THREE PHASE INDUCTION MOTOR SPEED CONTROL USING IGBTs AND PULSE WIDTH MODULATION TECHNIQUE

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By

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CERTIFICATION OF APPROVAL

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Approved:

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TRONOH, PERAK

June 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Mohd Hakim Bin Mohd Nor

ABSTRACT

Three-phase induction motor is widely been used in the industry because of its rugged construction and absence of brushes. However, users need to control the speed of the motor depending on the desired speed and application. So, this project is launched to control the speed of the three-phase induction motor by varying the electrical frequency. In this project, the frequency is adjusted by using the Pulse Width Modulation (PWM) technique as a variable frequency drive. The objective of this project is to study the general induction motor characteristic, the frequency changing principle, PWM technique, the use of Insulated Gate Bipolar Transistors (IGBTS) as switching devices and the motor speed control method. This project also aims to develop PWM control algorithm to control the speed of the three-phase induction motor. As the result, the control algorithm is successfully been designed using the Matlab/Simulink software. The speed of induction motor can now be control. As the conclusion, this project had achieved its objective to study on induction motor and PWM techniques. This project also meets its objective to designed control algorithm using Matlab/Simulink that can be used to control the speed of three-phase induction motor. This project has potential to be further developed and can be implemented in the real induction motor.

ACKNOWLEDGEMENT

Alhamdulillah. Thanks to the Almighty Allah, the Most Gracious and the Most Merciful. Without His guidance and blessing, I will not able to finish this Final Year Project (FYP). Thanks O Allah for lending me strength and determination to accomplish this FYP.

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Last but not least, many thanks to the others whose name was not mentioned in this page but has in one way or another contributed to the accomplishment of this project. Thank you very much.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC – Alternating Current

DC – Direct Current

IGBT – Insulated Gate Bipolar Transistor

MOSFET – Metal Oxide Field Effect Transistor

PWM – Pulse Width Modulation

CHAPTER 1

INTRODUCTION

1.1 Background of study

Induction motor or rotating transformer is widely been used in the industry nowadays. Therefore, the needed of using the simplest way to control the speed of induction motor is highly demanded by the user. Thus, this project was launched specifically to control the speed of three-phase induction motor. The title for this project is "Three-phase Induction Motor Speed Control using IGBTs and Pulse Width Modulation Technique".

This project focuses on controlling the electrical frequency of voltage supplied to the stator winding using PWM technique.

In order to generate the standard control algorithm for the speed control of induction motor, this project required the usage Sim Power System toolbox in MATLAB/SIMULINK.

1.2 Problem statement

The windings on the rotor of three-phase induction motor are not connected to a power supply, but are essentially short circuits. When the motor is initially switched on and the rotor is stationary, the rotor conductors experience a changing magnetic field sweeping at the synchronous speed. This changing magnetic field pattern induces current in the rotor conductors. This current interacts with the rotating magnetic field created by the stator and in effect causes a rotational motion on the rotor.

However, the magnetic field will not be moving and no current will be induced if it doesn't meet the principle of induction motor. It states that the speed of the physical rotor and the speed of the rotating magnetic field in the stator must be different. If not, the rotor will typically slow slightly until a current is re-induced and then the rotor continuous rotates as before. Seem that the speed of both rotor and rotating magnetic field at stator will never be the same, so the induction motor sometimes referred to as an asynchronous motor.

Users need to change the speed of induction motor depending on their application. However, it must meet some requirement to control of the speed. There are two techniques that could be identified.

1. The first technique is by changing the rotor resistance or terminal voltage. Its objective is to vary the slip of the motor.
2. The second technique is by changing the number of poles on the machine or the electrical supply frequency. Its objective is to vary the synchronous speed.

For the first technique, the first choice by changing the rotor resistance is not relevant in this project. It is because this technique requires the use of wound-rotor induction motor and any resistances inserted to the rotor circuit will seriously reduce the efficiency of the machines. However, it is possible to use second choice that is by changing the terminal voltage. But, it is not good enough since it has limited range of speed control.

For the second technique, changing the number of poles on the machine is possible but it requires a motor with special stator windings. So, the best solution to control speed that can be used in any induction motor is by changing the electrical frequency.

The magnetic field is directly proportional to any change of electrical frequency. So, the speed of induction motor will depends on the rate of rotation of its magnetic field. The limited accessibility to the drive parameter had made the users and researcher could not do further study and analysis on the effect of PWM parameter to the performance of the motor.

1.3 Objectives and scope of the study

The objectives of this project are:

1. To study the general characteristic of the three-phase induction motor and the speed control technique by using IGBTs and PWM.

2. To design PWM control algorithm for switching of IGBTs to control the speed of induction motor by manipulating electrical frequency using Matlab/Simulink.

The study covers the following scope:

1. The characteristic of the induction motor

2. The frequency changing principle

3. The use of IGBTs as switching devices

4. The motor speed control method using PWM technique.

5. Knowledge on how to use the Matlab/Simulink software to develop the algorithm.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Induction motor operating principle

2.1.1 Basic Concept

The three-phase induction motor (Figure 1) is a rotating electric machine designed to operate from a three-phase source of alternating voltage. Its convert electrical energy to mechanical work and it is designed to operate from a three-phase source of alternating voltage [1].

A unique fact about the induction motor is that the rotor voltage is induced in the rotor winding rather than physically connected by wires. Thus, it does not required to have separate field. The distinguishing feature of an induction motor is that, no dc field is required to run the machine [2].

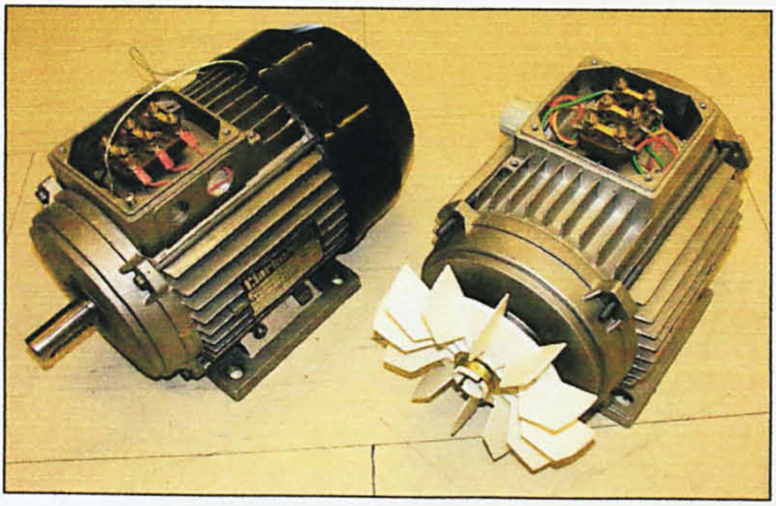

Figure 1: Three Phase Induction Motor

Induction motor does have two different types of rotors namely cage rotor and wound rotor. The most common type is the squirrel cage rotor which the aluminum conductors or bars are shorted together at both ends of the rotor by cast aluminum end rings. It is more preferable because of its simplicity and easy to handle [2].

The wound rotor has a complete set of three-phase windings that are mirror images of the windings on the stator. The connection of rotor windings is usually Y-connected. The rotor windings are shirted trough brushes riding on the slip rings. However, seem it uses brushes and slip rings, it required more maintenance thus increasing the cost and make it more expensive than cage induction motor [2]. Thus user are preferred to use cage rotor rather than wound-rotor induction motor.

2.1.2 Synchronous Speed

The synchronous speed, $n_{sync,}$ is also known as the speed of magnetic field's rotation at the stator. A three-phase set of voltages has been applied to the stator and resulting current flowing in the stator. The flowing current produces a magnetic field, **Bs**, which is rotating in counterclockwise.

The speed of this rotation can be calculated using the formula

$$n_{sync} = \frac{120 f_e}{P} \tag{1}$$

where

$f_e =$ electrical frequency in hertz and

P = number of poles in the machine.

Number of poles depends on the machine construction and the electrical frequency depends on supply voltage. The standard electrical frequency in Malaysia is 50 Hz.

Then, this rotating magnetic field, **Bs**, passes over the rotor bars and induces a voltage in them. Its follow the Faraday's Law that stated that any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be "induced" in the coil.

The voltage induced in a given rotor bar [2] is given by the equation shown below:

$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{I} \qquad (2)$$

where

v= velocity of the bar relative to the magnetic field,

B = magnetic flux density vector and

I= length of conductor in the magnetic field

2.1.3 Rotor Speed

Rotor current flow produces a rotor magnetic field **Br**. This magnetic field **Br** induced torque in the machine in counterclockwise direction by referring to following equation:

$$\tau_{ind} = k\mathbf{B_R} \times \mathbf{B_S}. \qquad (3)$$

where

τ_{ind} = induced torque in the machine

k = constant

$\mathbf{B_R}$= rotor magnetic field

$\mathbf{B_S}$ = rotating stator field

The rotor speed depends on the speed of the rotating magnetic field at the stator. If the speed of the rotor is as the same with the speed of rotating magnetic field, then the rotor bars would be stationary relative to the magnetic field and there would be no induced voltage. If there is no voltage induced, so the rotor current and the rotor magnetic field also will be zero. Thus, induced torque also would be zero and the rotor will slow down as a result of friction losses. Thus, its mean that the rotor speeds can't never exactly reach the synchronous speed.

The rotor speed can be explained by following equation:

$$n_r = n_s(1 - s) \tag{4}$$

where,

n_r = rotor speed

n_s = synchronous speed

s = slip

2.1.4 Rotor Slip

The induction motor depends on the rotor's voltage and current. The rotor voltage is depends on the speed of the magnetic field. So, it is a relative speed. The difference between synchronous speed and rotor speed is known as slip speed as following equation:

$$n_{slip} = n_{s\ ync} - n_m \tag{5}$$

where,

n_{slip} = slip speed of the machine

n_{sync} = speed of the magnetic fields

n_m = mechanical shaft speed

Other definition that can be use to describe relative motion is slip, which is the relative speed expressed on a per-unit or a percentage basis. Thus, slip is defined as

$$s = \frac{n_{slip}}{n_{sync}} \tag{6}$$

(If the rotor turns at synchronous speed, s = 0 while if the rotor is stationary, s=1. Thus, normal motor speed lies between 0 and 1.)

2.1.5 Equivalent Circuit

An induction motor operates on the induction of voltages and currents in its rotor circuit from the stator circuit (transformer action). Therefore, the equivalent circuit of an induction motor is very similar to that of a transformer. The model does not have internal voltage source, such as E_A since it does not have an independent field circuit.

The equivalent circuit of an induction motor differs from a transformer in the effect of varying rotor frequency on the rotor voltage and rotor impedances. The greater the relative motion between the rotor and stator magnetic fields, the greater the resulting rotor voltage and rotor frequency. The largest relative motion occurs when the rotor is stationary or *locked-rotor*; largest voltage, E_{R0} and largest rotor frequency are induced at this condition.

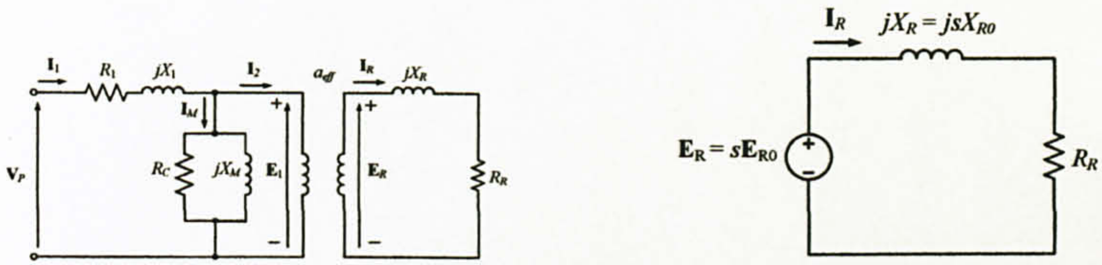

Figure 2: Equivalent Circuit

The magnitude and frequency of the voltage induced in the rotor is directly proportional to the slip, $E_R = sE_{R0}$ .The reactance of an induction motor is also affected by the varying rotor frequency. The rotor reactance, $X_R = \omega_r L_R = 2\pi f_r L_R$ and substituting $f_r = sf_e$, $X_R = sX_{R0}$ where X_{R0} is the blocked-rotor reactance.

2.2 Induction Motor Speed Control

Induction motor is not a good machine for applications requiring speed controllability. However, the induction motor speed still can be controlled. There are two techniques that could be identified.

1. The first technique is by changing the rotor resistance or terminal voltage. Its objective is to vary the slip of the motor.
2. The second technique is by changing the number of poles on the machine or the electrical supply frequency. Its objective is to vary the synchronous speed.

2.2.1 To vary the slip of the motor

2.2.1.1 Changing the Rotor Resistance

This method can be used in wound rotor induction motor. It works by inserting extra resistance into the rotor circuit of the machine in order to change the shape of the torque-speed curve. However, the induction motor efficiency had seriously reduced due to extra resistance into the rotor circuit.

2.2.1.2 Changing the Line Voltage

The torque developed by an induction motor is proportional to the square if the applied voltage. This method sometimes works on small motors driving fans and the speed of the motor may be controlled over a limited range.

2.2.2 To vary the synchronous speed

The synchronous speed of induction motor is given by following equation :

$$n_{sync} = \frac{120_{fe}}{p} \tag{1}$$

where

f_e = electrical frequency in hertz and

P = number of poles in the machine.

The only ways to do it is by manipulating the electrical frequency or the number of poles on the machine.

2.2.2.1 Changing the number of poles on the machine

To change the number of poles in an induction motor, there are two major approaches

1. The method of consequent poles
2. Multiple stator windings

The method of consequent poles is an old method that changes poles in stator windings of an induction motor by a factor 2:1 in coil connections.

The disadvantage of the consequent-pole method of changing speed is that the speeds must be in a ratio 2:1. However, there is a method to overcome this matter. It is solved by employing multiple stator windings with different numbers of poles and to energize only one set at a time. Unfortunately, this solution had increased the expenses of the motor and this method become unpopular to the user.

2.2.2.2 Changing the line frequency

The synchronous speed of the motor at rated conditions is known as the base speed. It is possible to adjust the speed of the motor either above or below base speed by using variable frequency control. The simple design of the variable-frequency induction motor can control the speed of an induction motor over a range from a little as 5 percent of base speed up to about twice base speed [2].

The flux in the motor will remain approximately constant if the voltage applied to an induction motor is varied linearly with the frequency below the base speed. Thus, the maximum torque remains fairly high.

To prevent the motor from overheating, the maximum power rating of the motor must be decreased linearly with decreases in frequency. The equation of power supply to a three-phase induction motor is given by

$$P = \sqrt{3} V_L I_L \cos\theta \tag{7}$$

where,

V_L = Line Voltage

I_L = Current Voltage.

In the past, this method does have disadvantage. It is because a dedicated generator or mechanical frequency changer was required to make it operate. However, this problem no longer relevance with the development of modern solid-state variable-frequency motor drives. Thus, this method has become the favorite for the user since it can be used with any induction motor.

2.3 Using IGBTs to Control Electrical Frequency

2.3.1 Introduction of IGBTs

The Insulated Gate Bipolar Transistor (IGBTs) is a three-terminal power semiconductor device, noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, variable speed refrigerators, air-conditioners, and even stereo systems with digital amplifiers [3-5].

Since it is designed to rapidly turn on and off, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters.

The IGBTs combines the simple gate-drive characteristics of the MOSFETs with the high-current and low–saturation-voltage capability of bipolar transistors by combining an isolated-gate FET for the control input, and a bipolar power transistor as a switch, in a single device.

The IGBTs is used in medium- to high-power applications such as switched-mode power supply, traction motor control and induction heating. Large IGBTs modules typically consist of many devices in parallel and can have very high current handling capabilities in the order of hundreds of amps with blocking voltages of 6,000 V.

The IGBTs combines the positive attributes of BJTs and MOSFETs. BJTs have lower conduction losses in the on-state, especially in devices with larger blocking voltages, but have longer switching times, especially at turn-off while MOSFETs can be turned on and off much faster, but their on-state conduction losses are larger, especially in devices rated for higher blocking voltages. Hence, IGBTs has lower on-state voltage drop with high blocking voltage capabilities in addition to fast switching speeds.

IGBTs has a vertical structure as shown in Figure 3 This structure is quite similar to that of the vertical diffused MOSFET except for the presence of the p+ layer that forms the drain of the IGBTs.

This layer forms a pn junction (labeled J1 in the Figure 3), which injects minority carriers into what would appear to be the drain drift region of the vertical MOSFET. The gate and source of the IGBTs are laid out in an interdigitated geometry similar to that used for the vertical MOSFET.

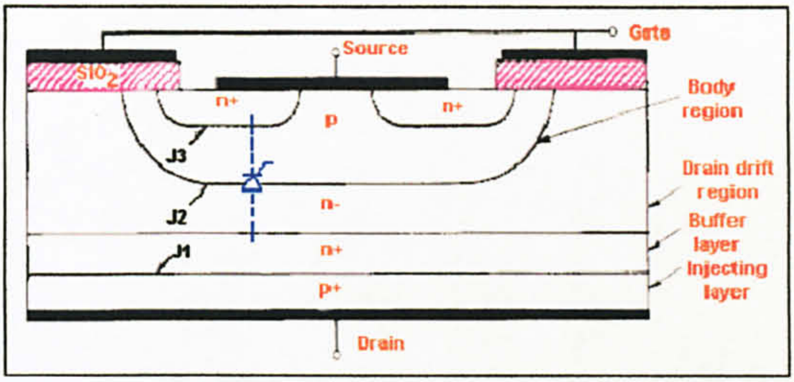

Figure 3: Physical structure of an IGBTs

The IGBTs structure shown in Figure 3 has a parasitic thyristor, which could latch up in IGBTs if it is turned on. The n + buffer layer between the p + drain contact and the n + drift layer, with proper doping density and thickness, can significantly improve the operation of the IGBTs, in two important respects.

It lower2 the on-state voltage drop of the device and, and shortens the turn-off time. On the other hand, the presence of this layer greatly reduces the reverse blocking capability of the IGBTs.

2.3.2 IGBTs Switching Characteristics

An important performance feature of any semiconductor-switching device is its switching characteristics. Understanding the device switching characteristics greatly improves its utilization in the various applications.

The main performance switching characteristics of power semiconductor switching devices are the turn-on and turn-off switching transients in addition to the safe operating area (SOA) of the device.

Since most loads are inductive in nature, which subjects devices to higher stresses, the turn-on and turn-off transients of the IGBTs are obtained with an inductive load test circuit as shown in Figure 4

The load inductance is assumed to be high enough so as to hold the load current constant during switching transitions. The freewheeling clamp diode is required to maintain current flow in the inductor when the device under test (DUT) is turned off.

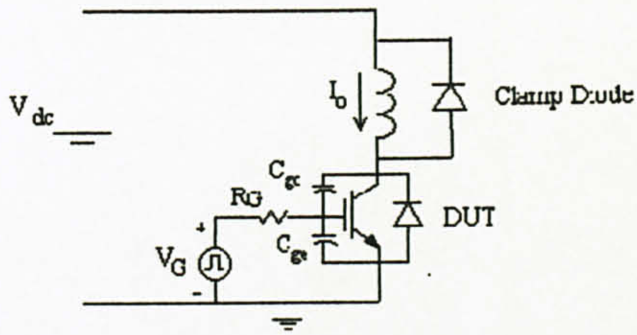

Figure 4: Inductive load test circuit

2.3.3 Turn-on Transients

The turn-on switching transients of IGBTs are very similar to MOSFETs since the IGBTs is essentially acting as a MOSFET during most of the turn-on interval.

With gate voltage applied across the gate to emitter terminals of the IGBTs, the gate to emitter voltage rises up in an exponential fashion from zero to $V_{GE(th)}$ due to the circuit gate resistance (R_G) and the gate to emitter capacitance (C_{ge}). The Miller effect capacitance (C_{gc}) effect is very small due to the high voltage across the device terminals.

Beyond VGE(th), the gate to emitter voltage continues to rise as before and the drain current begins to increase linearly as shown above. Due to the clamp diode, the collector to emitter voltage remains at Vdc as the IGBTs current is less than Io.

The gate to emitter voltage becomes temporarily clamped to VGE, Io. This means that the voltage required the IGBTs current at Io. At this stage, the collector to emitter voltage starts decreasing in two distinctive intervals tfv1 and tfv2.

The first time interval corresponds to the traverse through the active region while the second time interval corresponds to the completion of the transient in the ohmic region. During these intervals, the Miller capacitance becomes significant where it discharges to maintain the gate to source voltage constant.

When the Miller capacitance is fully discharged, the gate to emitter voltage is allowed to charge up to VG and the IGBTs goes into deep saturation. The resultant turn on switching losses are shown in the above figure.

The on energy loss is approximately estimated via this equation :

$$E_{on} = \frac{V_{dc} I_o}{2} t_{on} \tag{8}$$

where,

E_{on} = The on energy loss

V_{dc} = Dc Voltage

I_o = Current

2.3.3 Turn-off Transients

When a negative gate signal is applied across the gate to emitter junction, the gate to emitter voltage starts decreasing in a linear fashion. Once the gate to emitter voltage drops below the threshold voltage (VGE(th)), the collector to emitter voltage starts increasing linearly.

The IGBTs current remains constant during this mode since the clamp diode is off. When the collector to emitter voltage reaches the dc input voltage, the clamp diode starts conducting and the IGBTs current falls down linearly.

The rapid drop in the IGBTs current occurs during the time interval tfi1, which corresponds to the turn-off of the MOSFET. The tailing of the collector current during the second interval tfi2 is due to the stored charge in the n- drift region of the device.

This is due to the fact that the MOSFET is off and there is no reverse voltage applied to the IGBTs terminals that could generate a negative drain current so as to remove the stored charge.

The only way for stored charge removal is by recombination within the n-drift region. Since it is desirable that the excess carrier's lifetime be large so as to reduce the on-state voltage drop, the duration of the tail current becomes long.

This will result in additional switching losses within the device. This time increases also with temperature similar to the tailing effect in BJTs. A trade off between the on-state voltage drop and faster turn-off times must be made.

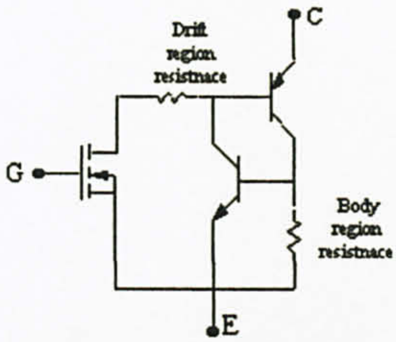

Figure 5: Equivalent circuit of the IGBTs

The removal of stored charge can be greatly enhanced with the addition of an n+ buffer layer, which acts as a sink for the excess holes and significantly shortens the tail time.

This layer has a much shorter excess carrier life time which results in a greater recombination rate within this layer. The resultant gradient in hole density in the drift region causes a large flux of diffusing holes towards the buffer region which greatly enhances the removal rate of holes from the drift region and shortens the tail time.

This device structure is referred to as Punch-Through (PT) IGBTs while the structure without the n+ buffer region is referred to as Non Punch-Through (NPT) IGBTs .The turn off energy los, can be evaluated in a similar fashion as the turn-on losses, namely,

2.4 Pulse Width Modulation

PWM is a powerful technique for controlling analog circuits with a processor's digital outputs. PWM is employed in a wide variety of applications, ranging from measurement and communications to power control and conversion [6-8].

In PWM, there are three main important elements, which are saw-tooth wave signal generator, input signal control voltage and comparator. It is important because it is involve in the process of modifying the width of the pulse. Insulated Gate Bipolar Transistor will be used in the inverter circuit. PWM signal is used to control the IGBTs switches gate.

The main purpose of using the PWM technique is to extract the low frequency signal from a train of high frequency signal square waves. However, in PWM, there are two classes available.

The first class is the non-sinusoidal PWM and the second class is the sinusoidal PWM. In the first class, all the pulses in the signal are having the same width and are normally modulated equally to control the output of the voltage.

In the second class, the pulse width is modulated sinusoidally (Figure 6). The width of each pulse is proportional to the instantaneous value of a reference sinusoid whose frequency equals to that of the fundamental components.

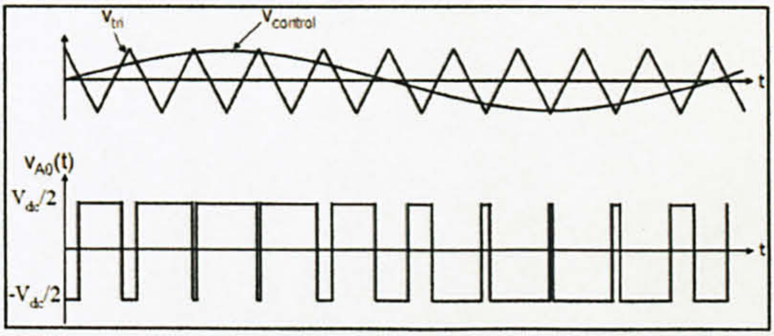

Figure 6: The sinusoidal pulse width modulation signal

CHAPTER 3

METHODOLOGY AND PROJECT WORK

3.1 Procedure identification

The key factor of this project is to manipulate the PWM signal in order to vary the electrical frequency of the motor and then control the speed of the three-phase induction motor. The PWM signal is used for IGBTs' switching.

At the beginning of this project, the MATLAB/Simulink is use to develop PWM algorithm model. The PWM algorithm model is tested and simulated. The PWM algorithm model is developed based on the application requirement such as frequency changing, acceleration and deceleration speed function.

3.2 Tools required

The project only involves software simulation. The software used is MATLAB 7.0 (R14) with Simulink 6.0. The purpose of the software is to design the PWM control algorithm and to perform simulation to control of the three-phase induction motor.

3.3 The project deliverables.

The project is to develop the speed control algorithm and simulate it using the Matlab/Simulink. The power IGBTS is used to implement the PWM technique. To simplify the order, Figure 7 is the simplified block diagram of the project outcome.

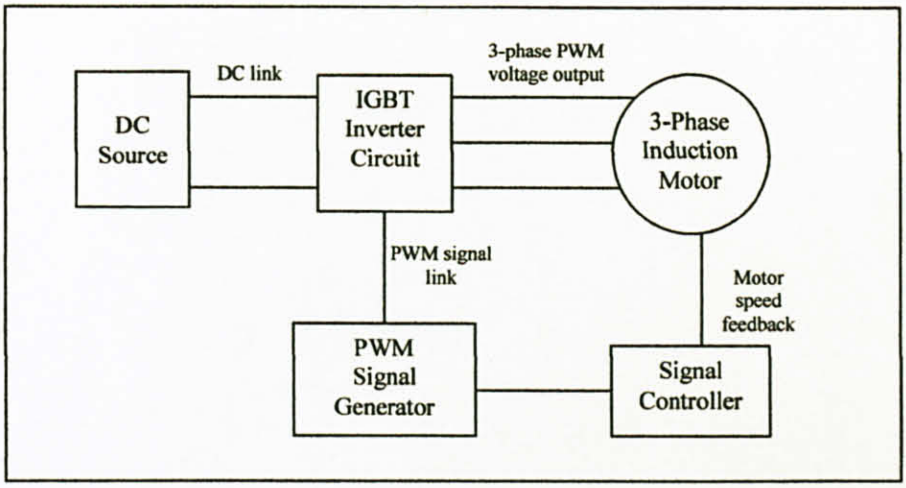

Figure 7: General block diagram of the project

3.4 The project flow

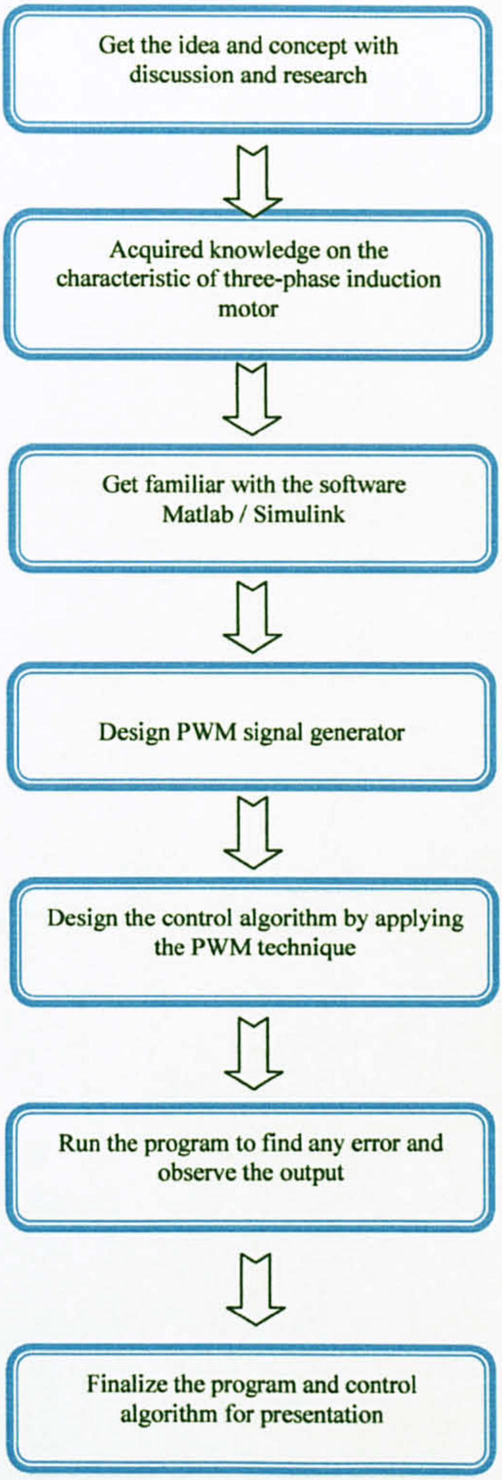

Figure 8: Project Flow

3.5 Toolbox in Matlab/Simulink related to the project.

This project is required the usage of Matlab/Simulinkdue to some special function inside the softare. It has some toolboxes that already available to do the simulation. Inside the Matlab, the toolbox that will be used can be found under the SimPowerSystems toolbox. Inside it, there were some demo files that seem similar to this project that are: *AC/DC Three-level PWM Converter (discrete), AC Motor Drive - Vector Control (discrete), DC/DC and DC/AC PWM Converters (discrete), Three-phase SV-PWM Converter (discrete), Three-phase Three-level PWM Converter (discrete), Three-phase Two-level PWM Converters (discrete),* and *Universal Bridge in DC-AC PWM Converter (discrete)* (Figure 9)

The entire demos are very specific to the complete set of simulation. So, some of the Simulink blocksets has been simplified due to the complexity of the model required. For example, *Three-phase Three-level PWM Converter (discrete).*

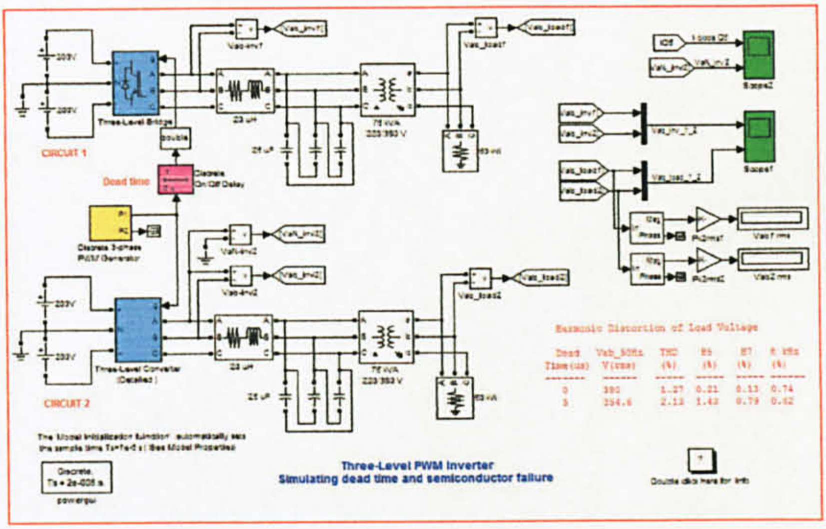

Figure 9: Three-phase Three-level PWM Converter (discrete)

This model represents two identical circuits modelling three-phase inverter. The IGBTs inverter uses SPWM technique, convert DC ower from a +/-200 Vdc source to 220 V AC, 50 Hz. L-C filters are used at the converter output to filter out harmonic frequencies The 12 inverter pulses required by the inverter are generated by the "Discrete 3-phase PWM Generator" block. The system operates in open loop at a constant modulation index.

CHAPTER 4

SYSTEM DESIGN, RESULTS AND DISCUSSIONS

4.1 Developing the Pulse Width Modulation signal

4.1.1 PWM signal

PWM technique is been used to modify the width of the pulse in a pulse train of electrical frequency [9]. It provides logic "1" and "0" for a controlled period of time. There are three important elements to create the PWM signal. The three elements are

1) Sawtooth or triangle wave generator or carrier waveform
   – To produce the PWM signal, this waveform is compared with the control signal.

2) Control or reference signal
   - The output of electrical frequency is controlled by this signal. So, when the output is been controlled, the motor speed also been controlled.

3) Comparator.
   - The carrier waveform and the control signal compared using comparator to produce PWM signal.

These elements will be used in the inverter circuit by implementing it to the switches gates of IGBTs. The comparator is very important element to generate the PWM signal. It compares both carrier waveform and control signal and produce respective output base on the condition of the signal. The output of the signal is high or "1" whenever the control signal is greater than sawtooth signal. However, when the control signal is less than the sawtooth signal, the output voltage for PWM signal is low or "0" [6].

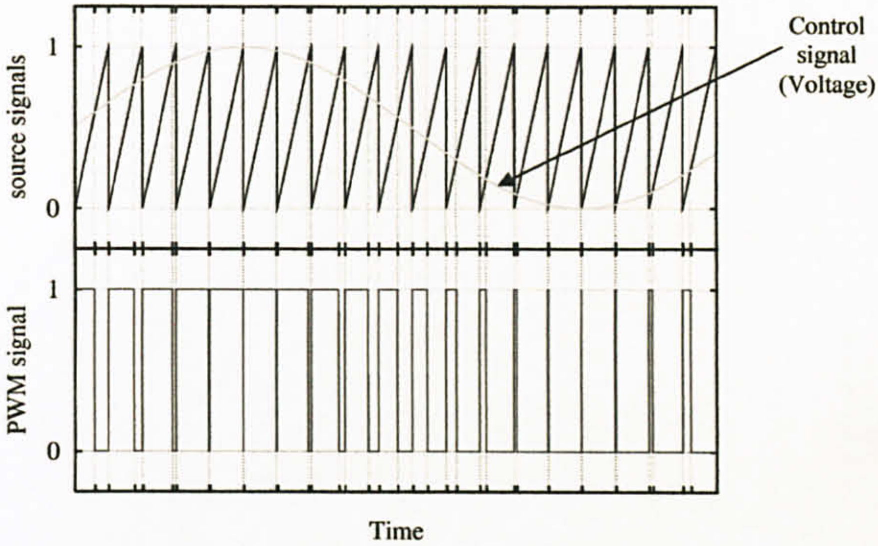

Figure 10: PWM signal waveform generation

By using Matlab/simulink software, the process of producing PWM signal is been designed. The designation is using the signal processing blocksets that available in the library. The blockset that has been used is sawtooth signal block and control signal block. Scope also has been used to see both signals.

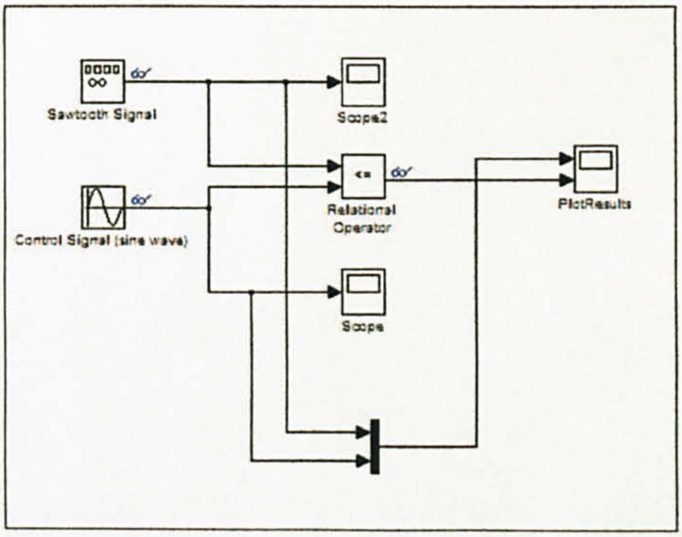

Figure 11: Comparator using the Relational Operator block.

The sawtooth signal is been set to 1 for the amplitude and used 1000 Hz for the frequency.

The output from the signal generator is based on the formula:

$$Y(t) = Amp*Waveform$$

where

$$Y(t) = output\ waveform$$
$$Amp = amplitude\ of\ the\ waveform$$

The setting for the waveform can be seen in the Figure 12.

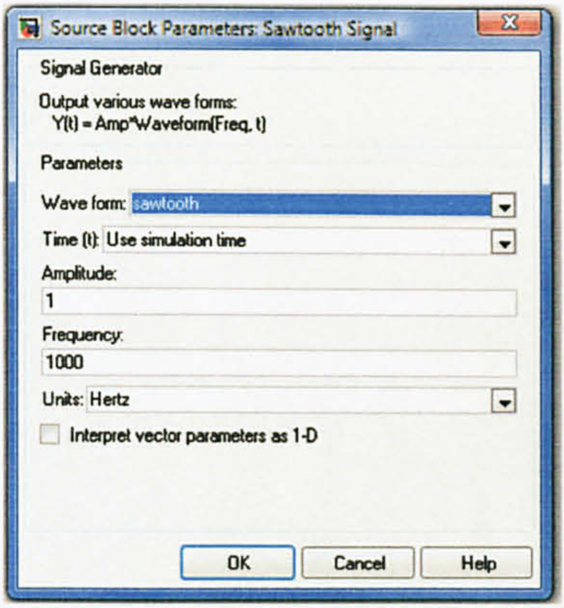

Figure 12: Sawtooth signal

For the control signal or sine wave, the amplitude is set to be lesser than the amplitude of sawtooth signal. The amplitude is set to 0.8 and the frequency is set to 100 Hz or 628 rad per seconds as been shown is Figure 13.

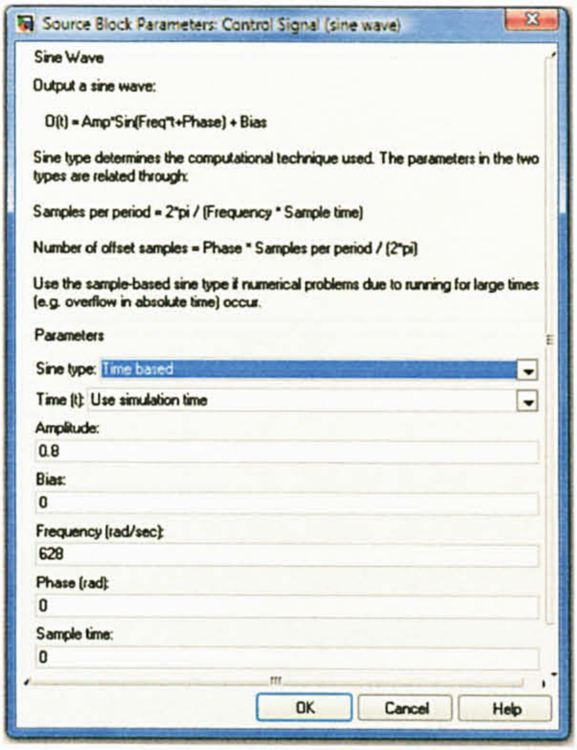

Figure 13: Control Signal (sine wave)

However, to make the sawtooth waveform and controller signal been compared, the comparator model need to be introduced. Thus, Relational Operator block has been used to compare both inputs. It has been set to be “<=” which means if the top input is less than the bottom input, the output will be 1. Vice versa, if the input is greater than the bottom input, the output will be 0. In this mode; the top input is sawtooth signal while the bottom input is the control signal. Refer to Figure 14 for the relational operator block parameters.

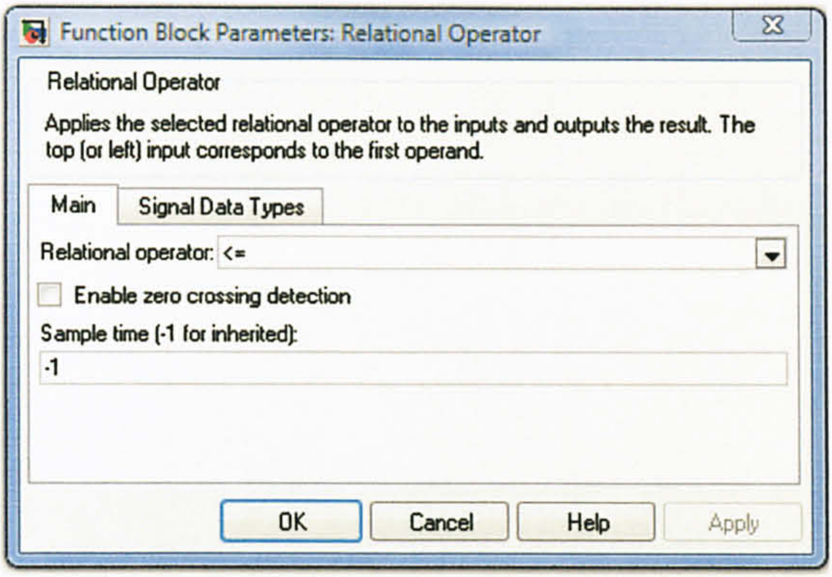

Figure 14: Relational Operator

To see the result of the comparator, two input scope is attached to the comparator block. One input is come from the relational operator and another input is from both sawtooth signal and controller signal that had been combined by using mux block. Mux block can be set to combine as many inputs and in this case, it has been set to have only two inputs. (See Figure 15)

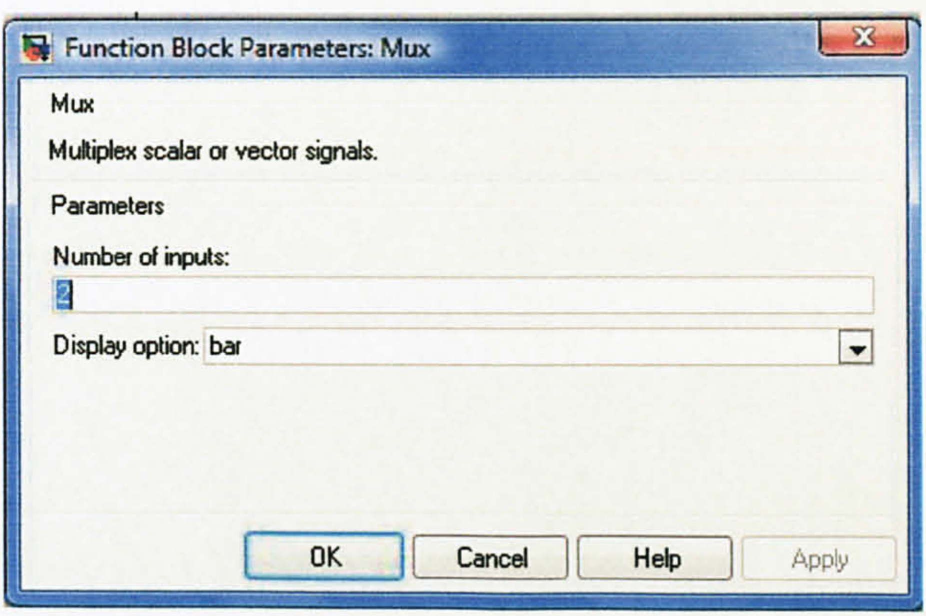

Figure 15: Mux block properties

The output waveform can be seen from the scope. By looking at the simulation, the result of the simulation is exactly as the same with the theoretical part shown in figure16.

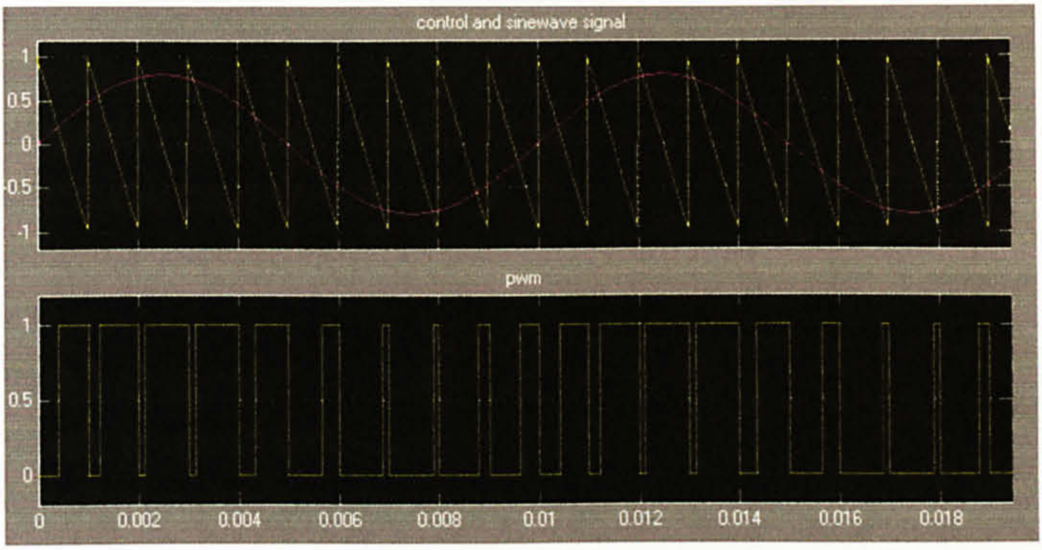

Figure 16: The generated PWM signal in the simulation

4.1.2 Simulating using three-phase signal

Three-phase PWM signal can be produced by creating another two PWM signal generator. However, the phase angel of each new block control signal must be different by 120° to create perfect 3-phase signal.

Thus, it has been set to 2*pi/3* radian and *4*pi/3* radian. The adjustment is made at the Phase (rad) value as shown in Figure 17.The block diagram of the three-phase PWM signal and its result also shown in Figure 18 and Figure 19.

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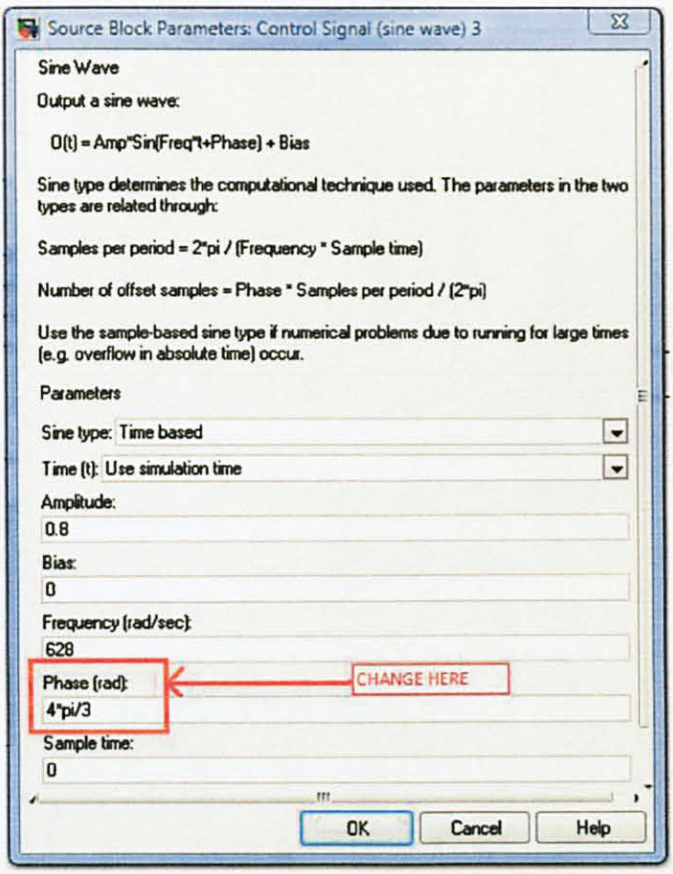

Figure 17: Change of phase for control sine wave

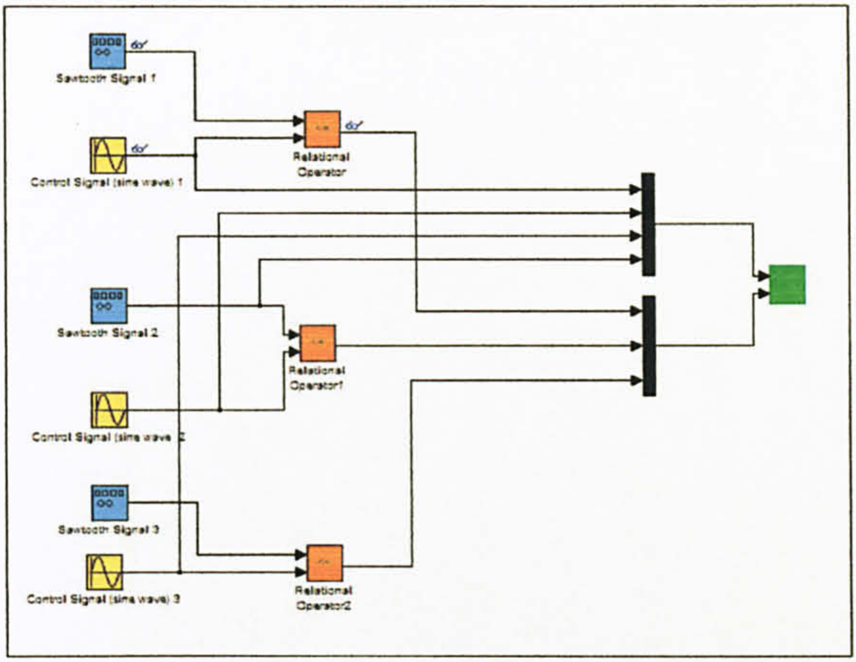

Figure 18: Simulink block for 3 phase pwm algorithm

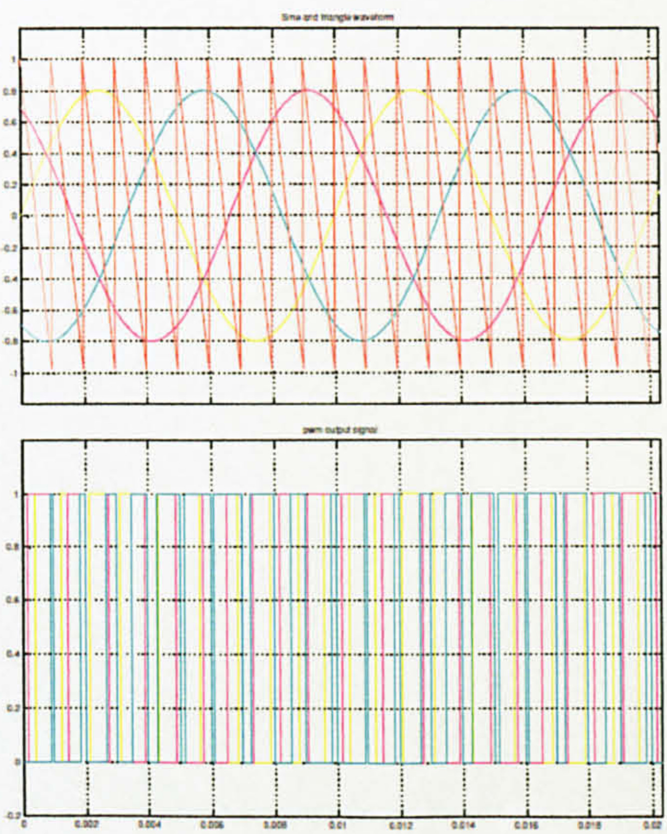

Figure 19: The 3-phase signal and its generated 3-phase PWM output signal

4.1.3 Understanding and simulating the inverter using IGBTs blockset.

IGBTs block set needs to be used to design the three-phase inverter inside the simulink. To produce three-phase inverter, the arrangement must be made into bridge connection from six IGBTs. In order to provide a constant direct current, the simulation is provided with 400DC source. The output symbol is represented by R, Y and B that indicates three-phase output (Red, Yellow and Blue) and it will be implemented into the motor model. (Figure 20) The simulation will produce line-to-line voltage output as shown in Figure 21.

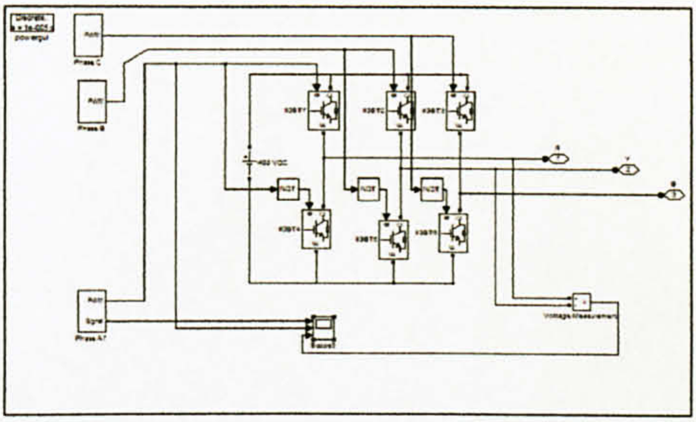

Figure 20: The blockset with IGBTs in bridge connection for simulation

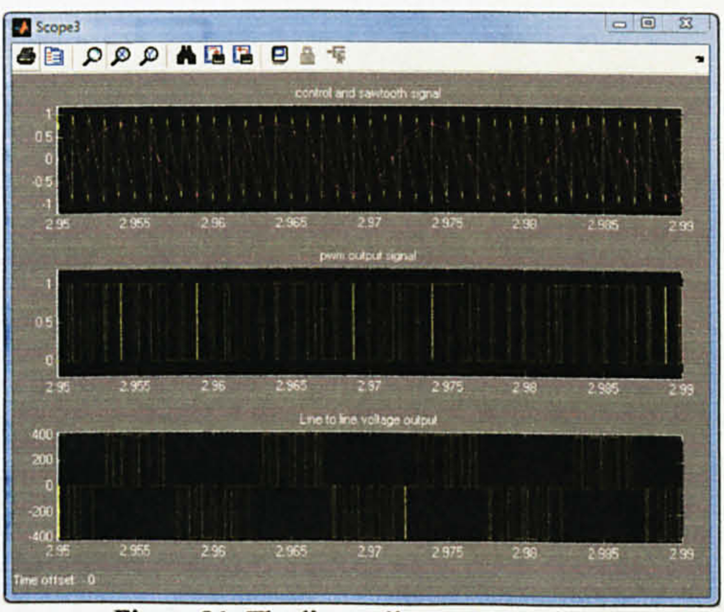

Figure 21: The line to line output voltage

4.1.4 Implementing the IGBTs inverter blockset into the load.

Next step is to connect the PWM inverter block to the DC source and loads. Simulink SimPowerSystems connection port block has been introduced to replace the DC source in the previous circuit. The simple load has been attached to the circuit represented by 1ohm resistance and 5mH inductor.

However, with the increasing of model and block in one window, it made it look complex and messy. So, the entire PWM inverter block with IGBTs in bridge connection is been group together into subsystem. Thus, the new PWM Inverter subsystem now can be connected to the DC source and the loads at the output and 400Vdc at its input as shown in Figure 22.

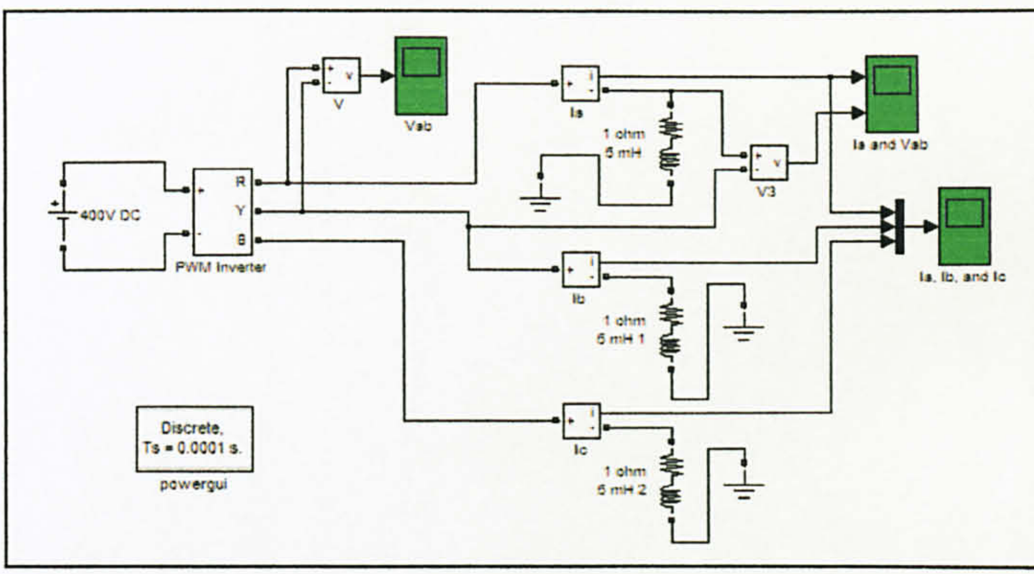

Figure 22: The PWM Inverter block connected to the DC source and loads.

The simulation of this system is unsuccessful since it does have discretized error when it is connected to the motor and DC source. The error occurred because the circuits containing six units of individual IGBTs that connected in bridge. Thus, to overcome this error, Universal Bridge block is been introduced to replace the six unit of IGBTs block as shown in Figure 23.

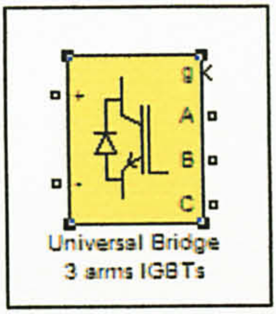

Figure 23: The Universal Bridge block with its input and output ports

By referring to Figure 23, the source input is represented by "+" and "-" sign while the phase output for the three-phase load input is represented by *A,B* and *C*. The gate input for the controlled switch devices is represented by symbol g in the block. The source that been used for this project is 400V DC source and *Asynchronous Machine* block is selected to be the three-phase load. The switch number is corresponds to the pulse ordering in the vector of the gate signals.

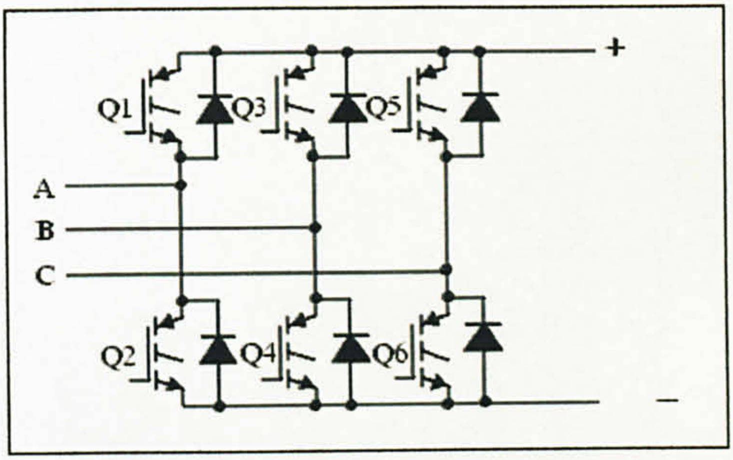

Figure 24: The circuit of 3-arm bridge connection

The PWM signal is been fed to the gate of each IGBTs at the input g for each arms *[Q1, Q2, Q3, Q4, Q5, Q6]*. The Universal Bridge Block requires six inputs in vector and need to be arrange into two-level-topology. By referring to Figure24, the arrangement of the pulse is made into upper and lower device. The upper devices will be fired by pulses 1,2 and 5 while the lower devices will be fired by pulses 2,4 and 6.

By comparing the reference modulation signal with the triangular carrier waveform, the pulse width modulation signal is generated for each arm. There are two ways to produce the PWM signal either by using PWM generator or connecting the external signal at the input of the block.

The pulse for a three-phase, single or double bridge is generated by three reference signal and it only required only one reference signal if want to generate the pulse of a single or a two-arm bridge. In order to control the output voltage of the bridge connected to the *PWM Generator Block*, the amplitude, phase and frequency of the reference signal is been set earlier.

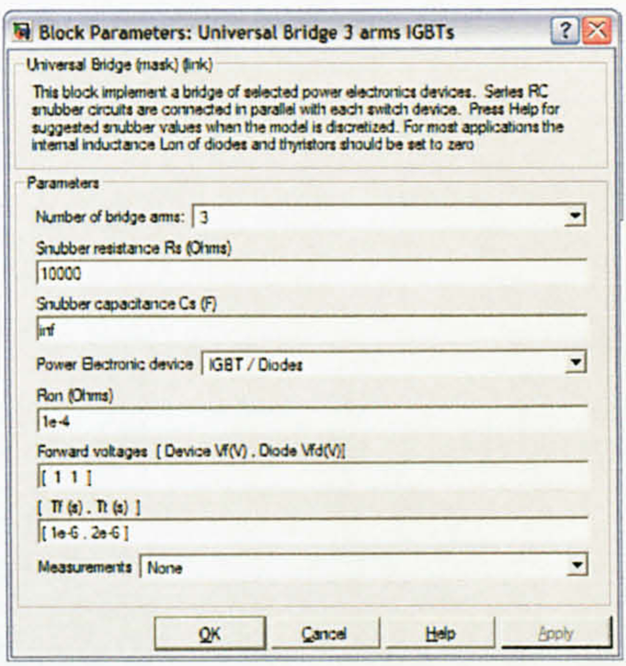

Figure 25: The Universal Bridge block parameter

Since the three-phase inverter is using six IGBTs connected in bridge of 3 arms, so the number of bridge arms is selected to be *3* as shown in Figure 25. At the column *Power Electronic Device*, IGBTs/ diode option is selected.

4.2 Designing the controllable PWM generator using fundamental theory

A control algorithm using PWM signal can be generate by manipulating the control signal, carrier signal and comparator. In this project, we can choose either to use frequency or desired RPM input to get the speed of the motor.

4.2.1 Sine wave generation

Base on the sine wave equation, a combination if Simulink block is designed to ease the operation of controlling and modifying the input variable. The equation that needs to be manipulated is shown below:

$$y = A \sin(\omega t + \theta) \qquad (9)$$

where,

A = peak deviation from center (amplitude)

ω = the angular frequency = $2\pi f$

f = frequency (Hz)

θ = initial phase shift when $t = 0$

(Phase shift is a constant difference/offset between two instantaneous phases, particularly when one is a standard reference)

From equation (9), replacing ω to $2\pi f$,

$$y = A \sin(2\pi f t + \theta) \qquad (10)$$

Converting equation (9) into the Simulink form,

$$Output = Amp * Sin(2 * pi * Freq * t + Phase) \qquad (11)$$

From equation (11), *Output* is the resulted sine wave, *Amp* is the amplitude of the sine wave, *Sin* is the trigonometric function, *Freq* is the frequency of the generated sine wave, *t* is the simulation time, and *Phase* is the phase shift for the sine wave.

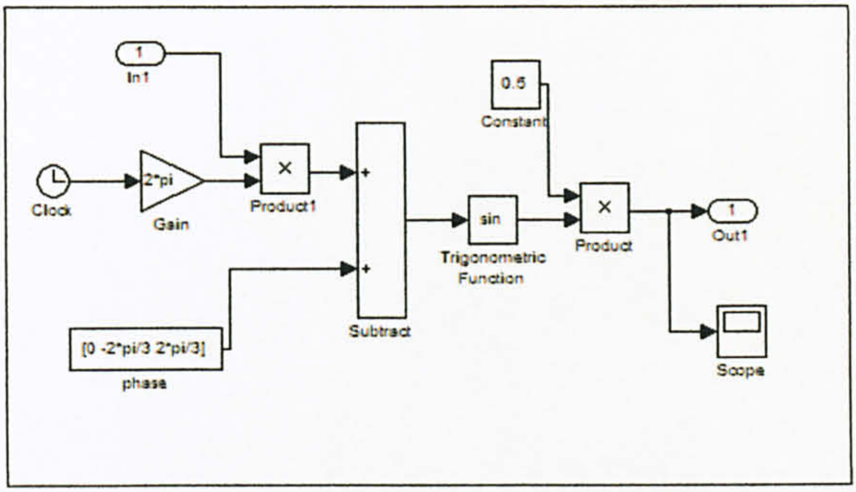

Figure 26: Controllable sine wave generator

The value of *t* is represented by the *Clock* block. The block outputs the current simulation time at each simulation step. *Amp* will be represented by the *Constant* block. *Freq* is represented by the *In1* input port, and *Phase* is represented by *phase* block.

Constant block is the amplitude of the sinusoidal signal. It must be greater than zero and lower than or equal to 1. Thus, the value is set to be 0.5. The fundamental component's amplitude is been controlled by this parameter.

The *In1* input port will determine the frequency of the generated sine wave. The port will left open to user to enter any desired frequency value so that it can be control freely by the user.

Phase block is the phase of the generated sinusoidal signal. Since this is a three-phase PWM generator, the parameter should have three values which are 0°, -120° and 120°. Converting those values into radians, they become 0, $-2\pi/3$, and $2\pi/3$ respectively. So, the parameter for the *Phase* can be written as *[0 -2*pi/3 2*pi/3]*.

Sin block is the sine trigonometric function where it received inputs and converts it into the sine wave. Since there is a vector of three inputs, 0°, -120° and 120° phase shift each, the generated output is the three-phase sinusoidal wave.

4.2.2 Triangle wave generation

The function repeating sequence (Figure 27) in the Simulink model is used to generate the triangle wave. The output signal of the block is depends on the values entered in the paramatern.

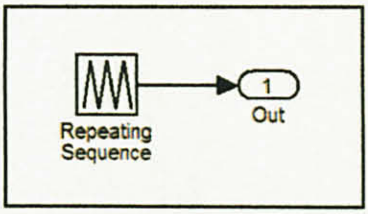

Figure 27: Repeating Sequence block

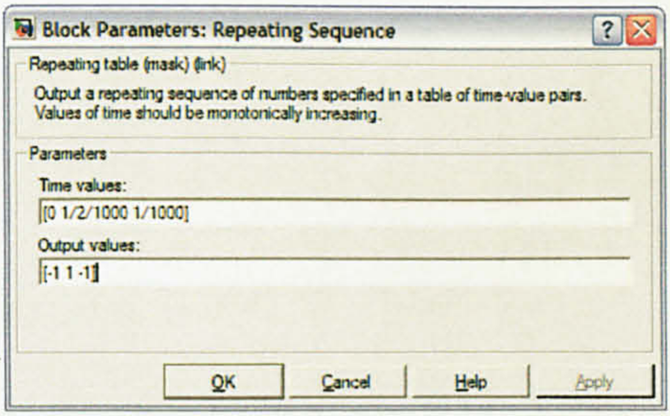

Figure 28: The block parameter to generate triangle wave of 1000 Hz.

In this project, we adjust the time values and the output values at the repeating sequence block to [0 1/2/1000 1/1000] and [-1 1 -1] respectively. This value will produce 1000Hz triangle wave signal that will repeats every 1/1000 seconds. It works by evaluate the output value to be -1 when the time is zero or when 1/1000 seconds. However, when the time is 1/2/1000 seconds, the output will be 1. So, the output value will become -1, 1 and -1 again as shown in Figure 28 and Figure 29.

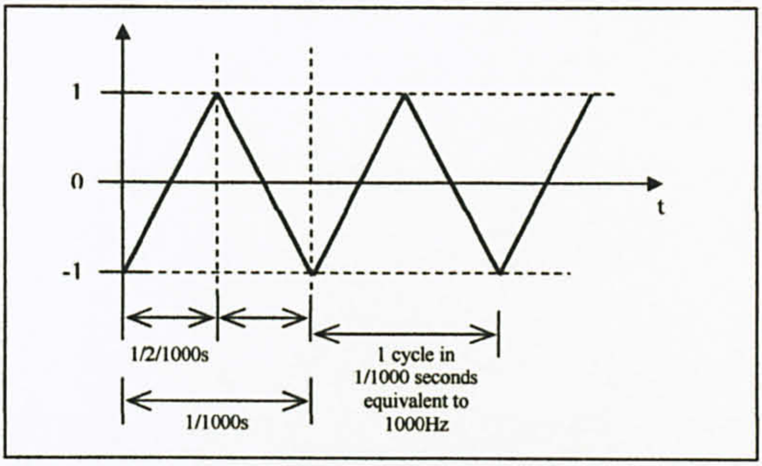

Figure 29: Triangle waveform frequency

Time values: [0 1/2/1000 1/1000]

Output values: [-1 1 -1]

In general, the *Repeating Sequence* block outputs a periodic scalar signal having a waveform that user specify. By using the using the block's *Time values* and *Output values* parameters, user can simply specify any desired waveform. The *Times value* parameter specifies a vector of sample times. *The Output* values parameter specifies a vector of signal amplitudes at the corresponding sample times. Together, the two parameters specify a sampling of the output waveform at points measured from the beginning of the interval over which the waveform repeats such as the signal's period.

4.2.3 Comparator for modulation

To get the PWM signal in this project, it is needed to compare both carrier and control signal by using modulation. In Simulink, the comparator process is been done by using the *Relational Operator and Logic block*. It will produce a logic 0 or LOW and 1 or high depends on which is larger between the sine wave and the carrier wave. If the sinewave is larger than the carrier wave, so it will output HIGH. It is because it has been set to be "<=" which means if the top input is less than the bottom input it will produce 1.

Since the requirement of using three-phase wave signal at inverter that have upper and lower arm, thus NOT block is introduced to feed the lower IGBTs at 2,4 and 6. The results of comparing both signals will generate multiplex of six forms of PWM signals in vector as shown in Figure 30.

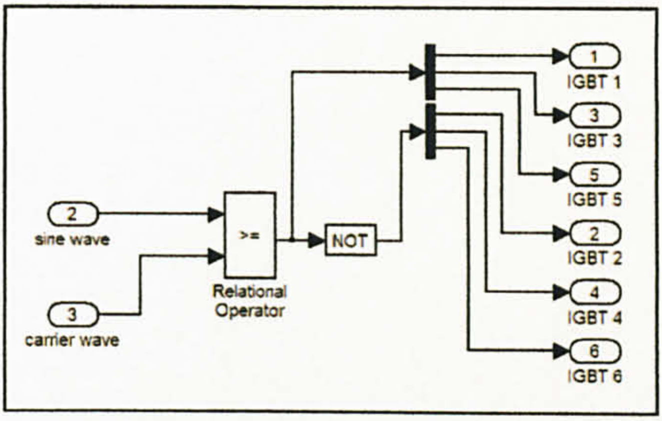

Figure 30: The inverter connected to a load.

The sine wave and carrier wave block in Figure 30 is been replaced with the algorithm in Figure 26 and Figure 27 to create complete controllable PWM generator as shown in Figure 31. User can manipulate this generator to get the desired value.

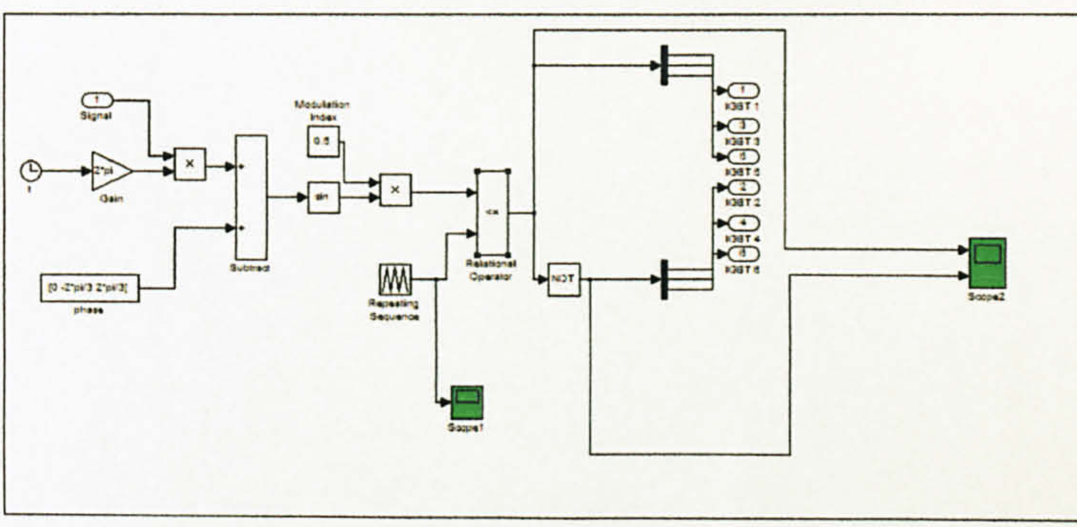

Figure 31: The controllable PWM generator

4.3 Simulation of PWM generator with various loads

After finish developed the PWM generator, it need to be connected to the IGBTs model to run with various load. Since the PWM generator is to complex, it need to group all together into one Subsystem block named *PWM Generator*. The signal frequency is been attached to the signal port of the PWM Generator. While the pulses port of the PWM Generator is connected to the input of g of Universal Bridge block. 400 Vdc source is connected to "+" and "-" port of the Universal Bridge block. While the A,B and C ports is used to connect to any three-phase load such as electrical machine.

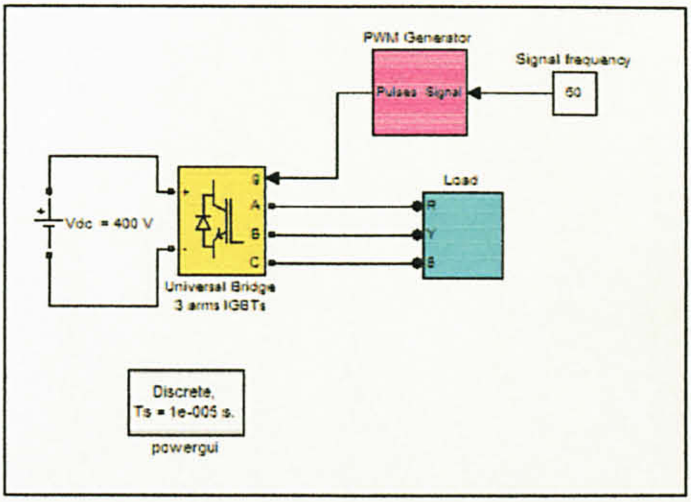

Figure 32: The inverter connected to a load.

4.3.1 Simulation of the PWM inverter with resistive and inductive load

It is important to connect a load to each phase of the inverter output before connect it to the induction motor model. It is because the user can observe the output voltage waveform during the simulation. In this project, 1 ohm resistive load and 5mh inductive load that been arranged in series is selected to be the load for each phase. By using scope, the current waveform can be observed. The observation of the inverter voltage waveform shows that it does not much different from the theoretical waveform of PWM technique.

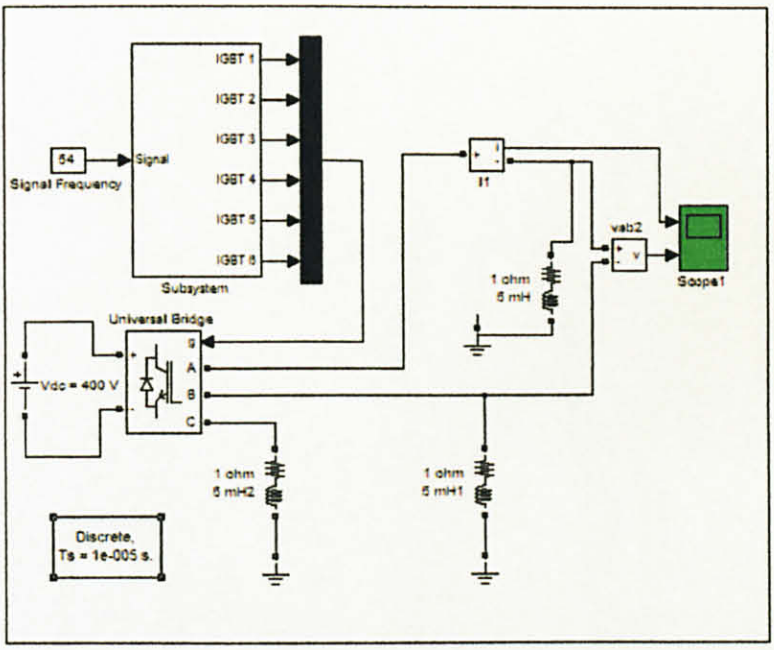

Figure 33: Inverter circuit connected to the resistive and inductive loads.

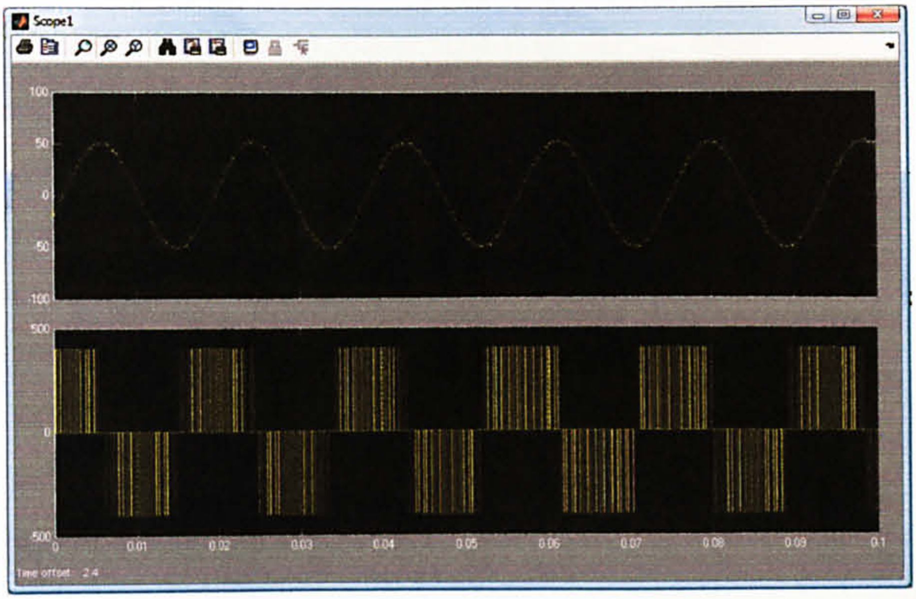

Figure 34: Current at the load and output voltage from the inverter.

From Figure 34, the current in the three-phase load is generated with a small ripple which is the effect of the sampling process during the pulse width modulation output generation since the output voltage for one of the phase is in the PWM waveform,

4.3.2 Simulation of the PWM inverter with induction motor model

The next step of the project is to implement the three-phase squirrel cage induction motor model as the load. The output waveform from the simulation of inductive and resistive load had satisfied the need of the project. Thus, the loads are replaced with the machine block as shown in Figure 35.

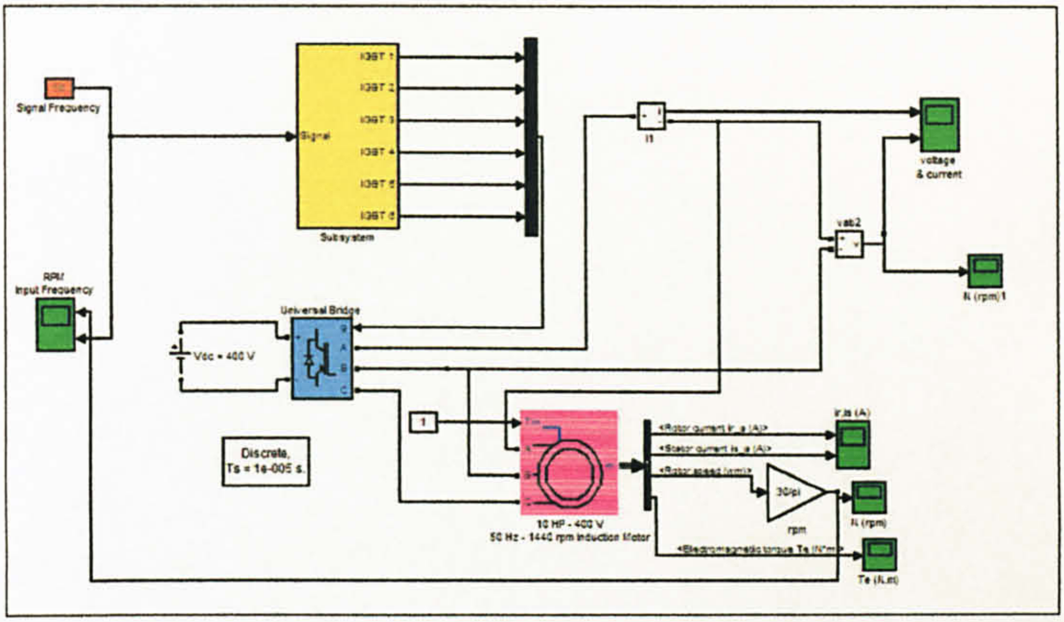

Figure 35: Inverter connected to the motor

The three-phase squirrel cage induction motor is represented by The *Asynchronous Machines* block inside the simulink model. However, this block can operate as the motor or generator. The sign mechanical torque is used to determine which mode of operation of the machine. If the torque, Tm is positive, the machine will operate as a motor. Vice versa, if the Tm is negative, the machine will operate as the generator. Thus, to make the machine operate as a motor, positive input with the value off 1 is entered to the Constant block.

Bus Selector block is introduced to demultiplexed the 21 signals vector output of the block to only three important signal which are *Rotor Current, Stator Current, Rotor Speed, and Electromagnetic Torque.*

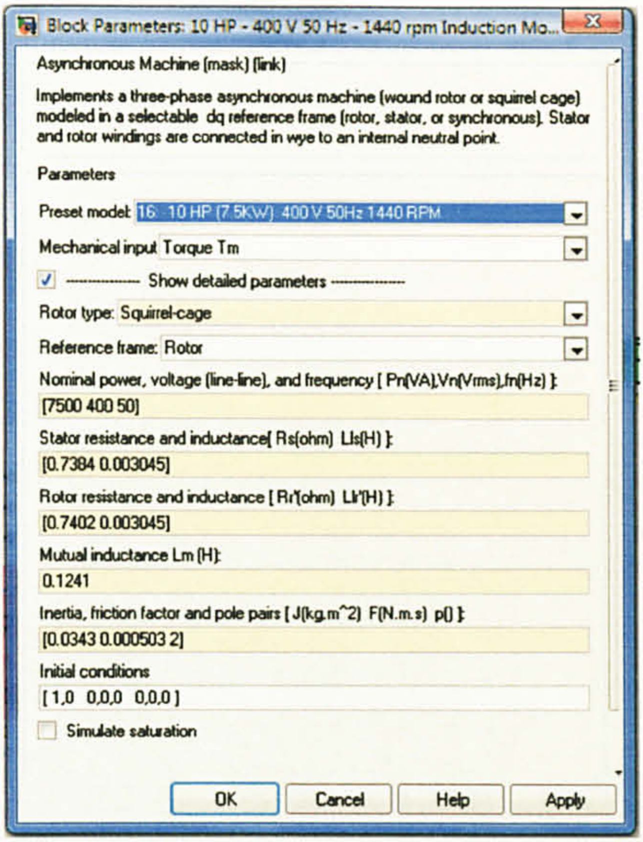

Figure 36: Asynchronous Machine block parameter

In the *Asynchronous Machines* block parameters (Figure 36) the preset model no. *16* is choose (*10 HP (7.5KW) 400 V 50 Hz 1440 RPM*). The branching for the rotor windings is specified as *Squirrel-cage* in the *Rotor type* option. The output from the motor is connected to the scope to observe the rotor current, stator current, rotor speed, and electromagnetic torque. At the PWM Generator, the input of signal frequency is set to be 50 Hz.

It needs about 10 seconds to finish the simulation. By looking at the result at the scope, the line to line voltage waveform gives the same result of PWM output voltage in *Figure 29.* For both stator and rotor windings, the starting current have big oscillate current waveform from 0 to approximately 0.6 seconds. After the motor has reach its constant speed after 0.6 seconds, the current oscillates will slowly produce a low magnitude. It also happened to the electromagnetic torque.

The simulation is done for about 10 seconds. From the output waveform, the line to line voltage (Figure 37) was the same as the PWM output voltage in *Figure 24*. By observing the current output waveform (Figure 38), the motor will draws high starting current for both rotor and stator windings. The currents oscillate in large magnitude from 0 to approximately 0.6 seconds. After that, currents oscillate in low magnitude because the motor already reach a constant speed. The same observation can also be seen from the electromagnetic torque (Figure 39).

Figure 37: Line to line voltage at inverter output

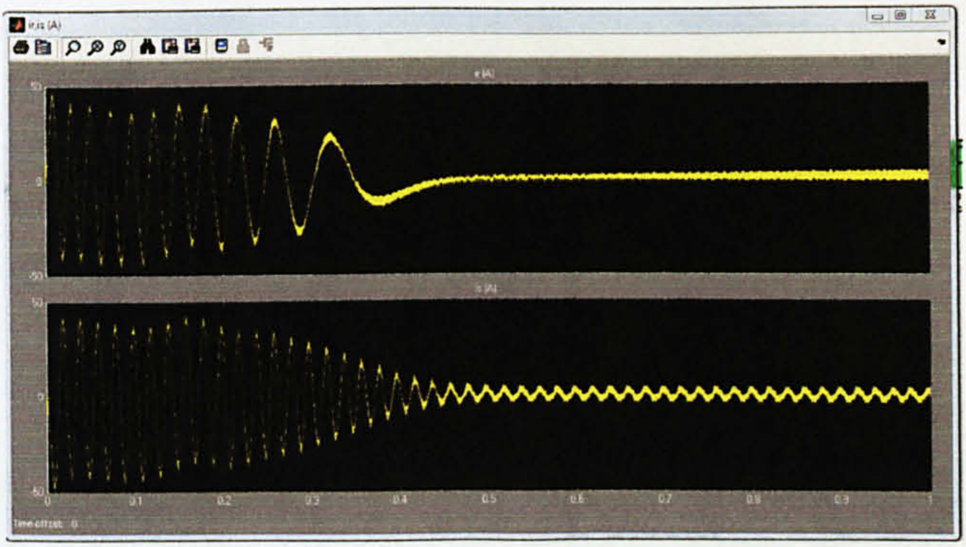

Figure 38: Rotor and stator current

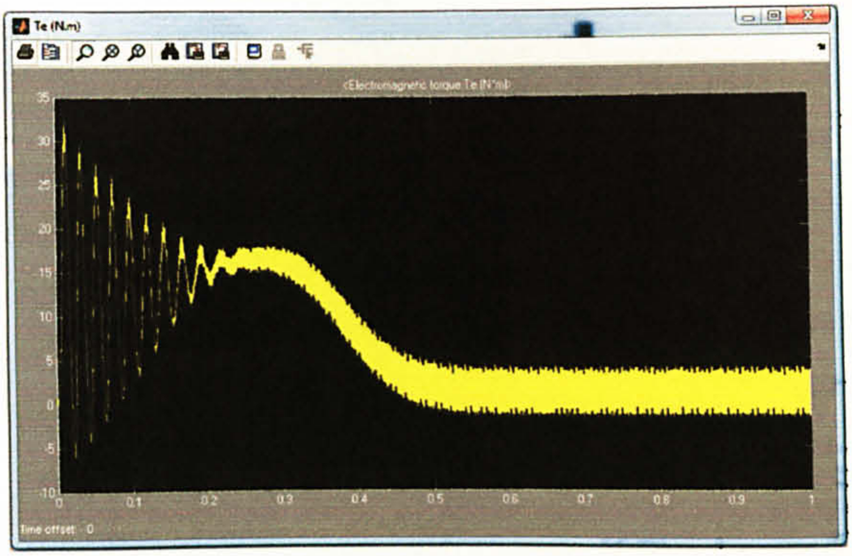

Figure 39: Electromagnetic torque of the motor

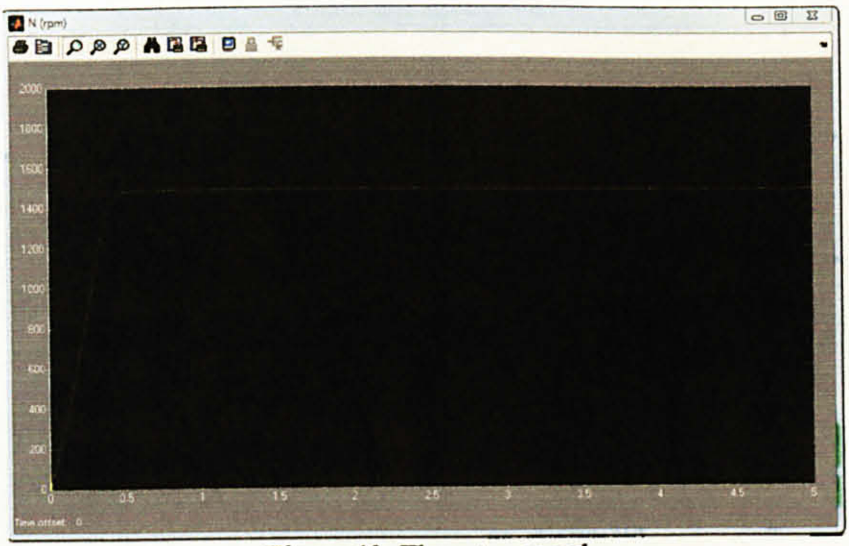

Figure 40: The rotor speed

When rpm value of 1500 in insert into the block diagram, (Figure 40) the rpm value show a very fast movement from 0 to 1485 rpm in just 0.5 seconds. The speed will never be 1500rpm since an induction motor can thus speed up to near synchronous speed, but ic can never exactly reach synchronous speed. If the induction motor's rotor were turning at synchronous speed, then the rotor bars would be stationary relative to the magnetic field and there would be no induced voltage. If it turns to zero, so there would be no rotor current and no rotor magnetic field. With no rotor magnetic field, the induced torque would be zero and the rotor would slow down as a result of friction losses.

For other frequency signal value, the motor speed is corresponding to its value as shown in Figure 41

Signal frequency (Hz)	Motor speed (rpm)
10	298
20	600
30	895
40	1190
50	1485
60	1775
70	2066
80	2355
90	2645
100	2930

Figure 41: The table of signal frequency and its corresponding motor speed.

4.4 Motor speed control by varying the frequency and rpm

To change the speed of induction motor using by changing the frequency, it is needed to identify the specific frequency available at the model. There are two type of frequency variable that are important in PWM speed control technique that are the fundamental signal frequency and the carrier frequency. The motor will received the power from the signal frequency and it is a constant value as shown in Figure 42 While carrier frequency is the modulation frequency for the PWM technique.

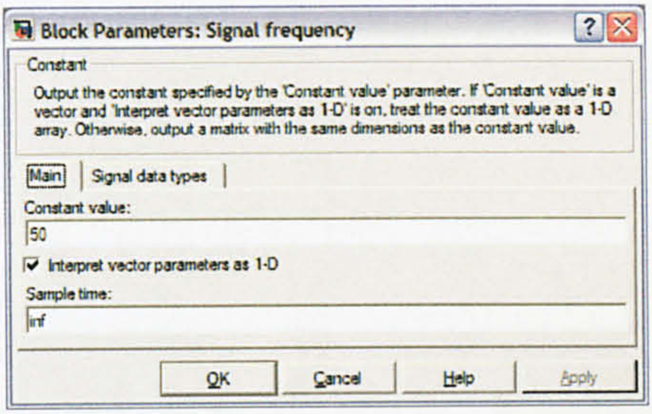

Figure 42: Signal frequency block parameter

Thus, user needs to change the signal frequency value to control the speed of induction motor. The change can be made at the Signal Frequency block Parameter. It is just so simple by clicking at the Signal Frequency block at the simulink and one small window will pop up and there is a space where user can just simply put the desire values to change the speed of the induction motor.

If user is more likely to use rpm mode, it also just simple as clicking the RPM block at the parameter. By manipulating the equation (1), the block diagram is designed as shown in Figure 43

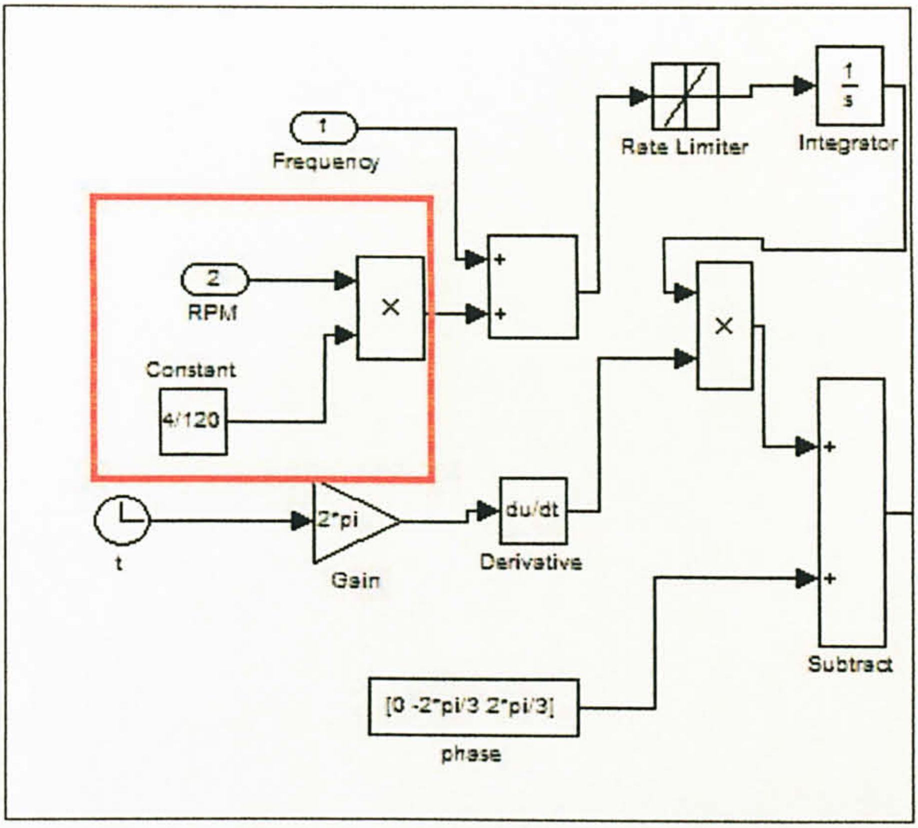

Figure 43: Designing the RPM value

In the simulation of varying the signal frequency (Figure 44), the initial speed is set to be 20 Hz. The speed increase immediately and maintained after 5 seconds. When the value is changed to 80 Hz, the large increase will make the speed of the motor increase gradually for about 3 seconds from 600 rpm until it reaches the constant speed of 2355 rpm. Then, the signal frequency is changed to 40 Hz and the speed decreased to 1190 rpm. After 15 second from starts, the frequency is changed to 100Hz and the speed slowly increases to 2930 rpm. Then, the signal frequency is set to be 10 Hz and the speed of the motor also drop immediately to 298 rpm as shown in Figure 44 below.

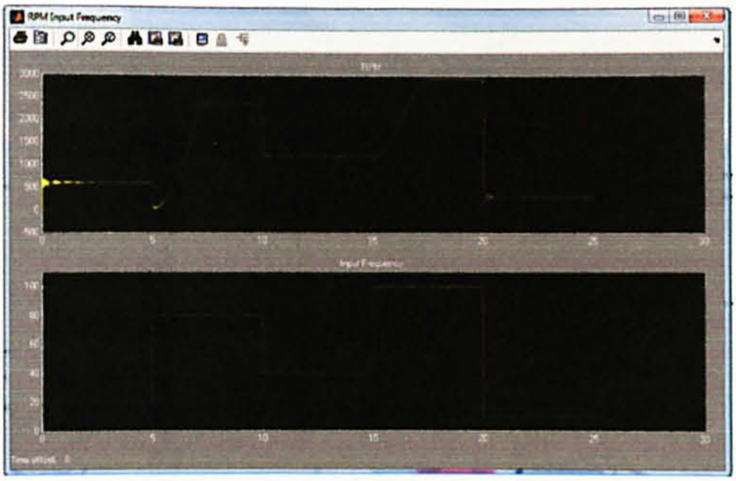

Figure 44: The rotor speed variation

The resulted waveform shows the unstable increase and decrease rate of every speed increment and decrement. To prevent the unstable condition of speed changing, a ramp system should be implemented in the signal frequency control.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Generally, the induction motor is chosen in this project because of its rugged construction, absence of brushes (which are required in most DC motors) and the ability to control the speed of the motor. The control of speed is using the PMW technique.

Thus, in this project, the focus is on the development of the control algorithm using Matlab/Simulink software. The design meets the requirement of varying the frequency to control the speed, acceleration and deceleration function.

At the end of this project, all of the objectives for this project had successfully achieved. Author had already covers the study of speed control technique using the PWM technique as long as the general characteristic of the three-phase induction motor. Author also had successfully come out with the PWM control algorithm to control the speed of induction motor by manipulating electrical frequency using Matlab/Simulink.

The control algorithm now can further be continued on hardware implementation. This project can be improved by implementing ramp function to make the motor safe from damaged with sudden change. This project also can be improved by implementing reverse direction function so that the motor can run both forward and reverse direction.

REFERENCES

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[9] http://www.netrino.com/Embedded-Systems/How-To/PWM-Pulse-Width-Modulation

GHANTT CHART

	First Semester July 2008		Start Date	End Date
	Final Year Project Planning Schedule July 2008 : Three-phase Induction Motor Speed Control Using IGBTs and Pulse Width Modulation Technique	16 weeks	21/Jul/08	7/Nov/08
1	Project selection	2 weeks	21/Jul/08	1/Aug/08
2	Study the main principle for the Induction Motor Speed Control	5 weeks	28/Jul/08	29/Aug/08
3	Preliminary Report Submission	1 week	19/Aug/08	1/Sep/08
4	Closed Presentation 1: Main Principle for Induction Motor Speed Control	1 day	2/Sep/08	2/Sep/08
5	Study and research on Pulse Width Modulation	4 weeks	3/Sep/08	8/Sep/08
6	Closed Presentation 2: Pulse Width Modulation	1 day	9/Sep/08	9/Sep/08
7	Study and research on Insulated Gate Bipolar Transistors	5 weeks	1/Sep/08	3/Oct/08
8	Closed Presentation 3: Insulated Gate Bipolar Transistors	1 day	8/Oct/08	8/Oct/08
9	Progress Report Submission	1 week	8/Sep/08	12/Sep/08
10	Seminar 1	1 week	8/Sep/08	12/Sep/08
11	Mid Semester Break	1 week	27/Sep/08	7/Oct/08
11	Development for simulation of the PWM Signal using Simulink	3 weeks	29/Sep/08	17/Oct/08
12	Draft Report Submission	1 week	7/Oct/08	13/Oct/08
13	Simulation using Simulink	1 week	20/Oct/08	24/Oct/08
14	Closed Presentation 4: Pre Oral Presentation	1 day	24/Oct/08	24/Oct/08
15	Interim Report Submission	1 week	21/Oct/08	27/Oct/08
16	Oral Presentation	1 day	4/Nov/08	4/Nov/08
17	Study Week	1 week	1/Nov/08	9/Nov/08
18	Exam Week	3 weeks	10/Nov/08	28/Nov/08
19	End of Semester Break	7 weeks	29/Nov/08	18/Jan/09

	Second Semester January 2009		Start Date	End Date
	Final Year Project Planning Schedule July 2008 : Three-phase Induction Motor Speed Control Using IGBTs and Pulse Width Modulation Technique	14 weeks	19/Jan/09	24/Apr/09
1	Develop and implementation the program	7 weeks	19/Jan/09	6/Mar/09
2	Progress Report 1 submission	1 week	9/Feb/09	13/Feb/09
3	Closed Presentation 1:	1 day	27/Feb/09	27/Feb/09
4	Improvement on Project	6 weeks	9/Feb/09	20/Mar/09
5	Closed Presentation 2	1 day	9/Mar/09	9/Mar/09
6	Submission of Progress Report 2	1 week	9/Mar/09	13/Mar/09
7	Seminar (compulsory)	1 week	9/Mar/09	13/Mar/09
8	Improvement on Project	4 weeks	9/Mar/09	3/Apr/09
9	Closed Presentation 3: improvement on project	1 day	20/Mar/09	20/Mar/09
10	Mid Semester Break	1 Week	21/Mar/09	29/Mar/09
11	Poster Exhibition	1 week	30/Mar/08	5/Apr/08
12	Closed Presentation 4 : Pre Final Preparation	1 day	8/Apr/09	8/Apr/09
13	Draft Report			24/Apr/09
14	Submission of Dissertation (soft bound)			4/May/09
15	Technical Report			4/May/09
16	Study Week	1 week	2/May/09	10/May/09
17	Exam Week	3 weeks	11/May/09	29/May/09
18	Submission of Project Dissertation (Hard Bound)	1 week	20/Apr/09	24/Apr/09
19	Oral Presentation		1/Jun/09	4/Jun/09
20	End of Semester Break	7 weeks	30/May/09	19/Jul/09