customers. This will cause voltage sag type B that is most common in electrical power system. We can see that this kind of sag produce less severe effect on induction motor.

Due to similar condition of sags, types C and G present identical effects on the induction machine for voltage sags with the same depth and duration. The reason for this is that they have the same positive-sequence and negative-sequence voltage. This is particularly most severe voltage sag type that can affect the machine mechanically if happen in longer time.

Due to similar condition also, types D and F present identical effects on induction machine for voltage sags. There are current imbalance when sag occurs and machine speed and torque will swing.

For type E, there is some time needed to stabilize torque and speed after sag ends.

We can see from experiment from chapter 3 that only voltage sag type B can be generated. Unfortunately, voltage sag type B has least severe effect to induction motor. It means, it is quite difficult to confirm all the effects of every type of voltage sag to induction motor.

4.3.2 Contactor

As the simulation for the contactor, simulation is used to see the different behavior of integral square of current from R-L-C component. When we see different behavior such as mentioned on the table, we can conclude that there will be unwanted disengagement of contactor. Current that flow in that component will be subtracted by normal voltage without sag. Thus, the result of that subtraction will be integer to see the break level of the current. By observing the level of integration, we can see the unwanted disengagement on the contactor.

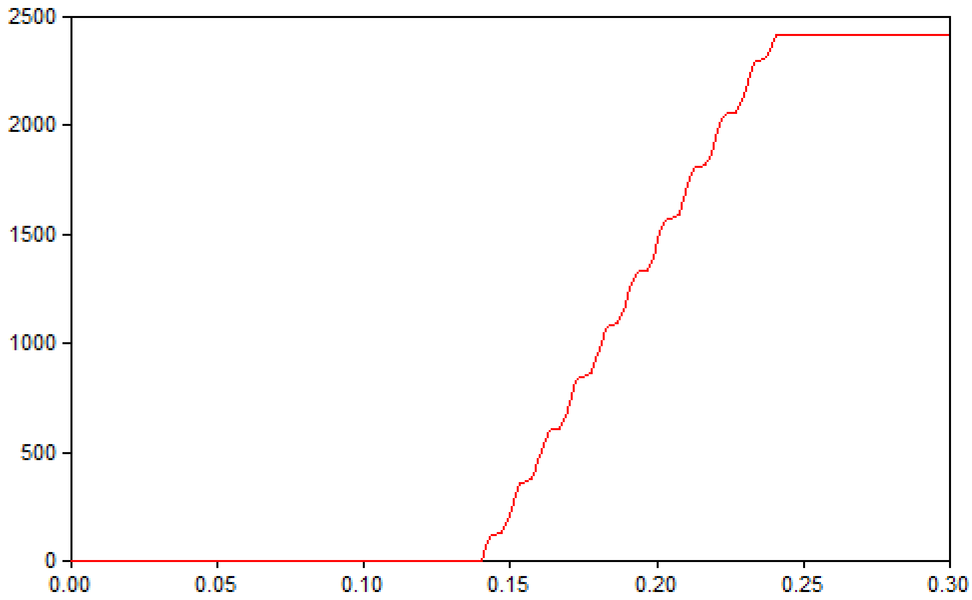


Figure 4.28 Integration of Current when Sag Happen

Table 4.2 shows one of results of experiment of contactor. And table 4.3 shows the result of simulation. Comparing both tables, we can see that the result of simulation is particularly similar to the experiment.

Table 4.2 Result of Contactor Experiment for 0 degree phase angle

duration (ms)	Voltage sags (%)												
	0	5	10	15	20	25	30	35	40	45	50	55	60
10	o	o	o	o	o	o	o	o	o	x	x	o	o
20	o	o	o	o	o	o	o	o	x	x	x	x	o
30	o	o	o	o	o	o	x	x	x	x	x	x	o
40	o	o	o	o	o	x	x	x	x			x	o
50	o	o	o	x	x	x	x	x					o
60	o	o	x	x	x	x							o
70	o	o	x	x	x								o
80	x	x	x										
90	x	x											
100	x	x											

From the result of Table 4.3, we can conclude the result of threshold by comparing the experiment and simulation.

Table 4.3 Result of Contactor Simulation for 0 degree phase angle

duration (ms)	Voltage sags (%)												
	0	5	10	15	20	25	30	35	40	45	50	55	60
10	241.9	241.4	239.6	236.6	232.3	226.9	220.2	212.4	203.3	193.0	181.5	168.8	154.9
20	484.0	482.8	479.2	473.1	464.6	453.8	440.4	424.7	406.6	386.0	363.0	337.6	309.8
30	726.0	724.2	718.7	709.7	697.0	680.6	660.7	637.1	609.8	579.0	544.5	506.4	464.6
40	967.6	965.6	958.4	946.2	929.3	907.5	880.9	849.4	813.1				619.5
50	1209.5	1207.0	1198.0	1182.8	1161.6	1134.4	1101.1	1061.8					774.4
60	1451.4	1448.4	1437.5	1419.3	1393.9	1361.3							929.3
70	1693.3	1689.8	1677.1	1655.9	1626.2								1084.2
80	1935.2	1931.2	1916.7										
90	2177.1	2172.6											
100	2419.0	2414.0											

CHAPTER V

CONCLUSIONS

Voltage sags due to fault in high voltage system can result in the operation of induction motor in low voltage system. Unsymmetrical faults lead to voltage sags, over motor current with high distortion and fluctuation of torque and speed of motor. The increasing level of fault resistance will reduce the effects of voltage sags on induction motor. Different cases of short circuit have been introduced to the system. It is obvious that every case has its own unique characteristic.

As previously implied that common experiment when testing equipment to voltage sag is varying sag level. Different behavior of voltage sag level to each component is observed. As observed in previous research that effect of voltage sag type B is usually only affect torque of the motor. Experiment of variation of voltage sag level is done with full loaded induction motor. Speed of motor and the current itself is not affected by this type of voltage sag.

Comparison of effects of severity by voltage sags can be made by comparison of corresponding graphs.

- Voltage sag type A which is symmetrical, and the single-phase voltage sags type B have different result. The transients of unsymmetrical sags are very different from the symmetrical ones. They are sensitive to the fault and recovery voltage instants. And among the unsymmetrical sags, type B produces lower current, torque peaks, and speed loss.
- Due to similar condition of sags, types C and G present identical effects on the induction machine for voltage sags with the same depth and duration. The reason for this is that they have the same positive-sequence and negative-sequence voltage. This is particularly most severe voltage sag type that can affect the machine mechanically if happen in longer time.
- Due to similar condition also, types D and F present identical effects on induction machine for voltage sags. There are current imbalance when sag occurs and machine speed and torque will swing.
- For type E, there is some time needed to stabilize torque and speed after sag ends.

Sensitivity of induction motor is ideally drawn using sensitivity chart. Because of the limitation of voltage sag experiment, the definition of fail for induction motor experiment is still hard to achieve.

The result from this experiment can be used for industry to plan a better protection to induction motor, especially if there is voltage sag type C and G occur. The minimum cost because of mechanical effect is expected.

In the future, voltage sag generator can be developed to generate all kind of voltage sag type so that the effect of every type of voltage sag using simulation model can be confirmed precisely. Voltage sag type B has least severe effect to induction motor so that it is quite difficult to confirm with the model.

But in this experiment, character of AC contactor to sags are confirmed. It means, to prevent any further damage to induction motor because of voltage sags, every induction motor should be work together with AC contactor.

REFERENCES

[1] IEEE Std. 1159–1995, Recommended Practice for Monitoring Electric Power Quality, IEEE, 1995.

[2] IEC 61000-4-11, Testing and measurement techniques – Voltage dips, short interruptions and voltage variations immunity tests. IEC, 2004.

[3] IEEE, Voltage Sag Indices, Draft 6 – working document for IEEE P1564, January 2004.

[4] M.F. McGranaghan, D.R. Mueller, and M.J. Samotyj. Voltage sags in industrial systems. IEEE Trans. on Industry Applications 29 (March/April 1993) : 397-403.

[5] J. Gocalves, J. Baptista, L. Neves, and F.T. Oliveira. Simulation of the effect of voltage transients on an induction motor with ATP/EMTP, International Conference on Renewable Energies and Power Quality 2009 pp.63-69, Bilbao:EHU, 2009.

[6] Math H.J. Bollen. Understanding Power Quality Problems. Voltage Sags and Interruptions. New York:IEEE Press, 2000.

[7] S.Z. Djokic, K. Stockman, J.V. Milanovic, J.J.M. Desmet, and R.Belmans. Sensitivity of AC adjustable speed drives to voltage sags and short interruptions. IEEE Trans. on Power Delivery 20 (January 2005) : 494-499.

[8] J.A Martinez, and J.M. Arnendo. Voltage Sag Analysis Using an Electromagnetic Transients Program. IEEE Power Engineering Society Winter Meeting 2 (1993) : 1135-1140.

[9] F. Córcoles and J. Pedra. Algorithm for the study of voltage sags on induction machines. IEEE Trans. Energy Conversion. 14 (December 1999) : 959–968.

[10] L. Guasch, F. Córcoles, and J. Pedra. Effects of unsymmetrical voltage sag types E, F, and G on induction motors. Int. Conf. Harmonics Quality Power pp.796-803, USA, 2000.

[11] G. T. Heydt. Electric Power Quality. Scottsdale, AZ: Starts in a Circle, 1991.

[12] D. Dour, and P. Lim. Resolving Voltage Quality Problems with AC Induction Motors. USA: Springler 2005.

[13] S.Z. Djokic, K. Stockman, J.V. Milanovic. Sensitivity of AC Coil Contactors to Voltage Sags Short Interruptions, and Undervoltage Transients. IEEE Transactions on Power Delivery 19 (July 2004) : 1299 - 1307.

[14] Leborgne, R. Voltage Sags Characterisation and Estimation USA: Springler 2005.

[15] ATPDraw Manual version 3.3

[16] Perez J.J., Cortes C.A., Gomez A. A study of voltage sags in electric motors. 9th International Conference of Electrical Power Quality and Utilisation pp. 1-6, Spain, 2007.

[17] L. Guasch, F. Corcoles, J. Pedra. Effects of Symmetrical and Unsymmetrical Voltage Sags on Induction Machine. IEEE Transactions on Power Delivery 19(April 2004) : 774-782.

APPENDICES

APPENDIX
RESULT OF CONTACTOR TESTING

0 degree

duration (ms)	Voltage sags (%)												
	0	5	10	15	20	25	30	35	40	45	50	55	60
10	o	o	o	o	o	o	o	o	o	x	x	o	o
20	o	o	o	o	o	o	o	o	x	x	x	x	o
30	o	o	o	o	o	o	x	x	x	x	x	x	o
40	o	o	o	o	o	x	x	x	x			x	o
50	o	o	o	x	x	x	x	x					o
60	o	o	x	x	x	x							o
70	o	o	x	x	x								o
80	x	x	x										
90	x	x											
100	x	x											

15 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	x	x	o	o	
20	o	o	o	o	o	o	o	o	x	x	x	x	o	
30	o	o	o	o	o	o	x	x	x	x	x	x	o	
40	o	o	o	o	o	x	x	x	x			x	o	
50	o	o	o	x	x	x	x	x					o	
60	o	o	o	x	x	x							o	
70	o	o	x	x	x								o	
80	x	x	x											
90	x	x	x											
100	x	x												

30 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	x	x	x	x	o	
20	o	o	o	o	o	o	o	x	x	x	x	x	o	
30	o	o	o	o	o	x	x	x	x	x	x	x	o	
40	o	o	o	o	o	x	x	x					o	
50	o	o	o	x	x	x	x	x					o	
60	o	o	x	x	x								o	
70	o	x	x	x	x								o	
80	x	x	x											
90	x	x												
100	x													

45 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	x	x	x	x	x	x	o		
20	o	o	o	o	o	x	x	x	x	x	x	o		
30	o	o	x	x	x	x	x	x	x	x	x	o		
40	o	o	x	x	x							o		
50	x	x	x	x	x							o		
60	x	x										o		
70	x	x										o		

60 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	x	x	x	x	x	x	x	o	o		
20	o	o	o	x	x	x	x	x	x	x	o	o		
30	o	x	x	x	x	x	x	x	x	x	x	o		
40	x	x	x									o		
50	x	x	x									o		
60	x											o		
70												o		

75 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	x	x	x	x	x	x	x	x	o	o	o			
20	x	x	x	x	x	x	x	x	o	x	o			
30	x	x	x	x	x	x	x	x	x	x	o			
40											o			
50											o			
60											o			
70											o			

90 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	x	x	x	x	x	x	o				
20	o	x	x	x	x	x	x	x	x	o				
30	x	x	x	x	x	x	x	x	x	o				
40	x	x	x							o				
50	x									o				
60										o				
70										o				

105 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	o	o	o		
20	o	o	x	x	x	x	x	x	x	x	x	o		
30	x	x	x	x	x	x	x	x	x	x	x	o		
40	x	x	x	x	x	x	x	x	x	x	x	o		
50	x	x										o		
60												o		
70												o		

120 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	x	x	x	x	x	x	x	x	o	o	o	o		
20	x	x	x	x	x	x	x	x	x	x	o	o		
30	x	x	x	x	x	x	x	x	x	x	o	o		
40									x	x	x	o		
50											x	o		
60											x	o		
70												o		

135 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	x	x	o	o	
20	o	o	o	o	o	o	o	o	x	x	x	x	o	
30	o	o	o	o	o	o	o	o	x	x	x	x	o	
40	o	o	o	o	x	x	x	x	x			x	o	
50	o	o	o	x	x	x	x	x					o	
60	o	o	x	x	x	x	x	x					o	
70	x	x	x	x									o	
80	x	x	x											
90	x	x												

150 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	o	o	x	o	
20	o	o	o	o	o	o	o	o	o	o	x	x	o	
30	o	o	o	o	o	o	o	o	o	o	x	x	o	
40	o	o	o	o	o	o	x	x	x	x	x		o	
50	o	o	o	x	x	x	x	x	x	x			o	
60	o	o	x	x	x	x	x	x	x	x			o	
70	o	x	x	x	x	x							o	
80	x	x	x											
90	x	x												
100	x													

165 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	x	x	x	x	o
20	o	o	o	o	o	o	o	o	x	x	x	x	x	o
30	o	o	o	o	o	o	x	x	x	x	x	x	x	o
40	o	o	o	o	o	x	x	x	x					o
50	o	o	o	o	x	x	x	x						o
60	o	o	o	x	x	x								o
70	o	x	x	x	x									o
80	x	x	x	x										
90	x	x	x											
100	x													

180 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	x	x	x	o	o
20	o	o	o	o	o	o	o	o	x	x	x	x	x	o
30	o	o	o	o	o	o	x	x	x	x	x	x	x	o
40	o	o	o	o	o	x	x	x	x				x	o
50	o	o	o	o	x	x	x	x						o
60	o	o	o	x	x	x								o
70	o	o	x	x	x									o
80	x	x	x	x										
90	x	x	x											
100	x	x												

195 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	o	o	o		
20	o	o	o	o	o	o	o	o	o	o	o	o		
30	o	o	o	o	o	o	o	o	o	o	o	o		
40	o	o	o	o	o	o	o	x	x	x	o	o		
50	o	o	o	o	o	o	x	x	x	x	x	o		
60	o	o	o	o	x	x	x	x	x	x	x	o		
70	o	x	x	x	x	x	x				x	o		
80	x	x	x	x	x	x								
90	x	x	x	x										
100	x													

210 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	o	o	o		
20	o	o	o	o	o	o	o	o	o	o	o	o		
30	o	o	o	o	o	o	o	x	o	o	o	o		
40	o	o	o	o	o	o	x	x	x	x	o	o		
50	o	o	o	x	x	x	x	x	x	x	x	o		
60	o	o	x	x	x	x	x		x	x	x	o		
70	o	o	x	x	x	x					x	o		
80	x	x	x											
90	x	x												
100	x	x												

225 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	x	x	x	o		
20	o	o	o	o	o	o	o	x	x	x	x	o		
30	o	o	o	x	o	o	x	x	x	x	x	o		
40	o	o	o	x	x	x	x	x				o		
50	o	o	x	x	x	x	x					o		
60	x	x	x		x	x						o		
70	x	x	x									o		
80	x	x												

240 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	x	x	x	x	x	x	x	o			
20	o	o	x	x	x	x	x	x	x	x	o			
30	x	x	x	x	x	x	x	x	x	x	o			
40	x	x	x								o			
50	x	x									o			
60											o			
70											o			

255 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	x	x	x	x	x	x	x	x	o	o	o			
20	x	x	x	x	x	x	x	x	x	o	o			
30	x	x	x	x	x	x	x	x	x	x	o			
40									x	x	o			
50										x	o			
60											o			
70											o			

270 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	o	o	o		
20	o	o	x	x	x	x	x	x	x	x	x	o		
30	x	x	x	x	x	x	x	x	x	x	x	o		
40	x	x	x	x	x	x	x	x	x	x	x	o		
50	x	x										o		
60												o		
70												o		

285 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	o	o	o		
20	o	o	x	x	x	x	x	x	x	x	o	o		
30	x	x	x	x	x	x	x	x	x	x	x	o		
40	x	x	x	x	x	x	x	x	x	x	x	o		
50	x	x									x	o		
60												o		
70												o		

300 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	o	o			
20	o	o	o	o	o	x	x	x	x	x	o			
30	o	o	o	x	x	x	x	x	x	x	o			
40	o	o	x	x	x	x	x	x	x	x	o			
50	x	x	x	x	x						o			
60	x	x	x								o			
70	x	x									o			

315 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	x	x	x	o		
20	o	o	o	o	o	o	x	x	x	x	x	o		
30	o	o	o	o	o	x	x	x	x	x	x	o		
40	o	o	o	o	x	x	x	x				o		
50	o	o	x	x	x	x						o		
60	o	o	x	x	x							o		
70	x	x	x	x								o		
80	x	x												
90	x	x												

330 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	x	x	x	x	o
20	o	o	o	o	o	o	o	o	x	x	x	x	x	o
30	o	o	o	o	o	o	o	o	x	x	x	x	x	o
40	o	o	o	o	o	o	x	x	x					o
50	o	o	o	x	x	x	x	x						o
60	o	o	o	x	x	x	x	x						o
70	o	o	x	x	x	x								o
80	x	x	x											
90	x	x	x											
100	x	x												

345 degree

duration (ms)	Voltage sags (%)													
	0	5	10	15	20	25	30	35	40	45	50	55	60	65
10	o	o	o	o	o	o	o	o	o	o	o	o	o	o
20	o	o	o	o	o	o	o	o	o	o	o	o	o	o
30	o	o	o	o	o	o	o	o	o	o	o	o	o	o
40	o	o	o	o	o	o	o	x	x	x	x	x	x	o
50	o	o	o	x	o	o	x	x	x	x	x	x	x	o
60	o	o	o	x	x	x	x	x	x	x	x	x	x	o
70	o	o	x	x	x	x	x							o
80	x	x	x		x	x								
90	x	x	x											
100	x	x												

BIOGRAPHY

Fikri Waskito was born in Saga, Japan, in 18th January 1985. He received his Bachelor's degree in electrical engineering from Gadjah Mada University, Yogyakarta, Indonesia, in 2007. He has been granted a scholarship by the AUN/SEED-Net (www.seed-net.org) to pursue his Master's degree in electrical engineering at Chulalongkorn University, Thailand, since 2009. He conducted his graduate study with the High Voltage Laboratory, Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University. His research interest focuses on understanding power quality problems, especially voltage sags.