Palestine Polytechnic University

College of Engineering & Technology

Electrical & Computer Engineering Department

Graduation Project

Speed Torque Control Of Single Phase Induction Motor Using Solid State Converter

Project Team

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Abstract

By the advent of power electronic and microelectronic devices and circuits, together with their steadily cost reduction, single phase induction motors (SPIM's) increasingly are considered as variable speed drives in recent years, especially, in the applications that need higher efficiency of low power drives . This project provides improved performance of the (SPIM) by operating it as two phase induction motor fed from two phase solid state converter. It improved the motor starting, ratd, and maxmum torques , the overall motor efficiency increased. The motor operated on closed loop speed control. It is controlled using PWM technique generated by Mat.Lab.

The system is tested experimentally. The simulation of the motor and the converte is presented using suitable software programs ; Mat. Lab and Simplorer. The simulation and some expiremental reults are presend.

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CHPTER ONE

Introduction

1.1 General Description For The Project

The project aims to operate a single phase induction motor (SPIM) as two phase induction motor , with purpose to run the motor at two windings instead of one running winding only . So the team designed and built a two phase solid state converter to drive the motor , where the converter is controlled by pulse width modulated sinusoidal (PWMS) generated by Matlab. It achieves 90 electrical degrees phase shift between the motor two currents . A closed loop control system is designed to control the motor speed. The motor is simulated using MATLAB software. The system is tested experimentally using Matlab and simplorer programs, some experimental results are presented.

1.2 Project Significance

The following can be achieved

- Operating the motor without need of additional mechanical switching components, therefore reducing the mechanical elements in such motors .
- Operating the motor without need to start and run capacitors.
- Increasing the starting and the rated torque of the motor with purpose to carry heavy loads at starting.
- Increasing the motor efficiency through improving the phase shift between the motor windings to be closed at approximately 90 dg time shifting, and reducing the flux harmonics and torque pulsations .
- The motor speed is controlled to operate in a wide speed range . So it will be significant in the applications operates at variable speed modes.

1.3 Applications of (SPIM)

Because of ruggedness and low price, single-phase induction motors are widely used in several commercial and domestic applications.

Although their performance is inferior when compared to that of poly-phase induction motors, they are still commonly used in small ratings where the three-phase supply is not usually available.

Some Applications

- Heating, ventilation, and air conditioning (HVAC) .Which needs variable speed modes to minimize power consumption.
- Low power industrial plants.
- Widely used in households.

1.4 Previous Studies

1. Modeling and simulation of single phase induction motor with adjustable switched capacitor . (Sedat Sunter, Mehmet Ozdemir, Belal Gumus) .

This Study is interested in controlling the starting torque by adjusting the switched capacitor connected with the auxiliary winding of the SPIM .But it still needs additional mechanical components . It does not guarantee 90° electrical degrees as phase shift between the main and the auxiliary currents of the (SPIM) .

2. Torque Control for a Single-Phase Induction Motor. J. L. Romeral, E. Aldabas, T. Arias.

In this study, the run capacitor of (SPIM) is a switched capacitor , the starting torque of the motor improved , and also the torque in the overall speed range . But the motor operation stills dependent on the value of the capacitor.

1.5 Time Plan

The time of the project is scheduled over 32 weeks; table 1.1 shows how the work scheduled over these weeks:

Week	1 2	3 4	5 6	7 8	9 10	11 12	13 14	15 16	17 18	19 20	21 22	23 24	25 26	27 28	29 30	31 32
Choosing The Project Subject	■															
Collecting, studying, and analyzing information		■	■	■	■	■										
Simulation						■	■									
Documentation and submitting the proposal							■	■								
Selecting and buying the hardware devices									■	■	■	■	■			
System implementation and testing												■	■	■	■	
Documentation and Submitting the project														■	■	■

Table(1.1) Project Time Plan

1.6 Project Cost

Component name	#	Price per component/NIS	Total price/NIS
IGBT (IRG4PC50S)	8	64	452
Opto-coupler (PC817)	8	4	32
Bridge rectifier	2	8	16
Diodes (999)	16	1	16
Capacitors 330μF	4	3	12
Capacitors 0.1μF	8	1	8
Board	4	10	40
Resistors	37		15
Packaging			70
Others			150
Total cost			**910**

Table(1.2): Project Cost

1.7 Project Contents

The project is divided into six chapters, follow each other logically to complete the design , simulate, and test it. Chapter 1 is an introductory description ,chapter 2 talks about the theory and modeling of the SPIM . chapter 3 includes the electrical design , chapter 4 includes the control design , chapter 5 contains the simulation and experimental results, chapter 6 summarizes the conclusions and presents some recommendations.

Chapter 1: Provides an introduction to the project, defines the objectives, applications, and project significance.

Chapter 2: Presents the theory of the induction motor , then specializes in single phase induction motors (SPIM's) ; theory and modeling.

Chapter 3: Electrical design of the converter (rectifier and inverter) according to the motor requirements. It contains thermal and electrical protection.

Chapter 4: Control of the (SPIM), concluding automatic speed control using computer, and needed interface device.

Chapter 5: Realization and simulation.

Chapter 6: Conclusions and recommendation.

CHAPTER TWO

Introduction to the Induction Motor

2.1.1 Construction and Operation of Induction Motor

The induction motor consists of two main parts, the stator and the rotor. The stator core consists of a stack of slotted ring shaped laminations blotted together in cylindrical core shape. The rotor of an induction motor is a slotted laminated cylinder. There are windings in the slots of two major types. One is the squirrel-cage winding which consists of heavy copper bars connected at each end with a metal ring, see figure (2.1) .The other is a wound rotor that consists of actual coils placed in the rotor slots.

Some of industrial applications of induction motors are : washing machines, refrigerator compressors, bench grinders, table saws, cutting machines ...

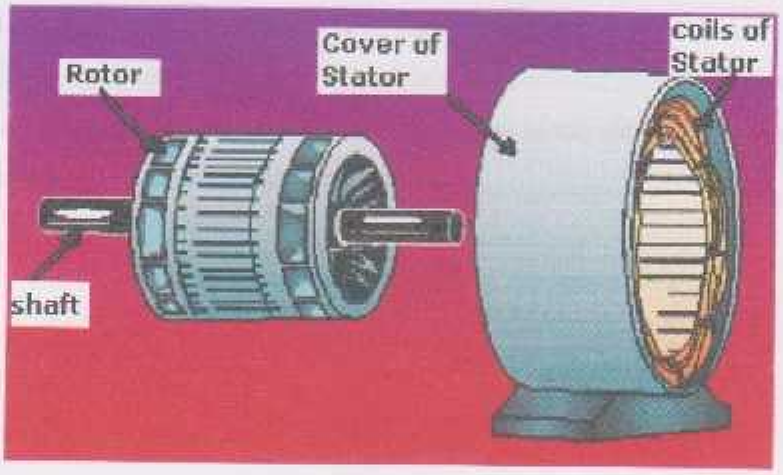


Figure 2.1 Stator and rotor construction of induction motor

2.1.2 Principle of Operation

In order for an induction motor to operate, we need to have a rotor with a short circuited winding inside a stator with a rotating magnetic field. The flux from the rotating field cuts through the rotor winding and induces a current to flow. The frequency of the current flowing is equal to the difference between the rotational speed of the stator field and the rotor. The rotor current causes a rotor magnetic field which is spinning relative to the rotor at the rotor current frequency and relative to the stator, at the same frequency as the stator field[1].

The interaction between these two magnetic fields generates the torque in the rotor. There must always be a small difference in speed between the stator field and the rotor in order to induce a current flow in the rotor. This difference in speed or frequency is known as the *slip*.

In three phase induction motor three identical windings are placed 120 electrical degrees in space phase with respect to each other . When these windings are excited by a balanced three-phase source , they set up a uniform magnetic field that revolves around the rotor periphery at synchronous speed . The flux cutting action induces an electromotive force (emf) and thereby a current in the rotor conductors . The interaction of the rotor current and the revolving magnetic field causes the rotor to rotate at speed somewhat lower than the synchronous speed[1] .

2.2 Single Phase Induction Motor (SPIM)

2.2.1 Construction and Operation on one Winding

If we take a stator with a single winding, and apply a single phase voltage to it, we will have an alternating current flowing and thereby an alternating magnetic field at each pole. Unfortunately, this does not result in a rotating magnetic field, rather it results in two equal rotating fields, one in the forward direction and one in the reverse direction. If we have a short circuited rotor within the stator, it will carry rotor current induced by the stator field, but there will be two equal and counter rotating torque fields This will cause the rotor to vibrate but not to rotate. In order to rotate, there must be a resultant torque field rotating in one direction only. In the case of the single winding and a stationary rotor, the resultant torque field is stationary. See figure 2.2

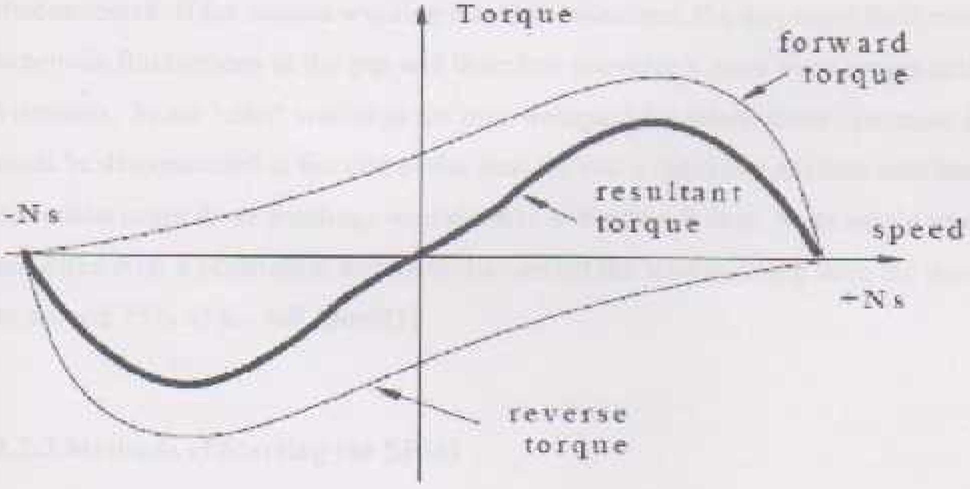


Figure2.2 : Mechanical Characteristic of SPIM for Stationary Rotor

2.2.2 Two Windings Operation

Now, if a second winding is added and physically displaced from the first winding, and apply a voltage equally displaced in phase, we will provide a second set of counter rotating magnetic fields, the net result is a single rotating field in one direction. If we reverse the phase shift of the voltage applied to the second winding, the resultant magnetic field will rotate in the reverse direction.

Once the rotor is up to full speed, it will continue to run with the second winding disconnected. If we consider the magnetic field rotating in the same direction as the rotor, the frequency of the current will be low, so the rotor current will be primarily limited by the rotor resistance. In the case of the counter rotating field, the frequency of the induced current will be almost twice line frequency and so the inductance of the rotor will play a much greater role in limiting the rotor current. In other words, once the motor is up to speed, it will lock on to one field only and the second winding can be disconnected. If the second winding remains connected, the displaced field reduces the magnetic fluctuations in the gap and therefore provides a more even torque and less vibration. Some "start" windings are only designed for intermittent operation and they must be disconnected at the end of the start. In some induction motors, continuous operation using these windings would cause a winding failure. Most single phase motors are fitted with a centrifugal switch to disconnect the start winding once the motor is close to around 75% of the full speed[1].

2.2.3 Methods of Starting the SPIM

2.2.3.1Capacitor Start

A capacitor is connected to the auxiliary winding to provide phase shift between the two phases. The motor will operate firstly as a "two phase" motor while the switch is closed. When the motor is almost up to speed, the switch opens disconnecting the auxiliary winding and the capacitor. The motor can be reversed by reversing the connections of either the main or the auxiliary winding (but not both!)

The start winding and the start capacitor provide for a rotating magnetic field in one direction enabling the motor to start. The figure (2.3) shows the motor circuit and characteristic[1].

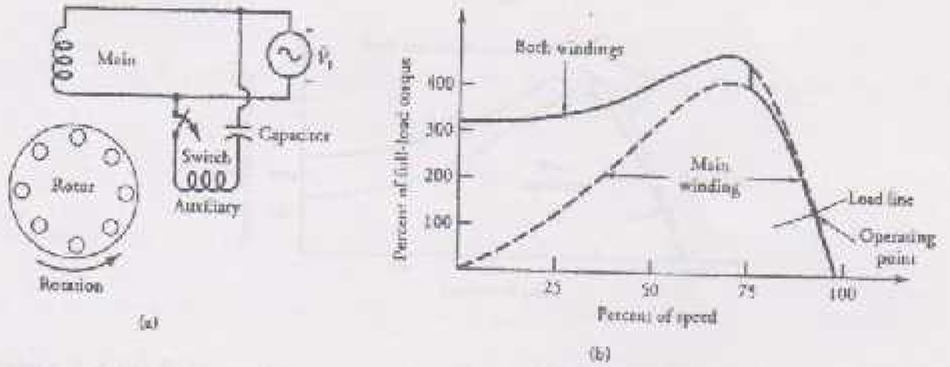


Figure 2.3 **(a)** Schematic representation and **(b)** Speed-torque characteristic of a cap-start motor.

2.2.3.2 Capacitor Start Capacitor Run

The capacitors provide a phase shift to the current flowing in the auxiliary winding and we therefore have a "two phase" motor. When the motor is almost up to speed, the switch opens disconnecting the start capacitor, where the run capacitor remains in the circuit to provide a continued second phase, reducing torque pulsations and noise. The motor can be reversed by reversing the connections of either the main or the auxiliary winding.

The start winding and the capacitors provide for a rotating magnetic field in one direction enabling the motor to start. Figure (2.3) shows the motor circuit and characteristic.

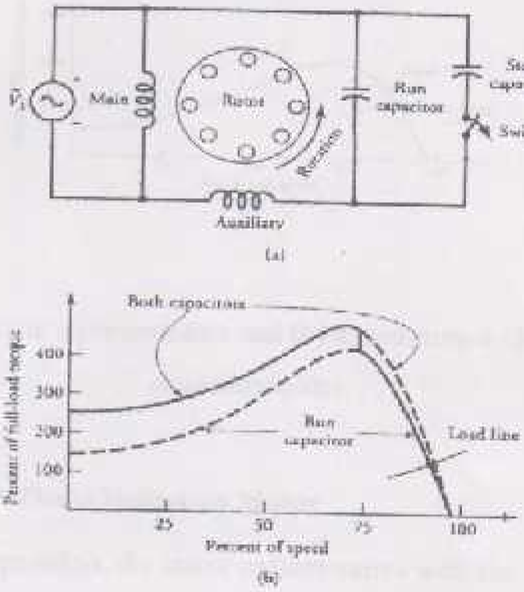


Figure 2.4 (a) Schematic representation and (b) Speed-torque characteristic of a cap-start cap-run motor.

2.2.3.3 Capacitor Start/Run

In this method, just one capacitor is connected to start the motor , and remains connected during motor running as figure (2.5) shows. In this method, the torque is improved with less torque pulsations[1] .

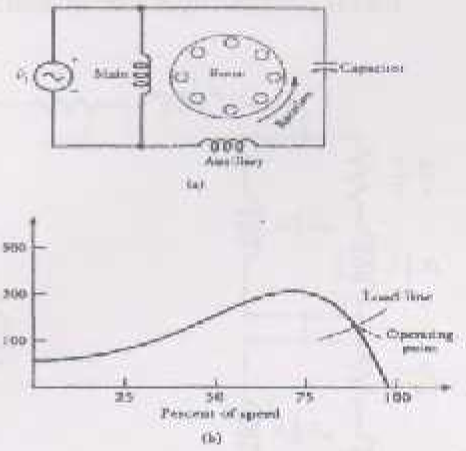


Figure 2.5 (a) Schematic representation and **(b)** speed-torque characteristic of a capacitor motor.

2.2.4 Modeling of Single Phase Induction Motor

During the steady-state operation, the stator current varies with the stator voltage frequency, while the rotor current varies with the slip frequency .

2.2.4.1 The Slip (s)

In forward

$$s = \omega_s - \omega / \omega_s \qquad \textbf{(2.1)}$$

In backward

$$s_b = 2 - s \qquad \textbf{(2.2)}$$

2.2.4.2 Single Phase Induction Motor Equivalent Circuit

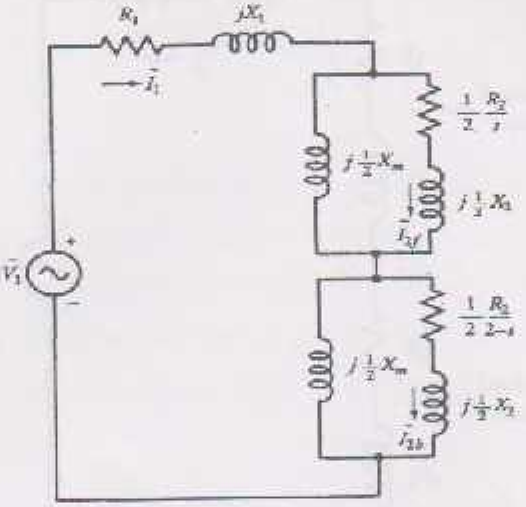


Figure 2.6 Equivalent circuit of SPIM.

2.2.4.3 Analysis of a Single-Phase Induction Motor

From the equivalent circuit of a single-phase induction motor (Figure 2.6), we obtain

$$Z_f = R_f + jX_f = 0.5\frac{jX_m[R_2/s + jX_2]}{R_2/s + j(X_2 + X_m)} \quad \text{.............................(2.3)}$$

as the effective impedance of the forward branch and

$$Z_b = R_b + jX_b = 0.5\frac{jX_m[R_2/2-s + jX_2]}{R_2/2-s + j(X_2 + X_m)} \quad \text{.............................(2.4)}$$

as the effective impedance of the backward branch.

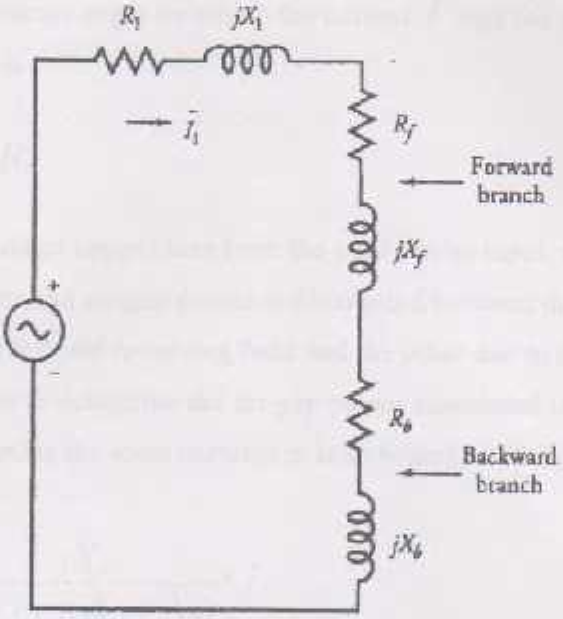


Figure (2.7): Simplified equivalent circuit of a single-phase induction motor.

The impedance of the stator

$$Z_1 = R_1 + jX_1 \text{..} (2.5)$$

The input impedance

$$Z_{in} = Z_1 + Z_f + Z_b \text{..} (2.6)$$

The stator winding current is

$$I1 = \frac{V1}{Zin} \text{..} (2.7)$$

The input power The power input is

$$P_{in} = R_e[V1I_1] = V_1 I_1 \cos\varphi \text{...} (2.8)$$

where θ is the power-factor angle by which the current I lags the applied voltage V_1. The stator copper loss is

$$P_{scl} = I_1^2 R_1 \tag{2.9}$$

When we subtract the stator copper loss from the total power input, we are left with the air-gap power. However, the air-gap power is distributed between the two air-gap powers: one due to the forward revolving field and the other due to the backward revolving field. In order to determine the air-gap power associated with each revolving field, we have to determine the rotor currents in both branches. If the rotor current in the forward branch, then

$$I_{2f} = \frac{jX_m}{R_2/s + j(X_2 + X_m)} * I_1 \tag{2.10}$$

Similarly, the rotor current in the backward branch I_{2b} is

$$I_{2b} = \frac{jX_m}{R_2/(2-s) + j(X_2 + X_m)} * I_1 \tag{2.11}$$

Hence, the air-gap powers due to the forward and backward revolving fields are

$$P_{agf} = I^2_{2f} R_2 \frac{0.5}{s} \tag{2.12}$$

$$P_{agb} = I^2_{2b} R_2 \frac{0.5}{s} \tag{2.13}$$

Since R_f and R_b are the equivalent resistances in the forward and backward branches of the rotor circuit, the power transferred to the rotor must also be consumed by these resistances. In other words, we can also compute the air-gap powers as

$$P_{agf} = I^2_{2f} R_f \tag{2.14}$$

for the forward branch and

$$P_{agb} = I^2_{2b} R_b \tag{2.15}$$

for the backward branch.

The net air-gap power is

$$P_{ag} = P_{agf} - P_{agb} \qquad (2.16)$$

The mechanical power developed by the motor is

$$P_d = (1-s)P_{ag} - T_d\omega_m = T_d(1-s)\omega_s \qquad (2.17)$$

Hence, the torque developed by the single-phase motor is

$$T_d = \frac{P_{ag}}{\omega_s} \qquad (2.18)$$

The power available at the shaft is

$$P_o = P_d - \mathrm{P}_r \qquad (2.19)$$

where P_r is the rotational loss of the motor. In this case, the rotational loss consists of the friction and windage loss, the core loss, and the stray-load loss. The load (shaft) torque of the motor is

$$T_l = \frac{P_o}{\omega_m} \qquad (2.20)$$

Finally, the motor efficiency is the ratio of the power available at the shaft P_o to the total power input

We could also have computed the torque developed by the forward and the backward revolving fields as

$$T_{df} = \frac{P_{agf}}{\omega_s} \qquad (2.21)$$

$$T_{db} = \frac{P_{agb}}{\omega_s} \qquad (2.22)$$

The net torque developed by the motor is

$$T_d = T_{df} - T_{db} \qquad (2.23)$$

The torques developed, T_{df} and T'_{db}, are plotted in Figure 2.8. These curves are also extended into the region of negative speed. This is usually done to show the torque that must be overcome when the motor is driven in the backward direction by a prime mover[1].

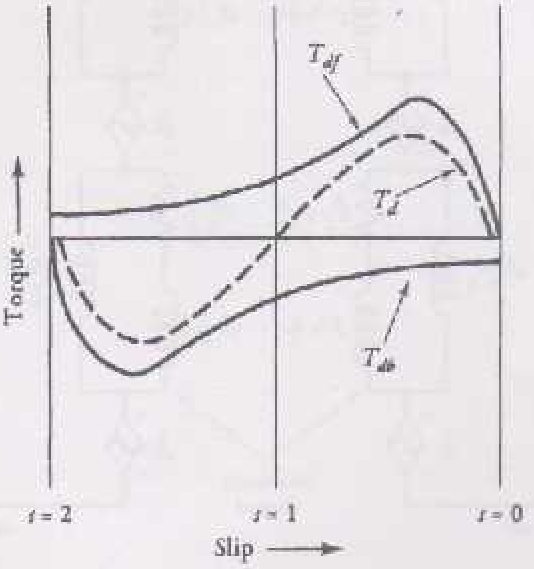


Figure 2.8 Speed-torque characteristic of a single-phase induction motor.

2.2.4.4 Analysis of a Single-Phase Motor Using Both Windings

We already knew how to determine the performance of a single-phase motor running on the main winding only. The analysis of the motor when it runs on both windings can be determined by following the same procedure of single phase operation with some modifications.

The figure 2.9 shows the equivalent circuit of the motor

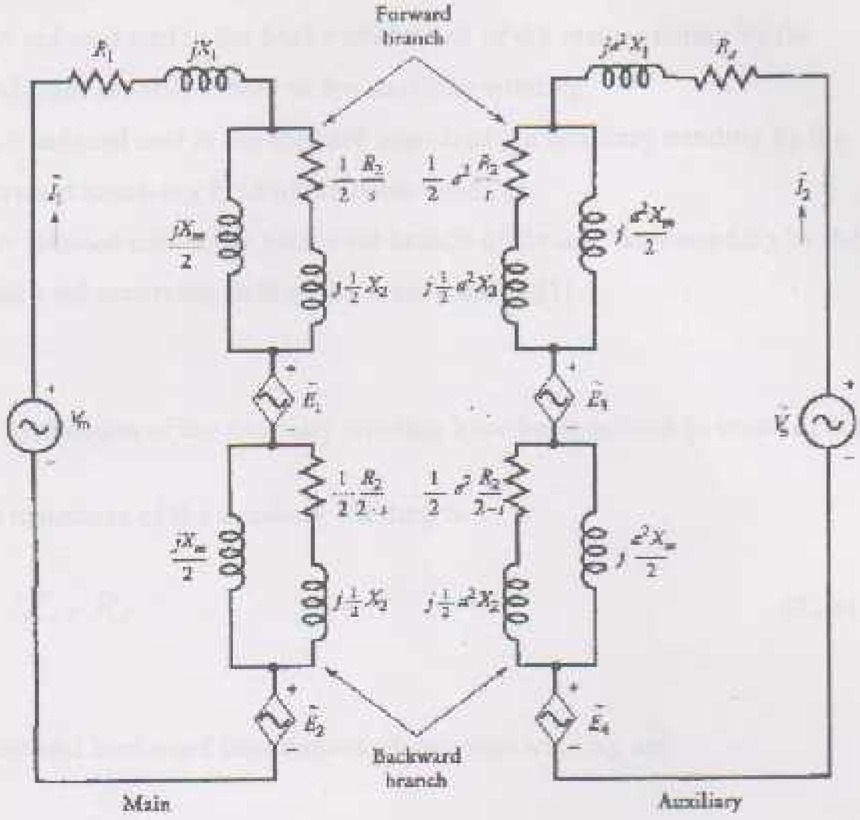


Figure 2.9 Equivalent circuit of tow phase induction motor.

where

R_1 = resistance of the main winding

X_1 – leakage reactance of the main winding

a = ratio of effective turns in the auxiliary winding to effective turns in the main winding

R_2– rotor resistance as referred to the main winding at standstill

X_2 = rotor leakage reactance as referred to the main winding

X_m = the magnetization reactance of the motor as referred to the main winding

Ra = resistance of the auxiliary winding

E_1 = induced emf in the forward branch of the main winding by the forward revolving field of the auxiliary winding

E_2= induced emf in the backward branch of the main winding by the backward revolving field of the auxiliary winding

E_3 = induced emf in the forward branch of the auxiliary winding by the forward revolving field of the main winding

E_4– induced emf in the backward branch of the auxiliary winding by the backward revolving field of the main winding[1]

The other parameters of the auxiliary winding have been defined in terms of the a-ratio.

The stator resistance of the auxiliary winding is

$$Z_a = R_a \tag{2.24}$$

The forward and backward impedances of the main winding are

$$Z_f = R_f + jX_f = 0.5\frac{jX_m[R_2/s + jX_2]}{R_2/s + j(X_2 + X_m)} \tag{2.25}$$

$$Z_b - R_b + jXb = 0.5\frac{jX_m[R_2/(2-s) + jX_2]}{R_2/(2-s) + j(X_2 + X_m)} \tag{2.26}$$

A simplified equivalent circuit of a two-winding single- phase induction motor is given in Figure 2.10.

The induced emfs in the main winding by its forward and backward revolving fields are

$$E_{fm} = I_1 Z_f \tag{2.27}$$

$$E_{bm} = I_1 Z_b \tag{2.28}$$

The induced emf in the auxiliary winding by its forward and backward revolving fields are

$$E_{fa} = I_2 a^2 Z_f \tag{2.29}$$

$$E_{ba} = I_2 a^2 Z_b \tag{2.30}$$

Since the main winding is displaced 90° electrical ahead of the auxiliary winding, the induced emf in the main winding by the forward revolving field of the auxiliary winding must lag by 90° the induced emf in the auxiliary. In addition, the induced emf in the main winding must be 1/a times the induced emf in the auxiliary. That is,

$$E_1 = -j\frac{1}{a}E_{fa} = -jaI_2 Z_f \tag{2.31a}$$

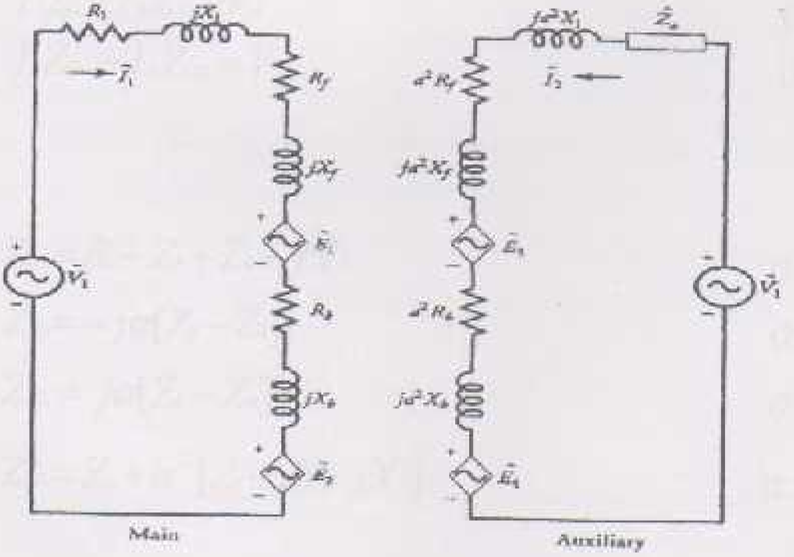


Figure 2.10 Simplified version of figure 2.9.

By the same token, the induced emf in the main winding by the backward revolving field set up by the auxiliary winding must lead by 90^0 the emf it induces in the auxiliary winding. Thus,

$$E_2 = jaI_2Z_b \qquad (2.31b)$$

Similarly, the induced emfs in the forward and backward branches of the auxiliary winding by the forward and backward revolving fields of the main winding are

$$E_3 = jaI_{1f} \qquad (2.31c)$$

$$E_4 = -jaI_{1b} \qquad (2.31d)$$

Since all the induced emfs are now known, the application of Kirchhoff's voltage law to the coupled circuit yields

$$\mathbf{I}_1(R_1 + jX_1) + E_{fm} + E_{bm} + E_1 + E_2 = V_1 \qquad (2.32)$$

$$\mathbf{I}_2(\mathbf{Ra} + jaX_1) + E_{fa} + E_{ba} + E_3 + E_4 = \mathbf{V}_2 \qquad (2.33)$$

After substituting for the induced emfs, we can express the above equations in concise form as

$$I_1Z_1 + I_2Z_{12} = V_1 \qquad (2.34)$$

$$I_1Z_{21} + I_2Z_{22} = V_2 \qquad (2.35)$$

where =

$$Z_{11} = R_1 + Z_f + Z_b + jX_1 \qquad (2.36a)$$

$$Z_{12} = -ja[Z_f - Z_b]] \qquad (2.36b)$$

$$Z_{21} = ja[Z_f - Z_b] \qquad (2.36c)$$

$$Z_{22} = Z_a + a^2[Z_f + Z_b + jX_1] \qquad (2.36d)$$

The currents in the main and the auxiliary windings are

$$I_1=\frac{V_1[Z_{22}-Z_{12}]}{Z_{11}Z_{22}-Z_{12}Z_{21}}, \qquad (2.37)$$

$$I_1=\frac{V_1[Z_{11}-Z_{21}]}{Z_{11}Z_{22}-Z_{12}Z_{21}}, \qquad (2.38)$$

The line current is

$$I_L=I_1+I_2 \qquad (2.39)$$

The power supplied to the motor is

$$P_{in}=\mathrm{Re}[V_1I_L]=V_1I_L\cos\theta \qquad (2.40)$$

where θ is the power-factor angle by which the line current lags the applied voltage.

The stator copper losses for both the windings are

$$P_{scl}=I^2{}_1R_1+I^2{}_2R_a \qquad (2.41)$$

By subtracting the stator copper losses from the power supplied to the motor, we obtain the air-gap power. The air-gap power is distributed among the four revolving fields in the motor. We can also write an expression for the air-gap power just as we did for the motor operating on the main winding only. However, we have to take into account the presence of speed voltages and the power associated with them. On this basis, the air-gap power developed by the forward revolving field of the main winding is

$$\begin{aligned}P_{agfm}&=\mathrm{Re}[(E_{fm}+E_1)I_1]\\&=\mathrm{Re}[(I^2{}_1-jaI_1{}^*I_2)Z_f]\end{aligned} \qquad (2.42)$$

Similarly, the air-gap power produced by the forward revolving field of the auxiliary winding is

$$\begin{aligned}P_{agfa}&=\mathrm{Re}[(Ea+E_3)I_2]\\&=\mathrm{Re}[(I^2{}_2-jaI_1{}^*I_2)Z_f]\end{aligned} \qquad (2.43)$$

The net air-gap power due to both forward revolving fields is

$$P_{agf} = P_{agfm} + P_{agfa}$$

$$= (I^2_1 + a^2 I^2_2)R_f + 2aI_1 I_2 R_f \sin\theta \qquad (2.44)$$

By the same token, the air-gap power developed by the backward revolving fields is

$$P_{agb} = (I^2_1 + a^2 I^2_2)R_b + 2aI_1 I_2 R_b \sin\theta$$

$$Pagb = Re[(Ebm + E2)I_1 + (Eba + E4)I_2] \qquad (2.45)$$

Hence, the net air-gap power developed by the motor is

$$P_{ag} = P_{agf} - P_{agb}$$

$$P_{ag} = (I^2_1 + a^2 I^2_2)(R_f - R_b) + 2a(R_f + R_b)I_1 I_2 R_b \sin\theta \quad (2.46)$$

At standstill (i.e., the blocked-rotor condition, or at the time of starting) the per- unit slip of the motor is unity. The rotor impedance in the forward and the backward branches is the same. The net air-gap power developed by the motor, from the above equation when $Rf = Rb = R$, is

$$Pags = 4aI_1 I_2 R \sin\theta \qquad (2.47)$$

Note that the net power developed at the time of starting is proportional to the sine of the angle between the currents in the two windings. The air-gap power is maximum when the angle between the currents in the windings is 90°[1] .

CHAPTER THREE

Electrical Design

3.1 Introduction

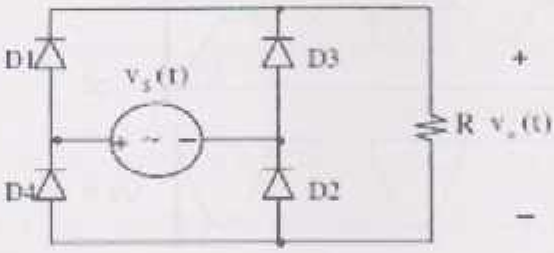
In modern drive systems of AC motors, the input ac source is rectified firstly, then, it is converted to ac source again. To control the output voltage, whether the rectifier or the inverter is controlled or both. But to achieve amplitude and frequency control, the inverter must be controlled rather than the rectifier.

3.2 Theoretical Background

3.2.1 Single Phase Full Wave Rectifier

The conversion of the electrical power from alternating current (AC) to direct current (DC) is called rectification, and their are many types of rectifiers, single phase, and poly phase [2].

Since there is no need to high voltage source to feed the motor, we are familiar with the single phase uncontrolled bridge rectifier type,



Figure(3.1) Single phase bridge rectifier

3.2.1.1 Principle of Operation

During the positive half wave, the current flows from source through diode D1 to the dc link and returns to the source through D3. And during the negative half wave, the current flows from source through D2 to the dc link and returns to the source through D4.

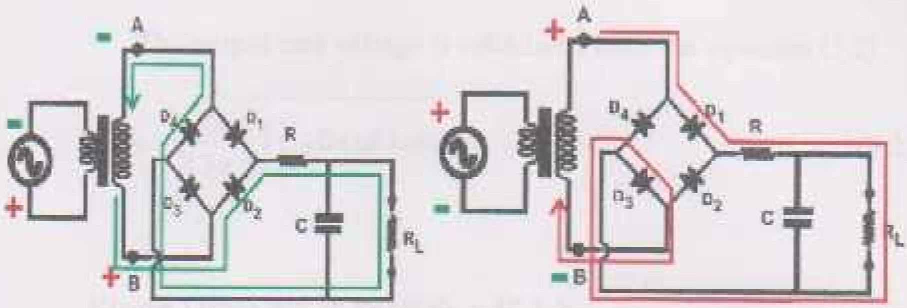


Figure (3.2a) The current path during the positive half cycle of the bridge rectifier

(3.2b) The current path during the negative half cycle of the bridge rectifier .

3.2.1.2 Rectifier Waveforms

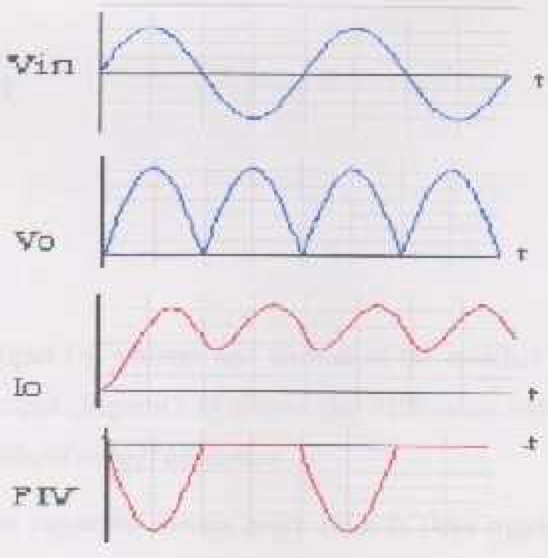


Figure (3.3) Rectifier waveforms

3.2.1.3 Rectifier Equations

The output dc voltage is calculated from the equation (3.1) .

$$V_{dc} = \frac{2}{2\pi}\int_0^\pi V_m Sin\omega t d\omega t \tag{3.1}$$

The output rms voltage is calculated from the equation (3.2) :

$$V_{rms} = \sqrt{\frac{2}{2\pi}\int_0^\pi (V_m Sin\omega t)_2 d\omega t} \tag{3.2}$$

Ripple factor RF = Pac/Pdc = 48.3 % (3.3)

Power factor PF = Pac/VA = 0.9 (3.4)

The peak-inverse-voltage (PIV) across the diode

PIV=Vm

The diode currents

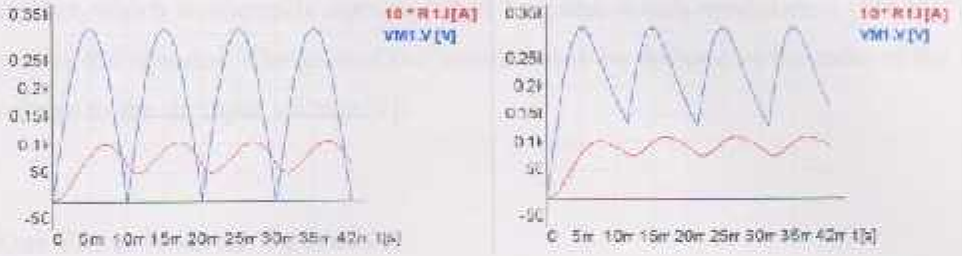
$$\mathbf{I_R = I_{rms}/\sqrt{2}} \tag{3.5}$$

$$\mathbf{I_D = I_{rms}/1.11} \tag{3.6}$$

3.2.2 DC Link

To improve the output DC voltage and current of the rectifier , capacitor is added parallel to the rectifier output .Figure(3.4) shows the difference between the case with capacitor , and the case without output capacitor .

Larger value of the capacitor means more smooth (less ripples) DC voltage and current .



(a) (b)

Figure(3.4) (a) Output current and voltage without capacitor.**(b)**Output current and voltage with capacitor.

3.2.3 Single Phase Inverter

3.2.3.1 Inverter Function

An inverter is a DC to AC converter , which function is to change a dc input voltage to a symmetric ac output voltage of desired magnitude and frequency . The output voltage could be fixed or variable at a fixed or variable frequency[2] .

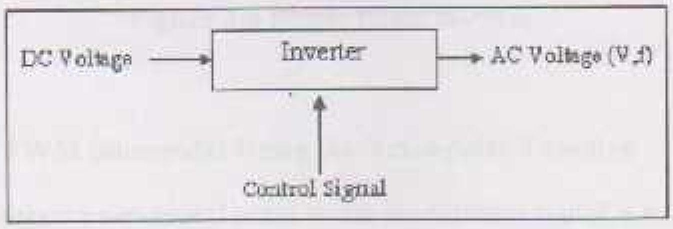


Figure (3.5) Block diagram of inverter

A variable output voltage can be obtained by varying the input dc voltage and maintaining the gain of the inverter constant. On the other hand, if the dc input voltage is fixed and not controllable, a variable output voltage can be obtained by varying the gain of the inverter, which in normally accomplished by pulse-width-modulation (PWM) control within the inverter. The gain of the inverter may be defined as the ratio of the ac output voltage to the dc input voltage[2].

3.2.3.2 One Phase Inverter Operation

Once the transistors T1 and T4 are on, so the load voltage is positive , and when T2 and T3 are on then the output voltage is negative , The free-wheeling diode protects the power switch from the reverse current produced in the case of the inductive load.

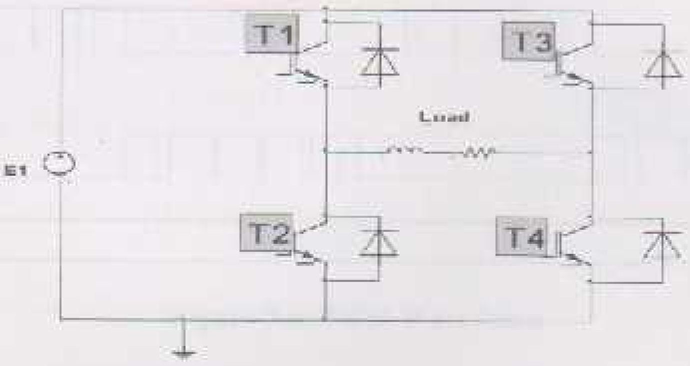


Figure 3.6 Single Phase Inverter .

3.2.4 Generation of PWM Sinusoidal Using the Triangular Function

In order to generate a sinusoidal pulse width modulation signal, a sinusoidal carrier with reference frequency f_r , and a triangular function with frequency f_c are needed, these two signals should be input to a comparator as the figure (3.7) shows to produce the PWM signal that increases in sinusoidal function.

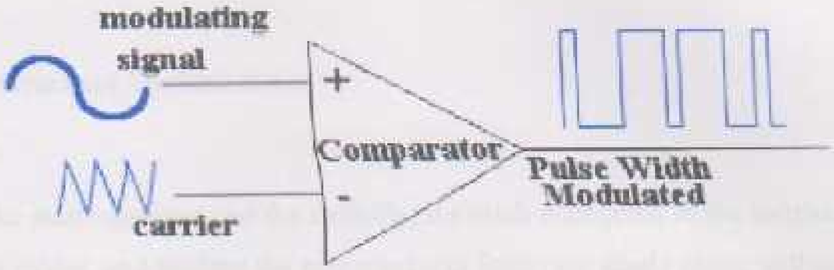


Figure 3.7 Generation of PWM sinusoidal using comparator

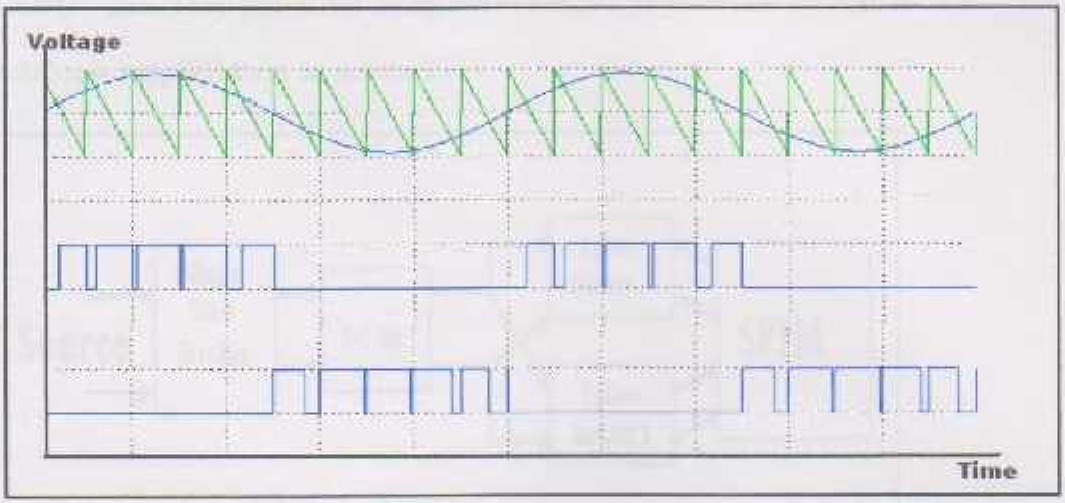


Figure 3.8: PWM Waveforms

Modulation Index

The modulation index M is the ratio between the amplitude of the reference signal (sinusoidal), and the amplitude of the carrier signal (triangular).

$$M=A_r/A_c \qquad (3.7)$$

Where A_r is the reference signal amplitude.

A_c is the triangular signal amplitude.

By varying A_r, the modulation index M changes, and thereby the output rms voltage (Vo) [2].

3.3 Motor Performance Optimization

The strategy is

1.Removing the start capacitor and the centrifugal switch connected to the auxiliary winding of the motor, and feeding the two windings from two single phase voltage source inverters shifted with 90 electrical degrees.

2.The two inverters are connected in parallel, and fed from single phase bridge rectifier through the DC link. They controlled using PWM sinusoidal generated by Matlab.

3.The rectifier is supplied from ac source 220V.

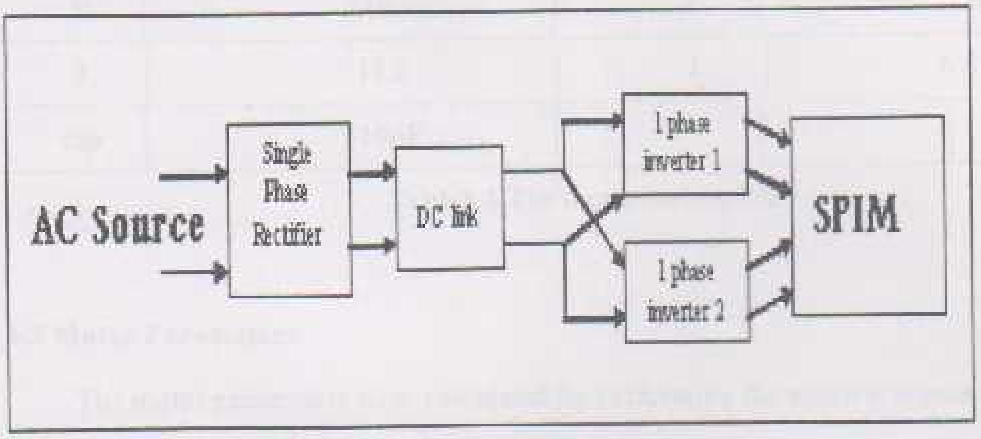


Figure 3.9 Block diagram of the converter.

3.3.1 The Tested Motor (SPIM)

The tested motor is (1hp) squirrel cage single phase induction motor with start capacitor.

3.3.2 Motor Name-Plate

SQUERIL CAGE ASYNCHRONUS MOTOR					
Type	SgoC	N: 064154S		year	79
kw	0.75 kw	Hp	1	Hz	50 Hz
RPM	1425	Ph	1	Ins.CI 5	
Amb.Tem	10	cos δ	0.76	eff	64.8
Duty	S1		Pro	TP54	
V	110 v		V	220	
I	13.6		I	6.8 A	
cap	310µF				

Table3.1 The motor name-plate

3.3.3 Motor Parameters

The motor parameters were calculated by performing the motor test presented in (appendix A) .

The Test Results

The test is contained of the three following parts

DC test: to find the resistances values of the main and auxiliary windings.

Blocked rotor test: to find the stator and rotor reactance's of the two windings and. The rotor resistance can be calculated in this test, too.

The ratio of the auxiliary winding turns to the main winding turns (a) was found in this test, too .

No load test with auxiliary winding open :

To find the magnetization reactance Xm

The table (3.2) shows the test results

Motor Parameters	
R_{m1}	4.25 Ω
R_2	3 Ω
R_{a1}	3 Ω
X_{m2}	3.6 Ω
X_{a2}	3.6 Ω
X_m	86 Ω
a	1.07
Rotational Power	116.5 Watt

Table 3.2 Motor Parameters

The Impedances of Motor Windings

According to the equivalent impedance of the motor phases, the rated motor impedances at 50Hz are

$Z_m = 24 + 20j\ \Omega$, so $\theta m = \theta 1 = \arctan(20/24) = 39.8°$

$Za = 23.15 + 20j\ \Omega$, so $\theta a = \theta 2 = \arctan(20/23.15) = 40.8°$

The rated phase shift angle $\theta = \theta 2 - \theta 1 = 1°$

3.3.4 Motor Torque At One Phase Operation

The motor rated torque Tn = hp/ ωn

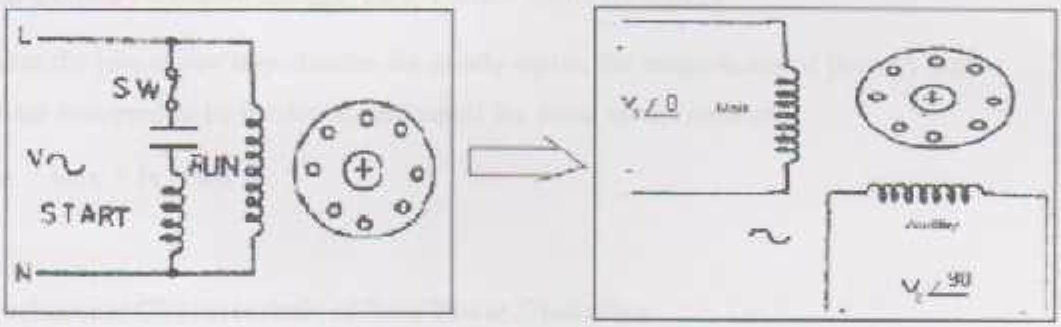
=746/149.2 = **5 Nm**

3.3.5 Operating the Motor on the Two Windings

There are two steps to operate the motor on it's two windings, see figure (3.10)

1. Removing the start capacitor and the centrifugal switch connected to the auxiliary winding of the motor .

2. The motor will operate (start and run continuously) on the two windings; the main and the auxiliary . Each winding will be fed from single phase voltage source inverter. But they are shifted by 90 electrical degrees. See figure (3.11).



Figure(3.10: Operating the motor on two windings instead of one only.

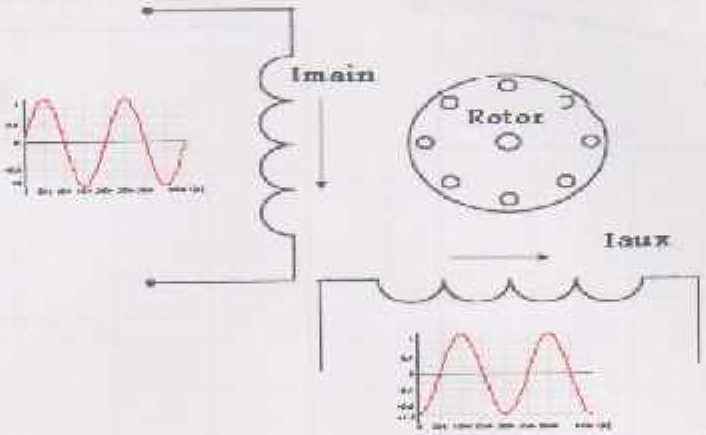


Figure 3.11 Motor Currents

3.3.6 Motor Voltages and Currents

The rated main winding voltage Vm=220 V.

The rated auxiliary winding voltage Va = Vm/a = 220/1.07 =205V.

Due to that the two motor impedances are nearly equal, the magnitudes of the two motor currents are assumed to be the same, and equal the rated motor current

Imain = Iaux = In = 6.8 A .

3.3.7 Mechanical Characteristic of Two Phase Operation

The figure below shows the optimized characteristic of the motor when it is operated on it's both windings compared with motor characteristic when it runs on one winding only. This figure represents the motor characteristic It is simulated in Matlab file located in chapter 5.

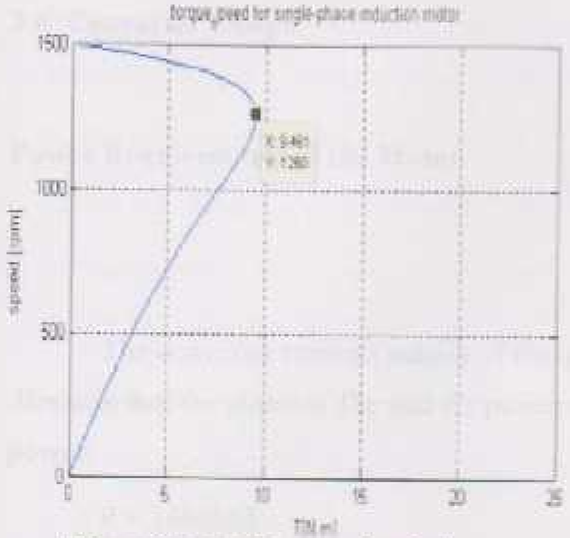


Figure 3. 12 Motor mechanical characteristic (one running winding)

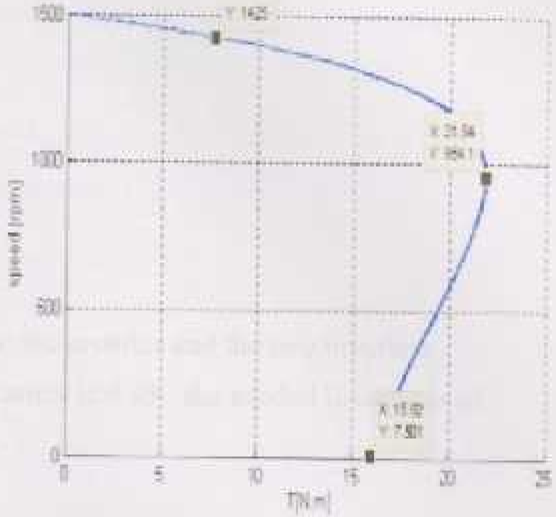


Figure 3.13 : Motor mechanical characteristic (two running windings)

This figure is very important because many motor critical values can be determined from it.

The rated torque **Tn = 7.68 Nm**

The starting torque Ts = 15.9 Nm

The maximum torque Tmax = 21.8 Nm

At torque Tmax , the speed n = 954 rpm

So, the critical slip **sm** = (1500-954)/1500= 0.364

3.4 Converter Design

Power Requirements of the Motor

The converter consists mainly of two parts; the rectifier and the two inverters .Because that the motor is 1hp and it's power efficiency is 0.65 ; the needed inverter is of power

$$P = 746/0.65$$

$$=1.2\ KW$$

The two inverters will be supplied from DC voltage through the DC link from 3 KW single phase rectifier.

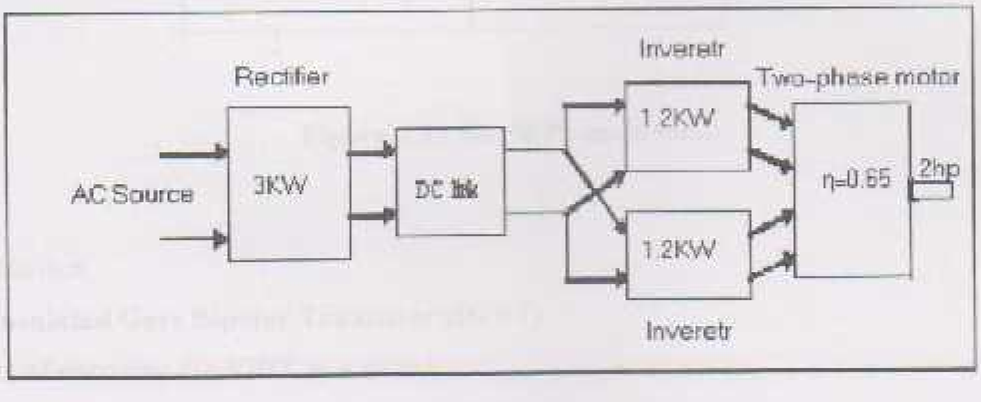


Figure 3.14 Power requirements

3.4.1 Single Phase Inverter Design

The peak inverse voltage applied on each transistor or diode equals the DC voltage .

The maximum rms current of each inverter equals the motor rated current In=6.8A.

Because the inverter operates as a rectifier in the reverse direction (AC to DC) , it's device parameters can be calculated in the same way as in the rectifier case.

So, the rms current of the IGBT ; $I_r=6.8/\sqrt{2} = 4.8A$.

The reverse blocking voltage on the IGBT ; $V_r= V_{dc} =310V$.

Taking the safety factor to be 2, the values above becomes

$I_r=2*4.8=9.6A$.

$V_r=2*310=620V$.

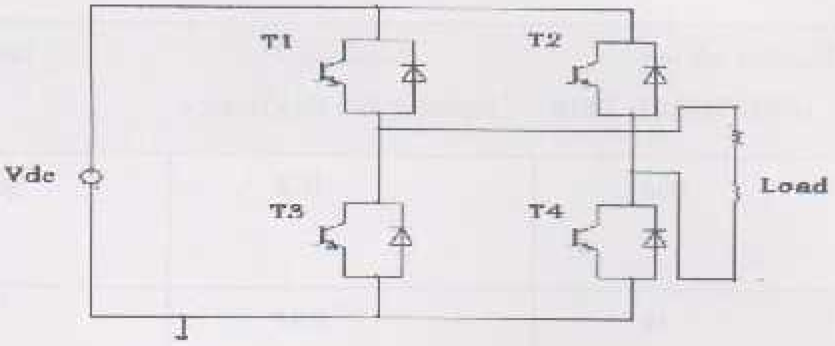


Figure 3.15 Single Phase Inverter

Chose Switch

Insulated Gate Bipolar Transistor (IGBT)

Reasons of choosing the IGBT as a switch

1) Combination of BJT and MOSFET characteristics.

Compromises include:

- Gate behavior similar to MOSFET - easy to turn on and off (doesn't need high gate current)
- Low losses like BJT due to low on-state Collector-Emitter voltage (2-3V).

2) Ratings: Voltage: $V_{CE}<3.3$kV, Current: $I_C<1.2$kA currently available. Work in under progress for 4.5kV,2kA device. Constant improvement in voltage and current ratings.

3) Good switching capability (up to 100 KHz) for newer devices.
Typical application, IGBT is used at 20-50 KHz.

4) Good forward characteristic at high voltages.

The chose IGBT is **(IRG4PC50S)** which data sheet is located in appindex(D).The table (3.1) below shows the IGBT calculated and used parameters.

Parameter	Calculated values(with safety factor)	For the selected IGBT **(IRG4PC50S)**
Blocking voltage(V)	620	600
I_{CE}(A)	10.2	41

Table 3.3 IGBT main parameters

3.4.2 Design of the Uncontrolled Bridge Rectifier

The rectifier will feed two parallel inverters, each with maximum rms current of 6.8A (The rated current of the motor for each phase), but they are spaced with 90 electrical degrees, so,

The total output rms current of the rectifier

$It= 6.8 + 6.8j$ A , so $|It| = 9.6$ A .

Taking the safety factor to be 1.5 , $|It| = 14$ A.

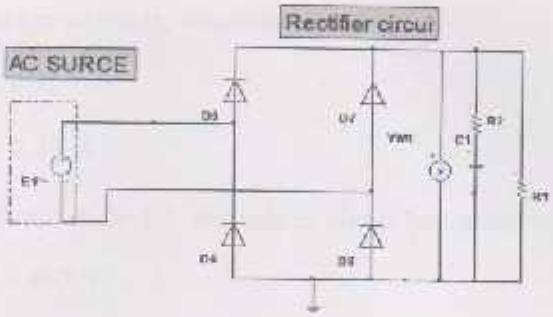


Figure 3.16 Un-controlled Bridge Rectifier

The output dc voltage is calculated from the equation (3.1) .

$$V_{dc} = \frac{2}{2\pi}\int_{0}^{\pi} V_m Sin\,\omega t d\omega t$$

For $V_{rms} = 220$ V

$$V_{dc} = \frac{2V_m}{\pi} = \frac{2 * 220 * \sqrt{2}}{\pi} = 198 \text{ V}$$

The output rms voltage is calculated from the equation (3.2)

$$V_{rms} = \sqrt{\frac{2}{2\pi}\int_{0}^{\pi}(V_m Sin\,\omega t)^2 d\omega t}$$

$$V_{rms} = \sqrt{\frac{2}{2\pi}\int_{0}^{\pi}(311\ Sin\ \omega t)^2 d\,\omega t} = 220 \text{ V}$$

The diode parameters

The peak-inverse-voltage (PIV) across the diode

$$PIV = V_m$$

$$V_m = \sqrt{2} * V_{rms} = \sqrt{2} * 220 = 311 \text{ V}$$

Diode rms and average currents, respectively are

$I_R = 9.6/\sqrt{2} = 6.8$ A.

$I_D = I_{rms}/1.11 = 6.12$ A

Taking the safety factor to be 1.5, the values above becomes :

$Vm = 311*1.5 = 467$ V

$I_R = 6.8*1.5 = 10.2$ A

The available and suitable rectifier used is a bridge rectifier with diode parameters as shown in table(3.4):

Parameter	Calculated value(with safety factor)	Used value (standard)
PIV(V)	467	600
I_R(A)	10.2	19.42

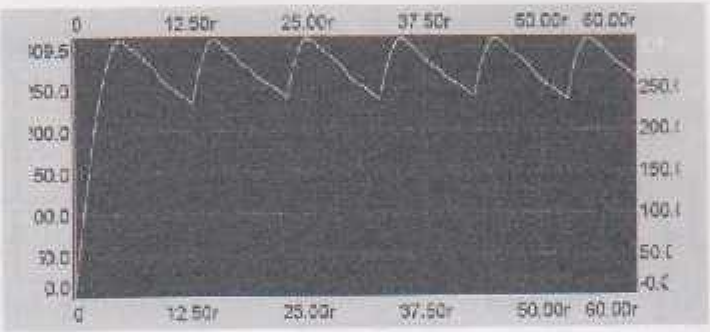
Table(3.4): Rectifier diode parameters

3.4.3 DC Link Design

The input DC voltage of the inverter Vdc = 198 V , but when the value of the smoothing capacitor is chosen carefully, the input dc voltage to the inverters can be adjusted to be 220V.

During the simulation, the suitable capacitor value that gives 220 DC output voltage is 330μF

At C=330uF, Vdc~Vrms = 220V.



Figure(3.17) DC voltage waveform of the filter output

3.4.4 Converter Power Circuit

The figure (3.18) shows the overall power circuit (rectifier , DC link and two inverters) that supplies power to the motor. The figure (3.11) shows the two currents supplied to the motor windings, it shows clearly the 90 electrical degrees phase shift between the motor currents .

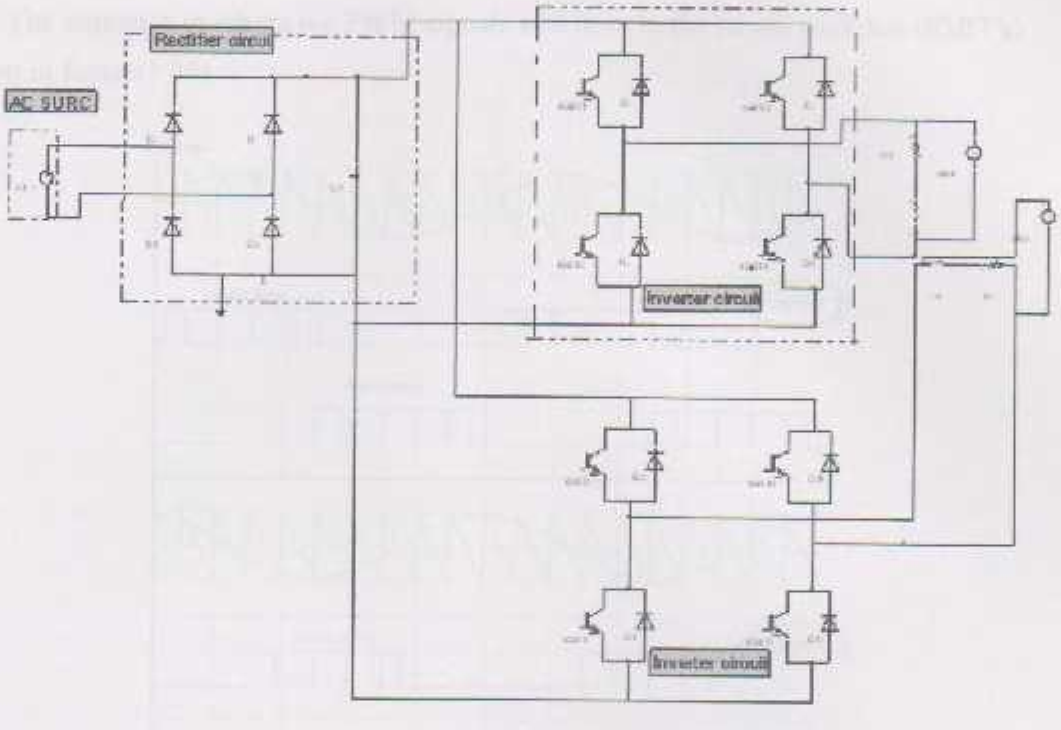
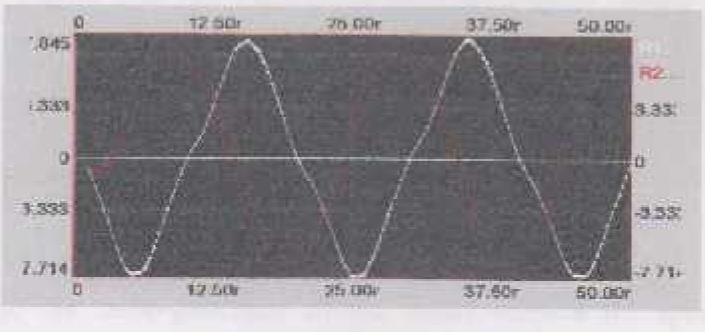


Figure 3.18 The overall circuit of the converter



Figure(3.19): Inverters currents

3.4.5 Pulse Width Modulation (PWM) Control

The inverter output will be controlled using PWM sinusoidal . The signal will be generated by the Matlab. program that supplies the gates of the IGBT's with the control signals through the DAQ .

The sequence in which the PWM signals will flow to the power switches (IGBT's) is shown in figure(3.20).

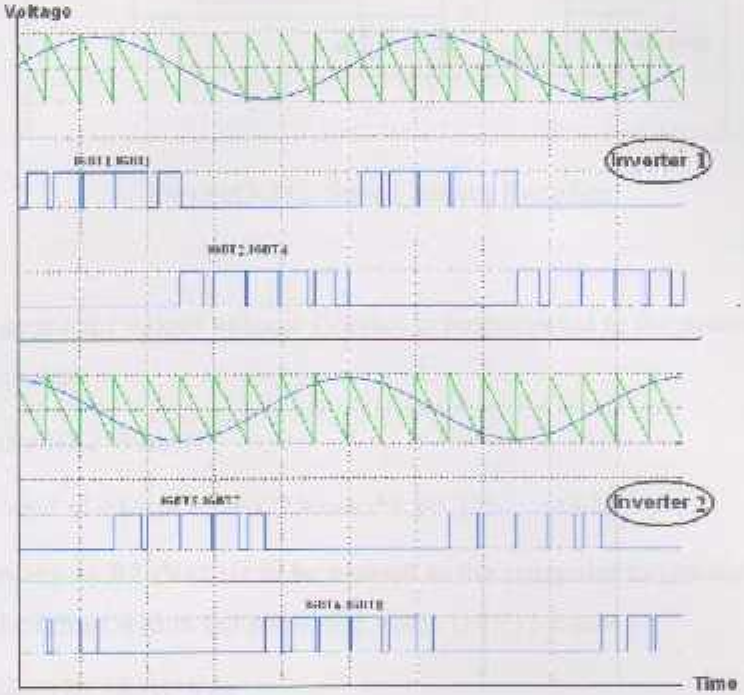
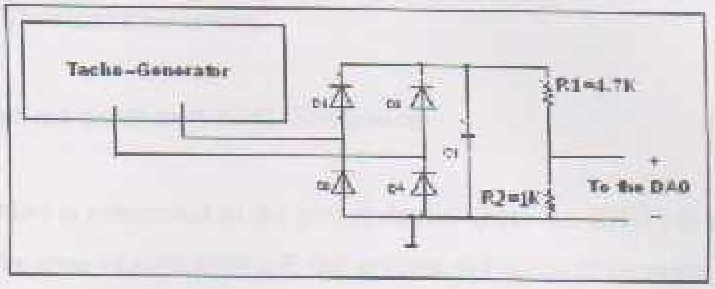


Figure 3.20 The sequence of the IGBT's gates signals

3.4.6 Design of the Rectifier of the Speed Sensor

Unfortunately, the tacho-generator of the motor outputs the speed as an ac voltage, so that a low power rectifier is designed to convert this voltage to dc in order to input it to the MatLab program through the DAQ



Figure(3.21): Speed Sensor Rectifier

The tacho-generator output voltage (V_{tacho}) is proportional to the motor speed according to the equation

$N\ (rpm) = 93.2 * V_{tacho}$.

$V_{dc} = V_m * (1-(1/4fRC) = \sqrt{2} * V_{tacho} * 0.99$ [2] (3.8)

The voltage across R2 (V_{R2})is to be entered to the computer to remain the voltage entere to the motor within the permitted value (10V) , where,

$V_{R2} = (R2/(R1+R2)) * V_{dc}$

$= 0.175 * V_{dc}$.

From the equations above

$N(rpm) = 376.6 * V_{R2}$.

Where, $V_{tacho} = 16.1$ V at $N = 1500$ rpm.

$R = R1 + R2 = 1K + 4.7K = 5.7K\Omega$

$C = 100\mu F$

$f = 50$ Hz.

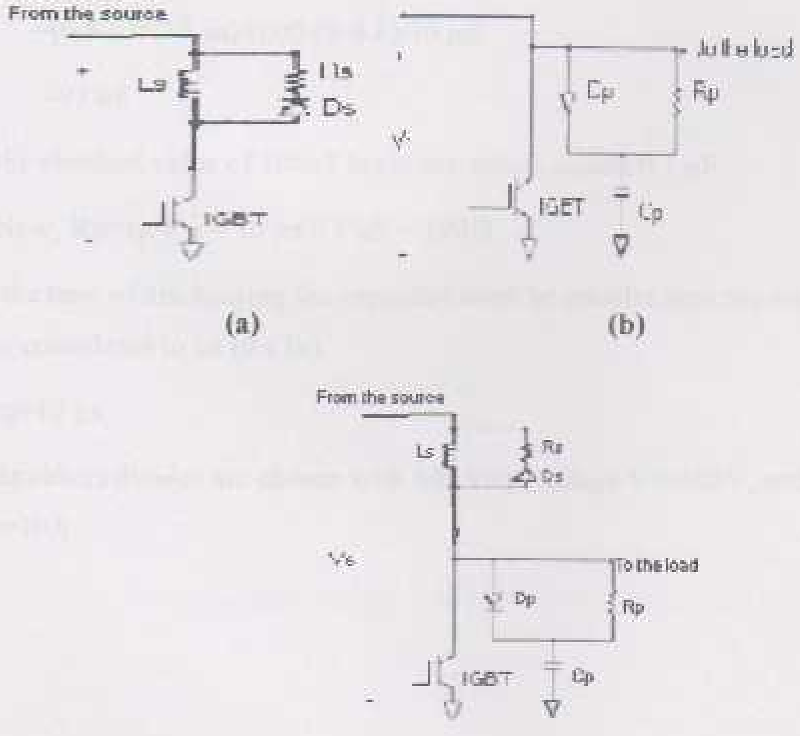
3.5 Electrical And Thermal Protection

3.5.1 Protection Against dv/dt and di/dt (Snubbers)

Parallel snubber is connected to the power device (here the IGBT) to protect it from high dv/dt in the case of switching off, the reverse voltage will increase gradually by the existance of the capacitor.

During the switching on period, the capacitor will discharge in the resistance Rp to be ready again to another blocking voltage.

Series snubber protects the power devivce from sudden and high di/dt at the time of switching on the device by adding series inductance to breake the high current. The energy stored in the inductance Ls discharges in the resistance Rs during the switching off time.



(a) (b)

(c)

Figure(3.22) (a)-Series snubber. (b)-Parallel snubber. (c)Both snubbers together.

Snubbers Design

Snubber parameters depend on the device switching frequency (fs), which is 10 Khz.

$Ts= 1/10000 = 100\mu s$

For the **series snubber**, the time needed to discharge the inductor Ls (ts) is considered to be (0.1Ts)

$ts = 0.1* 100\ \mu s = 10\ \mu s$

but $ts = Ls/Rs$

by choosing $Ls=0.1mH$, $Rs=10\Omega$.

In the **parallel snubber** the value of the capacitor can be calculated from the equation

$\mathbf{Cp=(\Delta Ic*\Delta t)/(Vr -Lsdi/dt)}$

$=(6.8-0)*(10\ \mu s)/(600-(0-6.8)/10\ \mu))$

$=97\ nF$

the standard value of 100nF is chosen which equals 0.1 μF .

Now, $\mathbf{Rp=tp/Cp} = 10\ \mu s/0.1\ \mu F = 100\Omega$

the time of discharging the capacitor must be smaller than the switching time (Ts), it is considered to be (0.1Ts)

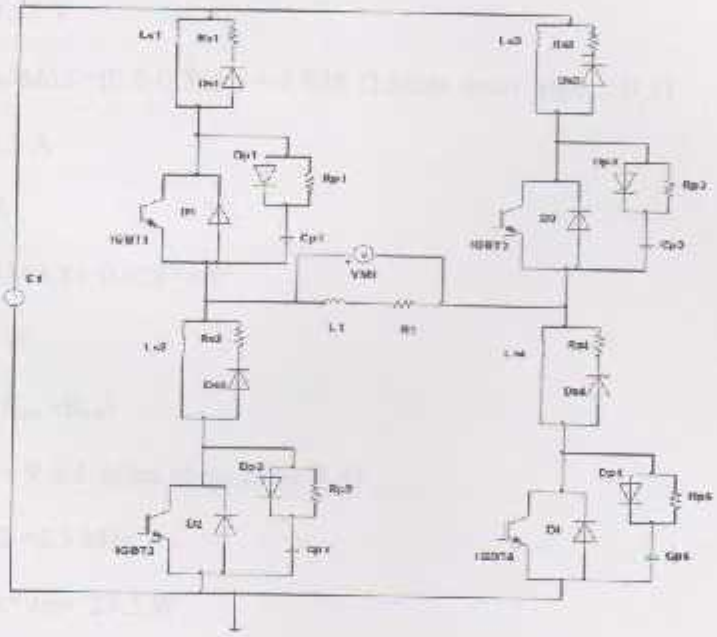
$tp=10\ \mu s$

Snubbers dioides are chosen with blocking voltage Vr=600V, and forward current If=1.5Ic=10A.

Series Snubber (Against di/dt)	Parallel Snubber (Against dv/dt)
Rs=10Ω	Rp=100Ω
Ls=0.1mH	Cp=0.1 μF

Table(3.5): Snubbers parameters

The figure (3.23) below of the inverter shows the connections of the snubbers for each IGBT.



Figure(3.23) Single phase inverter with snubber circuits.

3.5.2 Over Current Protection

A fuse of current 15A is connected to the rectifier input in order to protect the system from the high current danger.

3.5.3 Thermal Design Protection

Because the power devices dissipate a part of the electrical energy in the form of heat , it could cause danger upon it, so heat sinks are mounted on the power device to allow the heat dissipate quickly.

Heat Sink Design

The power dissipated in each power device (IGBT)

$P_{diss} = P_{fw} + P_{sw}$

$P_{fw} = V_{CE0} * I_{dc} + r_B * (I_{l\text{-}rms})^2$

$V_{CE0} = 0.55$ V.

$r_B = \Delta V_{CE} / \Delta Idc = (0.8-0.55)/9 = 0.028\ \Omega$.(data sheet -figure B.2)

$I_{l\text{-}rms} = 4.8$ A

$I_{dc} = 4.8$ A

$P_{fw} = 0.55*4.8+0.028*4.8^2$

$= 3.3W$

$P_{sw} = f* (E_{on} + E_{off})$

$E_{on} + E_{off} = 9$ mJ (data sheet table B.4)

$f = 5000/2 = 2.5$ kHz.

$P_{sw} = 2.5k*9m = 23.5$ W.

$P_{diss} = P_{fw} + P_{sw} = 3.3+23.5$

$= 26.8$ W

$R_{\theta JC} + R_{th.h} = (T_{J,max} - Tj) / P_{diss}$

$0.64 + R_{th.h} = 150-25/26.8$ (data sheet table B.1)

$\mathbf{R_{th.h} = 4.02\ C^o/W}$

Where

P_{diss} : the total power dissipated in the IGBT

P_{fw} : the power dissipated in the forward operation

P_{sw}: the switching power losses

V_{CE0}: the forward voltage across the IGBT at zero current

r_{B}: the forward resistance

E_{on} : the switching energy losses in switching on

E_{off}: the switching energy losses in switching off

R_{thJC}: junction case thermal resistance of the IGBT

$R_{th,h}$: heat sink thermal resistance

$T_{J,max}$: maximum allowed temperature of the IGBT

Tj: ambient temperature

$I_{F\text{-}rms}$ is the forward rms current

Idc is assumed to be equal to $I_{F\text{-}rms}$

3.6 Optocoupler Interface

Because that the computer digital output voltage is 5V only, the optocoupler is needed to amplify it to 15 voltage (the gate signal needed to turn on the IGBT).

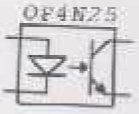


Figure 3.24:The Symbol of the Optocoupler

The advantages of an optocoupler is the electrical isolation between the input and the output circuits. Stated another way, the common for the input circuit is different from

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the common of the output circuit. Because of this, no conductive path exists between the two circuits. This means that you can ground one of the circuits and float the other.

3.7 Interfacing Using Data Acquisition Card (DAQ)

Data Acquisition Card (DAQ) is an interface hardware device connected to the computer to perform the following functions .

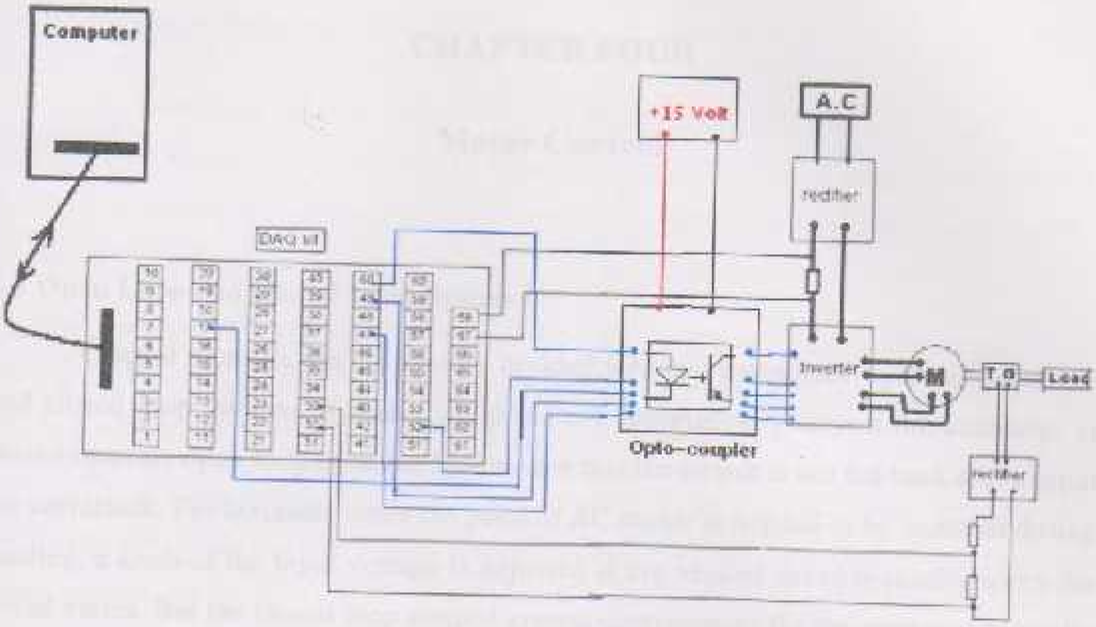
1.Input and output data to and from the computer . The transferred data could be analog or digital .

2. Guarantees the isolation between the computer and the outer connected devices .

Because the Mat lab software is the main used software in this project, and because the fact that the DAQ can be droved from the mat. lab , the DAQ is the interface device used to perform the followings :

- Inputs the analog signal of the motor actual speed to the mat lab .
- Input the motor current to be controlled within the rated value.
- Outputs the generated PWM signals that control the inverters output ac voltages.

The figure(3.25) shows the DAQ connections with the inputs and outputs through the opto-coupler circuit.



Figure(3.25): DAQ Connections (Interface Circuit)

In this project, the DAQ 6024E series is used, it's datasheet is located in Appendix C

CHAPTER FOUR

Motor Control

4.1 Open Loop and Closed Loop Systems

Control Systems can be broadly divided into two categories: open loop systems and closed loop systems. Systems which do not automatically correct the variations in their output are open loop systems. This means that the output is not fed back to the input for correction. For instance, when the peed of AC motor is needed to be constant during loading, a knob of the input voltage is adjusted at the needed speed manually when the speed varies. But the closed loop control system compensates for the error automatically at any load [8].

An open loop system can be modified into a closed loop system by providing feedback. The provision for feedback automatically corrects the changes in the output due to disturbances. Hence, the closed loop system is also called an automatic control system. The general block diagram of an automatic control system is shown below.

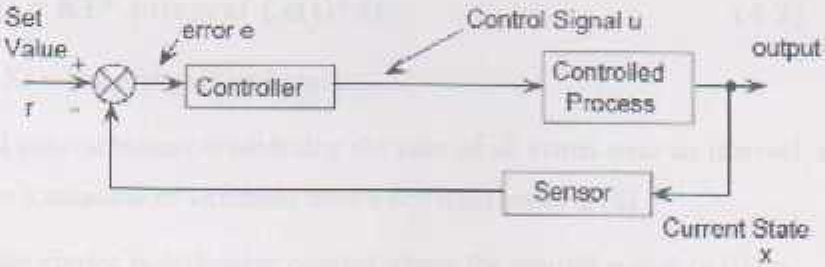


Figure 4.1 General block diagram of an automatic control system

4.2 Automatic Controller

A controller is a device introduced into the system to sense the error signal and to produce the required control signal. An automatic controller compares the actual value of the plant output with the desired value, determines the deviation, and produces a control signal which will reduce the deviation to zero or to a smaller value.

According to the manner in which the controller produces the control signal (called control action) controllers are classified as proportional (P), integral (I), derivative (D) and their combinations (PI, PD and PID).

The proportional controller is a device that produces a control signal u(t), which is proportional to the input error signal, e(t) (error signal, the difference between actual value and desired value), i.e.:

$$\mathbf{u(t) = Kp * e(t)} \qquad (4.1)$$

Where Kp = proportional gain or constant; a proportional controller amplifies the error signal by an amount Kp. The drawback of the P-controller is that it leads to a constant steady state error. Integral control is used to reduce the steady state error to zero. This device produces a control signal u(t) which is proportional to the integral of the input error signal:

$$\mathbf{u(t) = Ki * integral \{ e(t)*dt} \qquad (4.2)$$

Where Ki – integral gain or constant.

Integral control means considering the sum of all errors over an interval, so this always gives us a measure of variation over a constant interval [8].

The other choice is derivative control where the control signal (u (t)) is proportional to the derivative of the input error signal (e (t)). We consider the derivative of e (t) at a given instant as the difference between present and previous errors. A large positive derivative value indicates a rapid change in output variable (here, the speed of the motor). In other words, the rate of change of speed is greater. The drawback of the integral controller is that it may lead to oscillatory response. For these reasons combination of P, I and D are used. Most (75-90%) of controllers in current use are PID.

In this project, a PI controller will be designed to reduce the error and increase the speed response.

4.3 The PI Controller

$$u\ (t) = Ki \int\{\ e(t)*dt\ \} + Kp * e(t) \tag{4.3}$$

The integral of the error over a recent time interval.

This not only determines how much correction to apply, but for how long. Each of the above two quantities are multiplied by a 'tuning constant'(Kp and Ki respectively) and added together. Depending on the application, one may want a faster convergence speed or a lower overshoot. By adjusting the weighting constants, Kp and Ki, the PI can be set to give the most desired performance.

4.4 Speed Control of SPIM's

Since there are many of the SPIM applications need to operate the motor at predetermined fixed speed; the changes in the motor load must not affect the speed. So a closed loop speed control system is needed.

Methods of speed control in induction motors

4.4.1 Stator Voltage Control

By changing the motor input voltage to have constant speed, but this method decreases the robustness of the motor characteristic as the figure (4.3) shows.

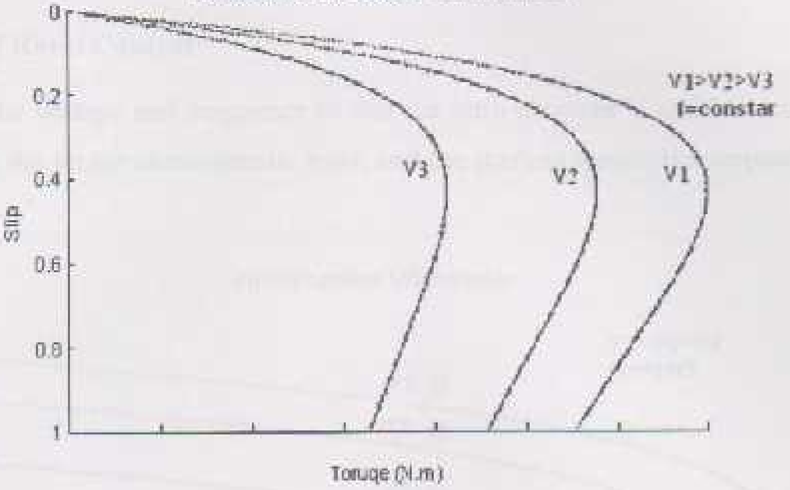


Figure 4.2 Motor Characteristic when the input voltage changes

4.4.2 Control with Constant Maximum Torque

By changing the voltage and the frequency at constant maximum torque, the characteristics of the motor still hard.

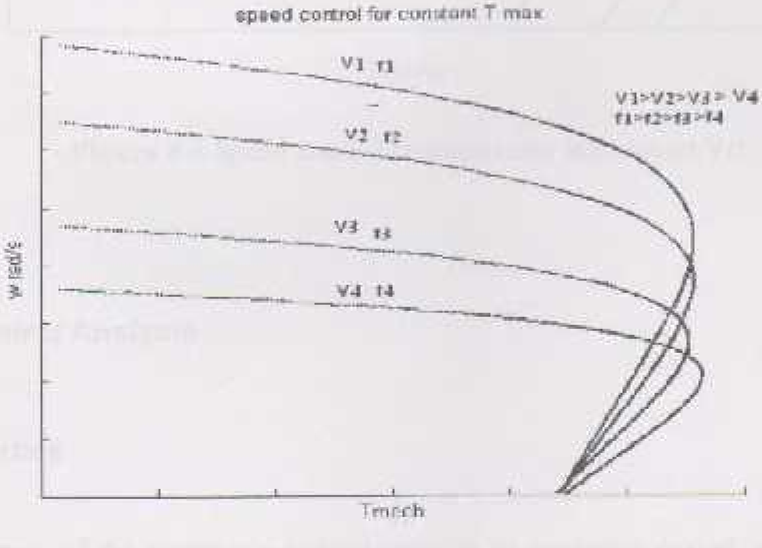


Figure 4.3 Speed control for constant Tmax

4.4.3 Constant V/f Ratio Control

Adjusting the voltage and frequency so that the ratio between V and f is constant . This method keeps the motor characteristic hard, and the starting torque is acceptable as figure (4.4) shows.

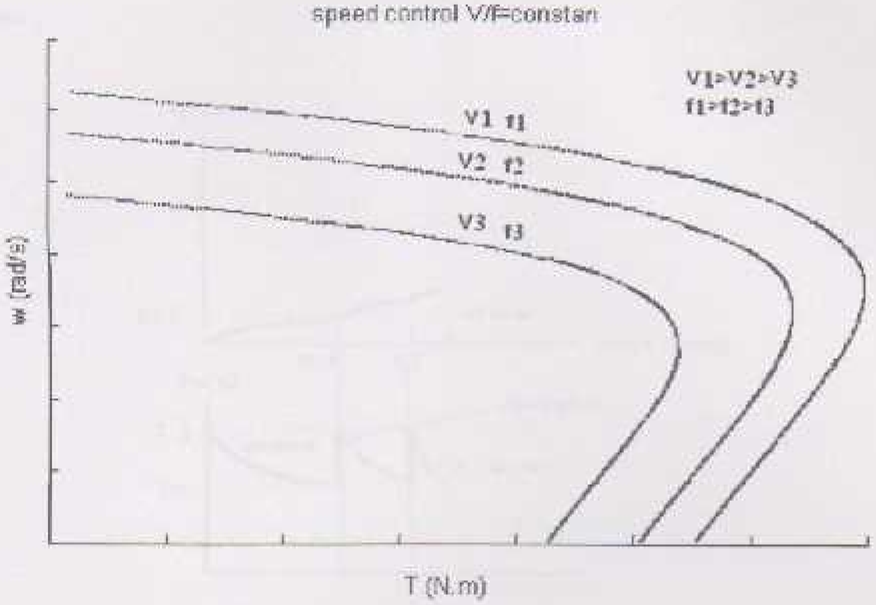


Figure 4.4 Speed control characteristic at constant V/f

4.5 Motor Control Analysis

4.5.1Motor starting

The starting of the motor is a critical stage in its operation period, so it must be controlled to achieve two aims; first to allow the speed increase smoothly, second to protect the motor and the converter from the high staring current.

To perform these tasks, the voltage must be increased smoothly, making the current not to exceed the maximum safe value (10A). According to motor simulation, the voltage that gives starting current (10 A) is (85V).When the speed becomes (372 rpm), the current becomes (6.8A), see figure (4.5). from the step response, at (85V) the increase in the speed above 85V is slower than the other stage (more than 85V). so the time taken in the first step of starting is safe The time taken to reach this speed (372rpm) is (0.4 sec) (see figure (4.6)). the voltage needed to get (10 A) at (372 rpm) is (107V) (see figure 4.5), and since the change of the voltage from (85 to 107) is the biggest to the change in time .

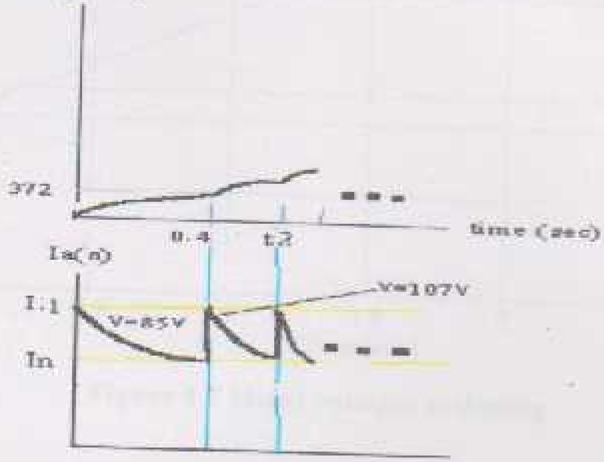


Figure 4. 5 Motor current at starting

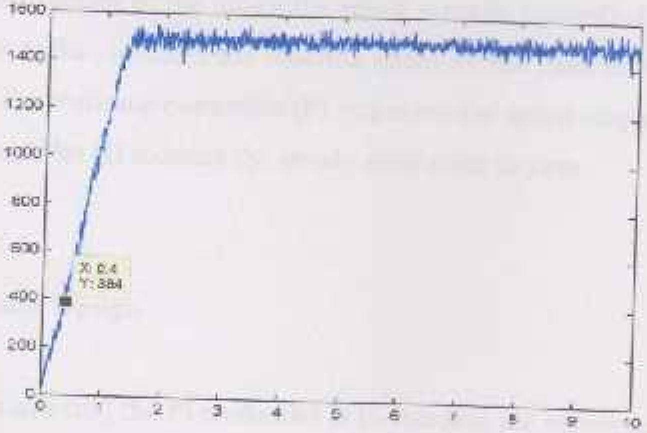


Figure 4. 6 Step response at 85 V

So we can say that the slope of the ramp function the starting voltage is

m = del (V)/del(t) = (107-85)/0.4 = 55 v/sec

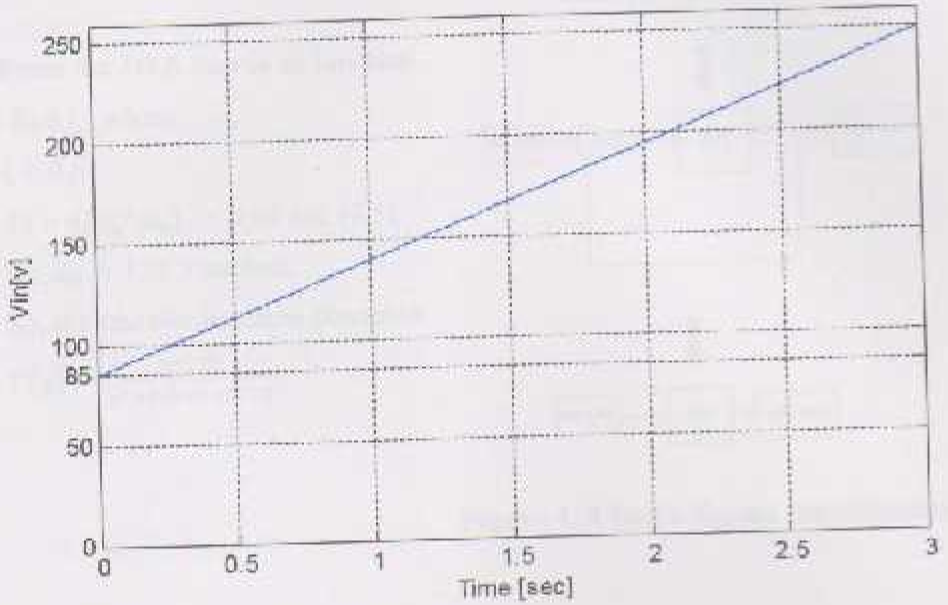


Figure 4.7 Motor voltages at starting

4.5.2 Speed Control

After the starting of the motor the speed must be controlled so we use controller which have tow tasks ; increase the reaction speed of the , and reduce the steady state error . that the Proportional controller (P) improves the speed response of the system and the integral controller (I) reduces the steady state error to zero .

Controller Design

The aim of using the PI controller is to increase the response of the motor speed and to reduce the error and then, to get a response with the following parameters

Settling time (Ts)= 0.05

Percentage overshoot (%O.S) = 10%

The transfer function TF, T(s) = ω(s)/V(s)

$$T(s) = \frac{K}{s^2 + 2\zeta\omega_n + \omega_n^2} \qquad (4.4)$$

From the %O.S curves as function of ζ we can find ζ, where

$\zeta = 0.6$

$T_s = 4/(\zeta * \omega_n) = 0.05$ sec.(4.5)

So, $\omega_n = 133.3$ rad/sec.

So, the transfer function becomes

$$T(s) = \frac{17778}{s^2 + 160s + 17778}$$

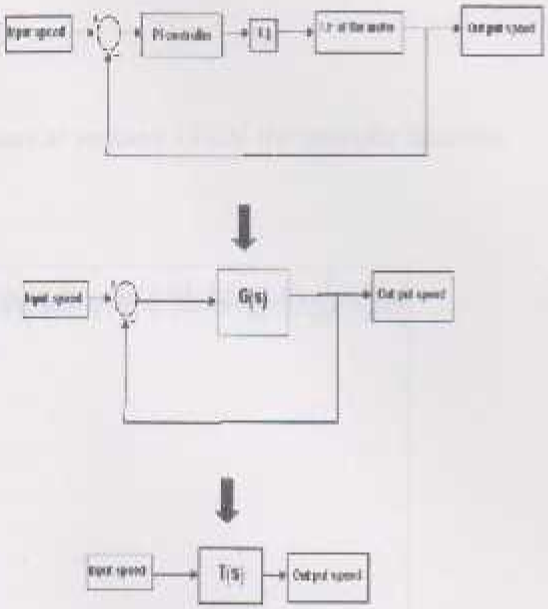


Figure 4. 8 Bolck digram simplification

The step response of the T.F is shown in the figure below

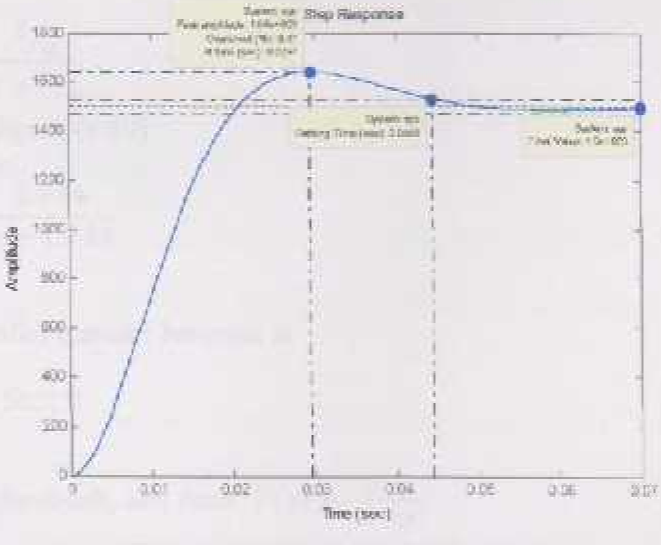


Figure 4.9 Desired step response

$K_1 = 220/1500 = 0.147$

According to the step response of the motor at voltage 170 V the transfer function can be derived as

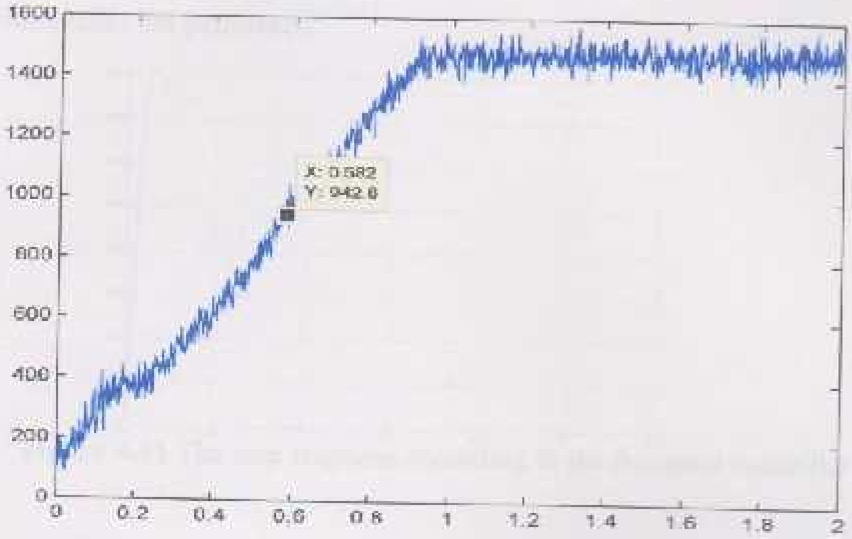


Figure 4.10 Step response of the motor at 170 V

$$G_2(s) = \frac{1/a}{s + 1/a} \tag{4.6}$$

From the figure (4.10)
a= 0.58 sec.

$$G_2(s) = \frac{1.724}{s + 1.724}$$

The controller transfer function is

$$G_1(s) = \frac{K_P s + K_I}{s} \tag{4.7}$$

For unity feedback, and from $T(s) = \frac{G(s)}{1+G(s)}$

So, $G(s) = \frac{17778}{s^2 + 160s}$

$$G(s) = K_1 * G_1(s) * G_2(s)$$

By substituting G(s), $G_1(s)$, and K_1 The controller becomes

$$G_1(s) = \frac{s + 30649}{0.253s^2 + 40.48s}$$

The step response according to the designed controller $G_1(s)$ in the figure (4.11) shows that the controller tasks are performed.

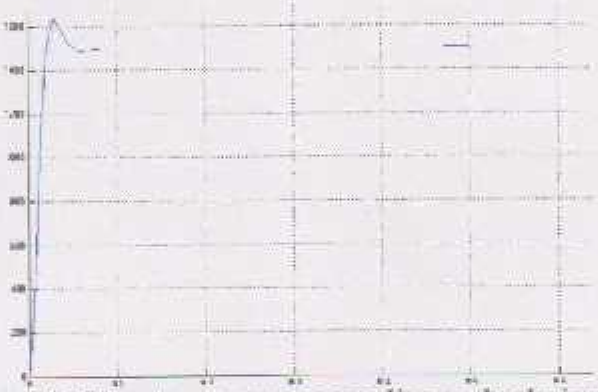


Figure 4.11 The step response according to the designed controller

4.5.3 The Steps of Speed Control Using Mat.Lab

According to the block diagram shown in figure (4.12) the control behaves as follows

1.The motor will operate under closed loop control system , with purpose to maintain the motor speed nearly constant under the load torques range .

2.The reference speed of the motor will be input to the matlab control program.

3.The Mat.Lab. will generate PWM signal to control the motor voltage through the inverters .

4.A tacho-generator performs as a sensor of the motor speed which is generated as ac voltage . It sends the signal to the DAQ in analog DC form after rectification.

5.The Mat.Lab program compares the actual and reference signals, produces the error, and inputs it to the PI controller, which reduces the deviations.

6. The compensation for the change in the speed is processed in the program so that the voltage and the frequency will change together to guarantee constant V/f ratio .

The control signal will be sent to generate the PWM signal to control the rms voltage and frequency of the inverter, and thereby the motor speed through digital output channels in the DAQ .

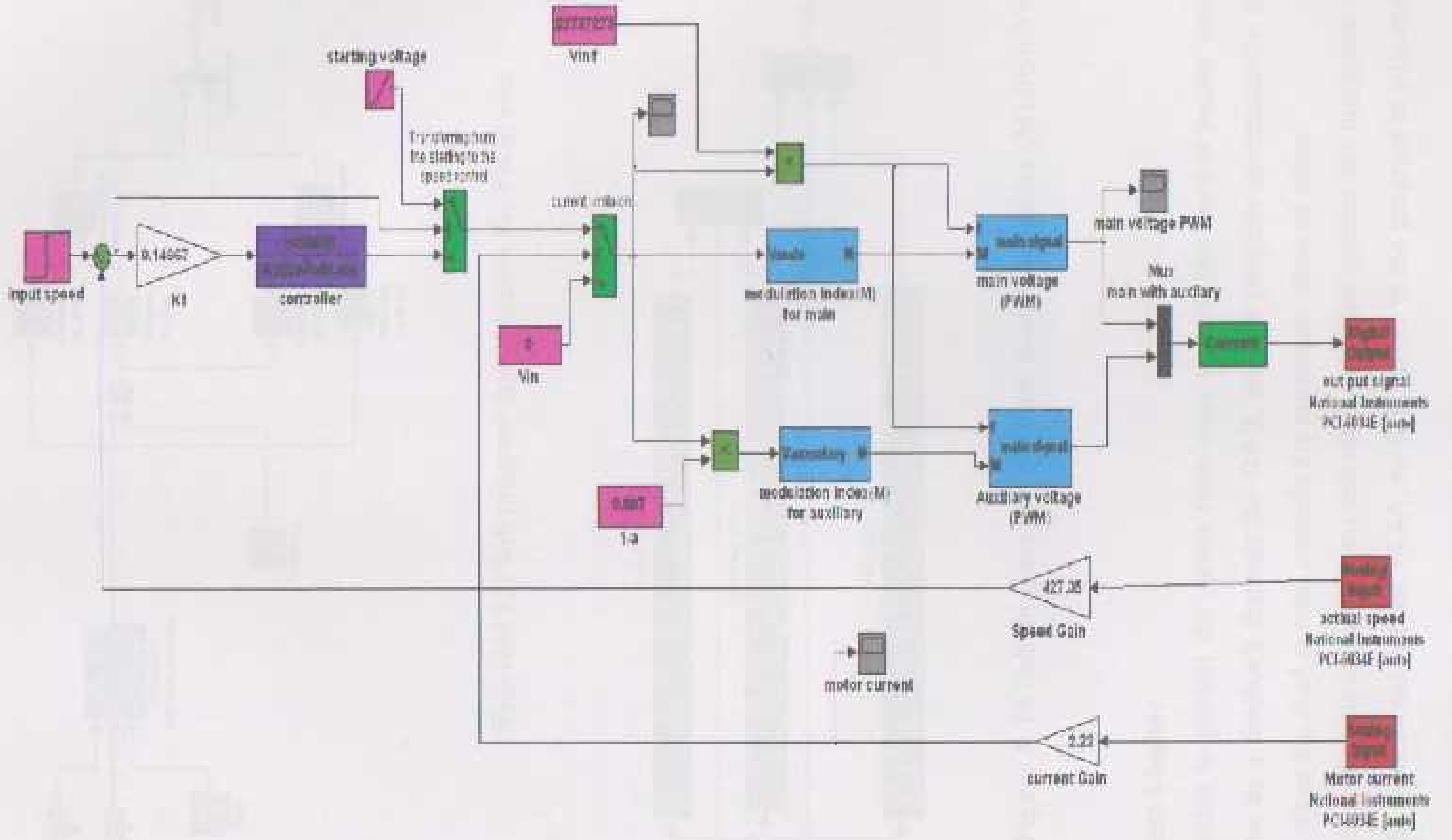
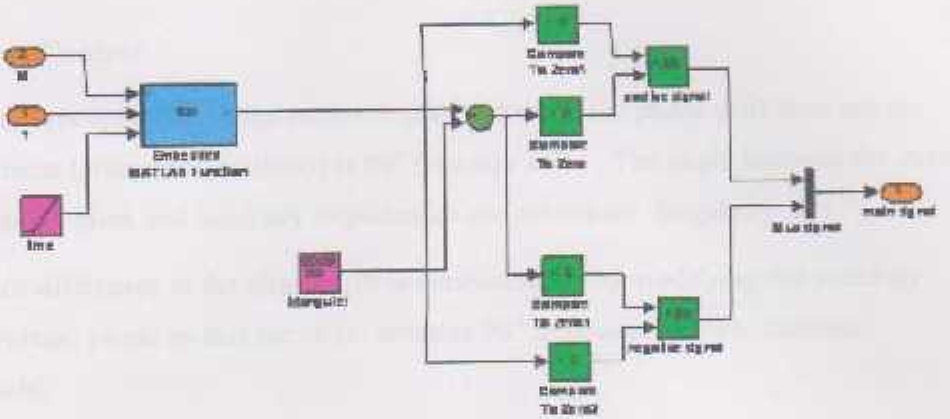


Figure 4.12 MatLab program that controls the System



Figure(4.13) Sub program that generates the PWM sine

Figure 4. 14 Sub program that calculate modulation index (M) from Vmain

4.5.4 Current Limiter

In order to protect the motor from over current, the current sensor returns the current value as a feedback through the DAQ, and the program automatically turns off the system, when the load current exceeds the maximum allowed value.

Because that the current sensor returns the rectifier current, the maximum allowed current is the total motor current 14.4A, so the current in the program is adjusted at this value.

4.5.5 Phase Control

The best operation of the motor is achieved when the phase shift between the motor currents (main and auxiliary) is 90° (see equ 2.46) . The angle between the current depends on the main and auxiliary impedances and on source frequency, too .

This difference in the phase shift is compensated by modifying the auxiliary winding voltage phase so that the angle remains 90° between the two currents continuously,

where

$$\text{Phase} = 90 + \Theta\text{main} - \Theta\text{aux} \qquad (4.8)$$

Where

Phase : the angle between the main and auxiliary voltages
Θmain : the phase shift of the main current
Θaux : the phase shift the auxiliary current

The following program calculates the phase shift between the main and the auxiliary depending on the frequency

```
clc
for f=10:0.1:50
ws=6.28*f;
ws1=157;

X1=j*ws*3.6/(ws1);
X2=j*ws*1.8/(ws1);
Xm=j*ws*43/(ws1);
R2=1.5;
s=.05;
Zf=R2/s+X2;
Zb=R2/(2-s)+X2;

Z1=X1+(Xm*Zf)/(Xm+Zf)+(Xm*Zb)/(Xm+Zb);

Zm=4.25+Z1;
thetamain=angle(Zm);

Zaux=1.07*(3.4+Z1);

thetaux=angle(Zaux);
phase1=90*(pi/180);
phase=phase1+thetamain-thetaux;
hold on
```

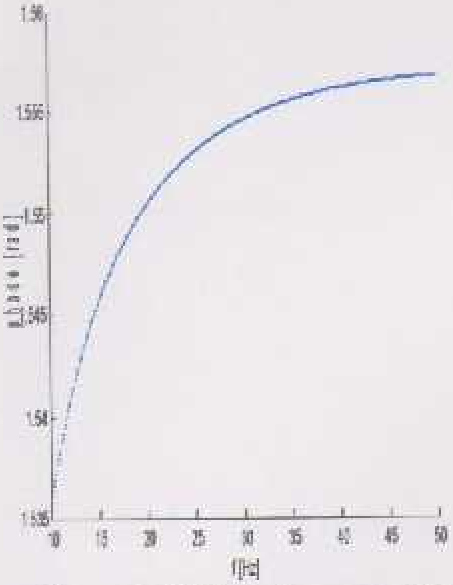


Figure 4. 15 Phase-frequncy relation

```
plot(f,phase)

end
```

The function that represents the relation between the phase shift and the frequency

Phase $= -5.9057e\text{-}013*f^{8} + 1.6063e\text{-}010*f^{7} - 1.8602e\text{-}008*f^{6} + 1.1957e\text{-}006*f^{5} - 4.6584e\text{-}005*f^{4} + 0.001126*f^{3} - 0.016528*f^{2} + 0.13608*f + 1.0594$

CHAPTER FIVE

Simulation And Experimental Results

5.1 Motor Simulation

5.1.1 Motor Mechanical Characteristic at Different Conditions

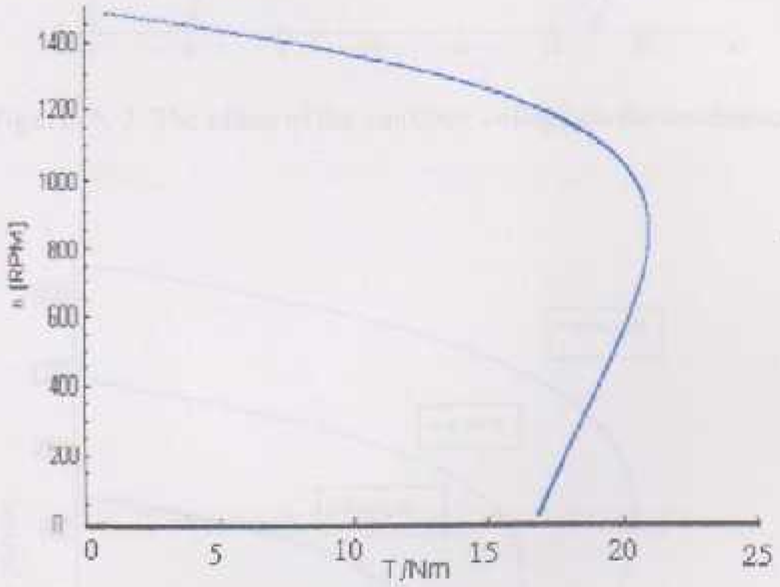


Figure 5. 1 The load characteristic at rated voltage

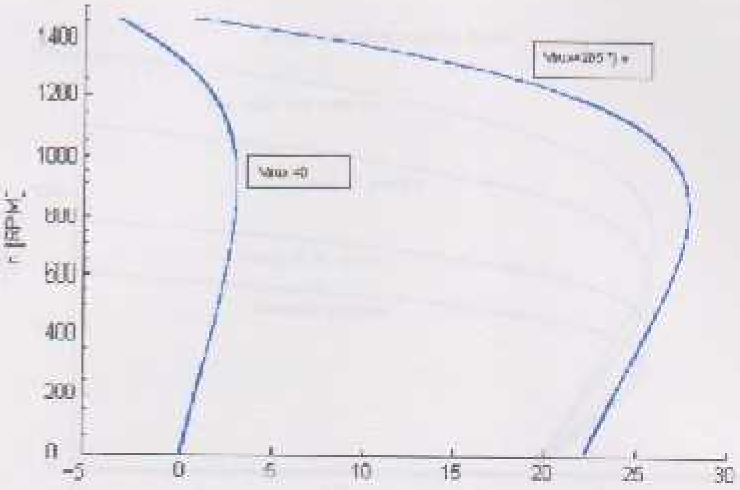


Figure 5. 2 The effect of the auxiliary voltage on the mechanical characteristic

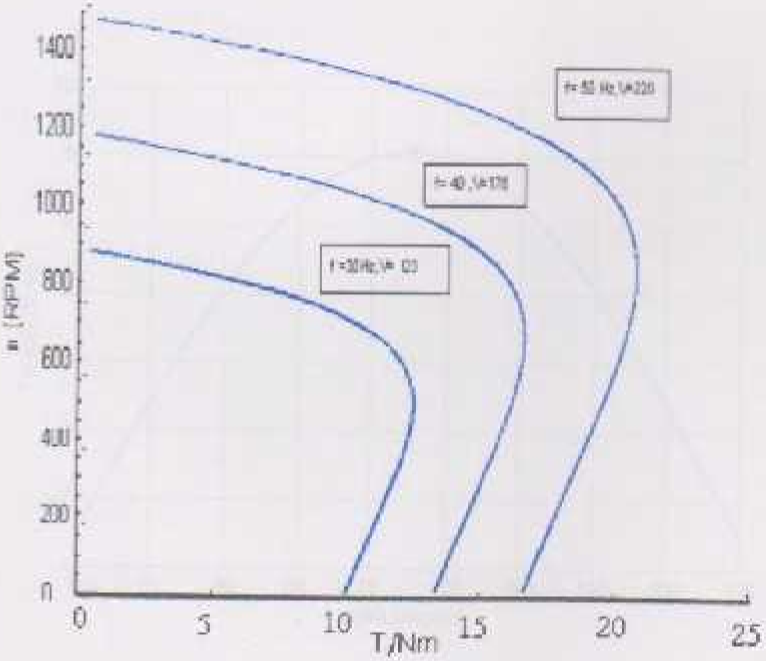


Figure 5. 3 Motor mechanical characteristic at V/f = constant

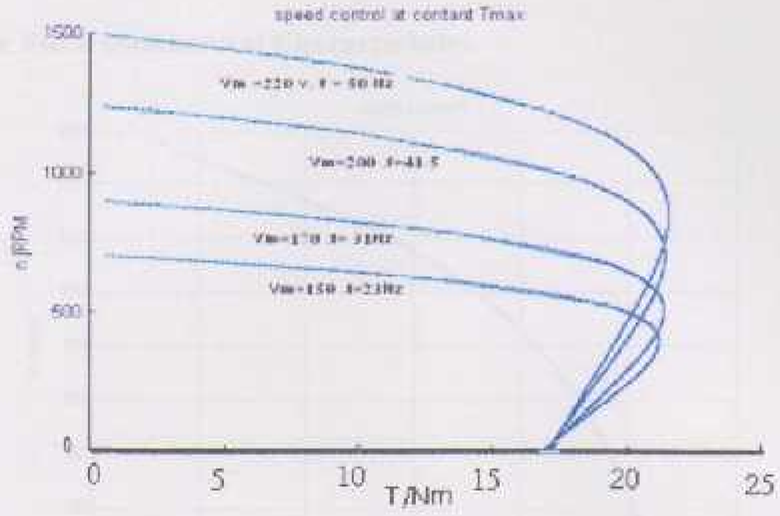


Figure 5. 4 Motor mechanical characteristic at Tmax =constant

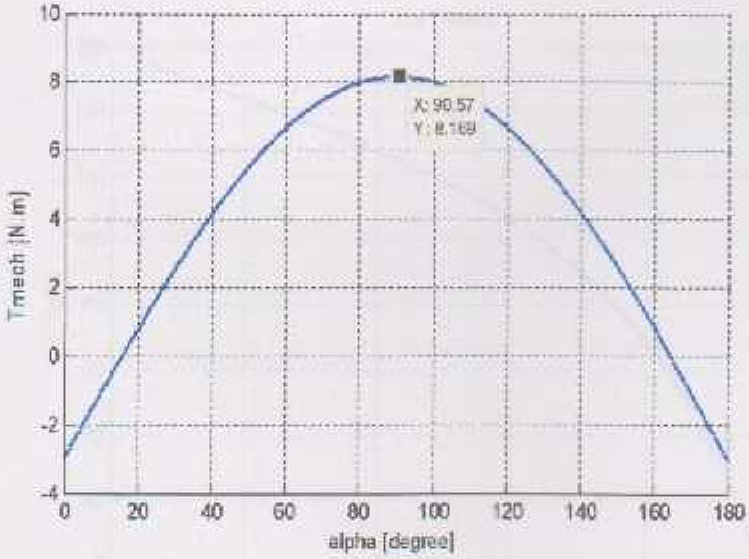


Figure 5. 5 The effect of alpha (the phase shift angle between the two motor phases) on the mechanical torque at rated main voltage

5.1.2 The Electromechanical Characteristics

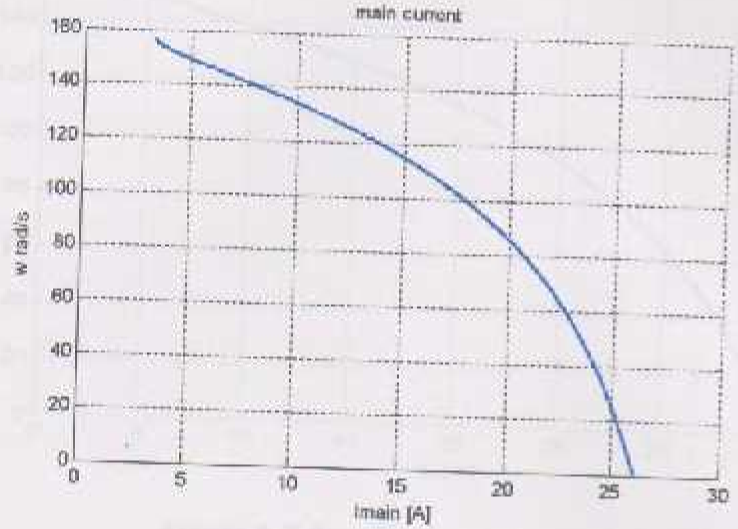


Figure 5.6 Speed and main current characteristic

Figure 5. 7 Speed and auxiliary current characteristic

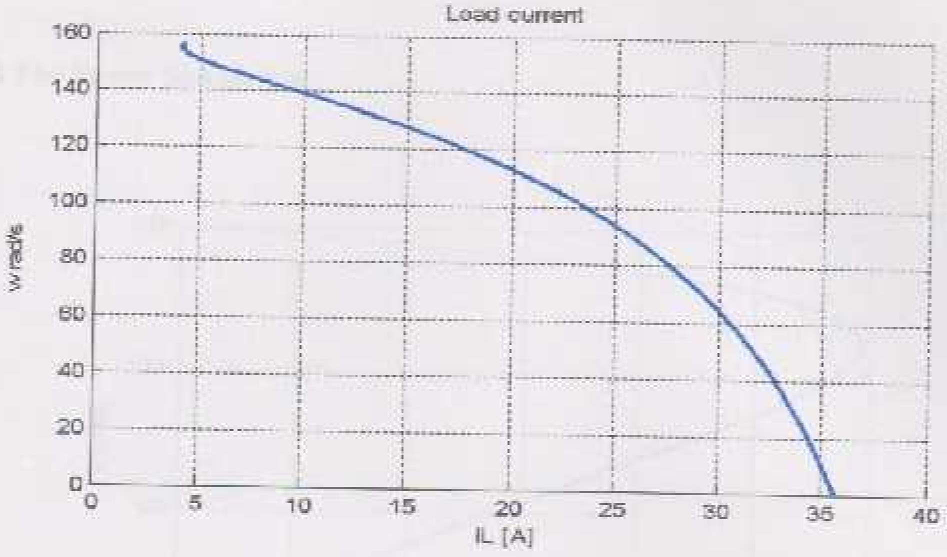


Figure 5. 8 Speed and motor current characteristic

5.1.3 The effect of the phase shift angle between the main and the auxiliary winding on the Load Current

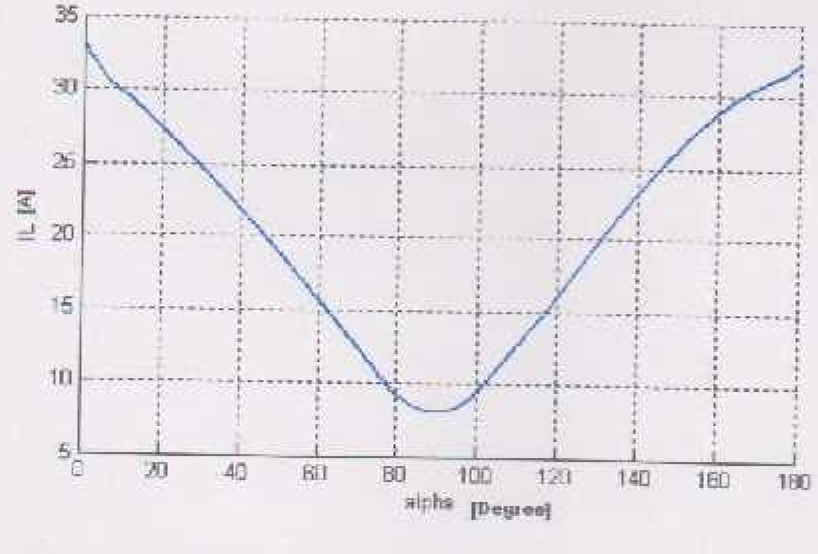


Figure 6. 9 The effect of alpha on the load current at rated main voltage

5.1.4 The Power Simulation

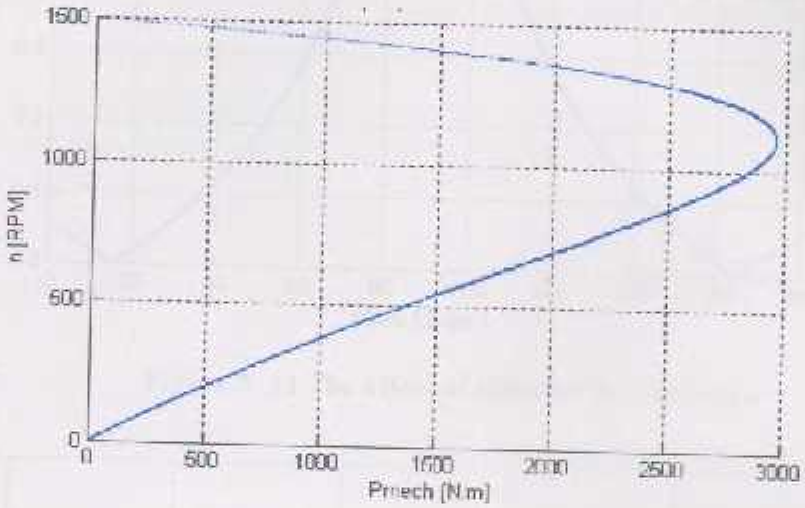


Figure 5.10 The Speed with output power

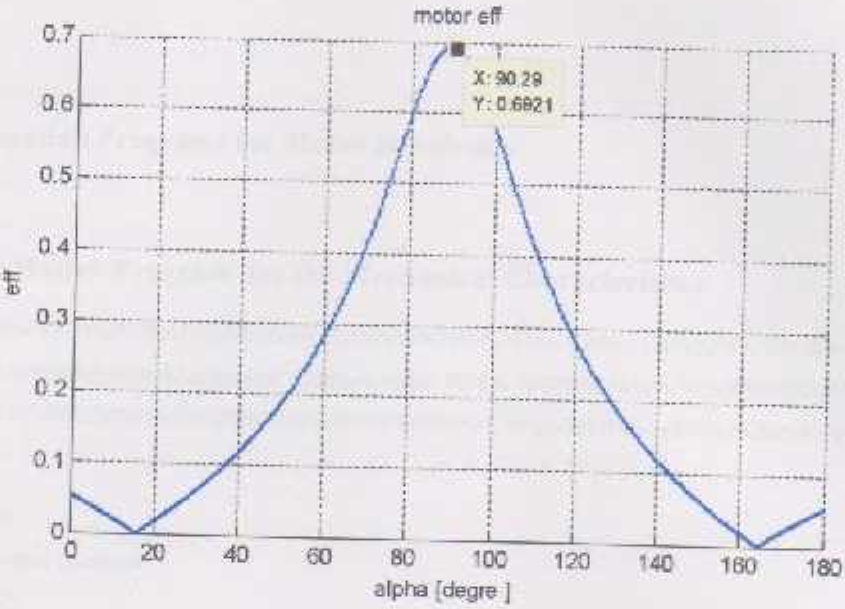


Figure 5. 11 The effect of alpha on the efficiency

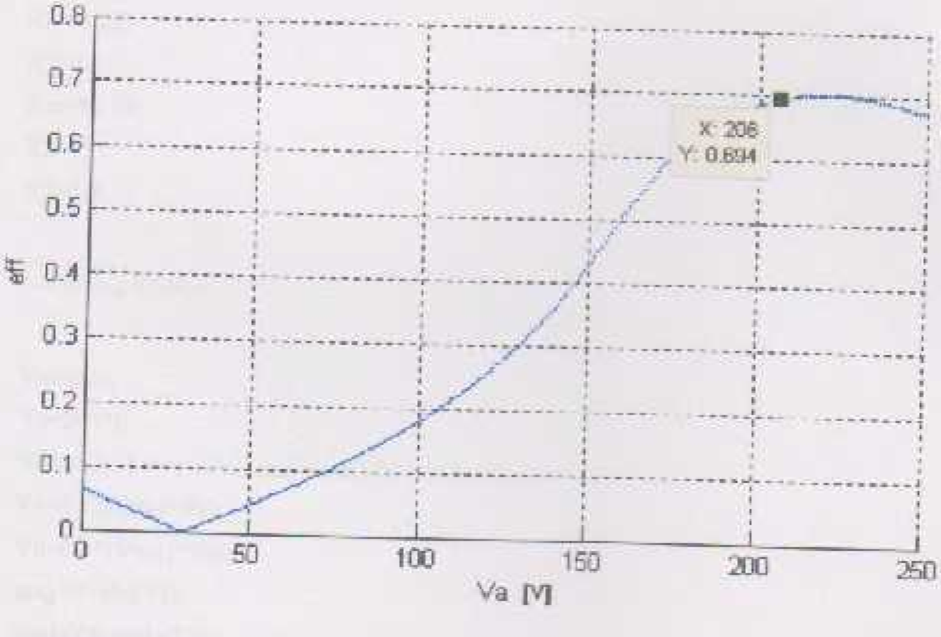


Figure 5. 12 The effect of changing the auxiliary voltage on the motor efficiency

5.2 The matlab Programs for Motor Simulation

5.2.1 The Matlab Program for the Mechanical Characteristics

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%% Mechanical Characteristic %%%% %%%%% %%%% %%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        clc
        clear
        %useful constant
        f=50;
        omega = pi*f;
        for s=.005:.001:.995; % slip
        R1= 4.25;
        X1=3.6;
        Xm=86.38;
        R2=3;
        X2=3.6;

        %winding voltage


        Vm=220;
        Va=205*j;
        % finf the forward(Vf) and back(Vb) word voltage
        Vf=0.5*(Vm-j*Va);
        Vb=0.5*(Vm+j*Va);
        magVf=abs(Vf);
        angleVf=angle(Vf);
        magVb=abs(Vb);
        angleVb=angle(Vb);
```

```
%the calculation of the input forward impedance of the motor
Zforward=R1+j*X1 +j*Xm*(R2/s+j*X2)/(j*Xm+(R2/s+j*X2));

% the forword current
If=Vf/Zforward;
magIf=abs(If);
angleIf=angle(If);

%the calculation of the input backward impedance of the motor
Zback=R1+j*X1 +j*Xm*(R2/(2-s)+j*X2)/(j*Xm+(R2/(2-s)+j*X2));

% the backward current
Ib=Vb/Zback;
magIb=abs(Ib);
angleIb=angle(Ib);

%winding current
Im =If+Ib;
Ia=j*(If-Ib);
magIm=abs(Im);
angleIm=angle(Im);
magIa=abs(Ia);
angleIa=angle(Ia);


% The power calculation

% the forward power
Pgf=2*(real(Vf*conj(If))-R1*magIf^2);

%the backward power

Pgb =2*(real(Vb*conj(Ib))-R1*magIb^2);
```

```
%mech power
Pmech= (1-s)*(Pgf-Pgb);

Tmech=Pmech/((1-s)*omega);
omega1=(1-s)*omega;
n1= omega1 *9.55 ;
hold on
plot(Tmech , n1)
end
```

[5]

5.2.2 Matlab Program for the Electromechanical Characteristics

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%The Electromechanical Characteristic %%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc
clear
%useful constant
f=50;
omega = pi*f;
for s=.005:.001:.995; % slip
R1= 4.25;
X1=3.6;
Xm=86.38;
R2=3;
X2=3.6;
%winding voltage

Vm=220;
Va=205*j;
% finf the forward(Vf) and back(Vb) word voltage
```

```
Vf=0.5*(Vm-j*Va);
Vb=0.5*(Vm+j*Va);
magVf=abs(Vf);
angleVf=angle(Vf);
magVb=abs(Vb);
angleVb=angle(Vb);

%the calculation of the input forward impedance of the motor
Zforward=R1+j*X1 +j*Xm*(R2/s+j*X2)/(j*Xm+(R2/s+j*X2));

% the forword current
If=Vf/Zforward;
magIf=abs(If);
angleIf=angle(If);

%the calculation of the input backward impedance of the motor
Zback=R1+j*X1 +j*Xm*(R2/(2-s)+j*X2)/(j*Xm+(R2/(2-s)+j*X2));

% the backward current
Ib=Vb/Zback;
magIb=abs(Ib);
angleIb=angle(Ib);

%winding current

Im =If+Ib;
Ia=j*(If-Ib);
magIm=abs(Im);
angleIm=angle(Im);
magIa=abs(Ia);
angleIa=angle(Ia);

realIm = real(Im);
imagnIm =imag(Im);
realIa = real(Ia);
```

```
imagnIa =imag(Ia);
IL=realIm +j*imagnIm +realIa +j*imagnIa ;
 magIL=abs(IL)

% The power calculation


% the forward power
Pgf=2*(real(Vf*conj(If))-R1*magIf^2);

%the backward power

Pgb =2*(real(Vb*conj(Ib))-R1*magIb^2);

%mech power
Pmech= (1-s)*(Pgf-Pgb);

Tmech=Pmech/((1-s)*omega);
omega1=(1-s)*omega;
hold on
plot( the need current ,omega1)
hold on
xlabel('   (A)')
ylabel('w rad/s')
end
```

[5]

5.2.3 Matlab Program for the Power Characteristic

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%The Out Power Characteristic %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc
clear
%useful constant
f=30;
omega = pi*f;
for s=.005:.001:.995; % slip
R1= 4.25;
X1=3.6;
Xm=86.38;
R2=3;
X2=3.6;
%winding voltage

Vm=170;
Va=158*j;
% finf the forward(Vf) and back(Vb) word voltage
Vf=0.5*(Vm-j*Va);
Vb=0.5*(Vm+j*Va);
magVf=abs(Vf);
angleVf=angle(Vf);
magVb=abs(Vb);
angleVb=angle(Vb);

%the calculations of the input forward impedance of the motor
Zforward=R1+j*X1 +j*Xm*(R2/s+j*X2)/(j*Xm+(R2/s+j*X2));

% the forward current
If=Vf/Zforward;
magIf=abs(If);
```

```
angleIf=angle(If);

%the calculation of the input backward impedance of the motor
Zback=R1+j*X1 +j*Xm*(R2/(2-s)+j*X2)/(j*Xm+(R2/(2-s)+j*X2));

% the backward current
Ib=Vb/Zback;
magIb=abs(Ib);
angleIb=angle(Ib);

%winding current
Im =If+Ib;
Ia=j*(If-Ib);
magIm=abs(Im);
angleIm=angle(Im);
magIa=abs(Ia);
angleIa=angle(Ia);
% The power calculation

% the forward power
Pgf=2*(real(Vf*conj(If))-R1*magIf^2);

%the backward power
Pgb =2*(real(Vb*conj(Ib))-R1*magIb^2);

%mech power
eff = Pmech/Power
Pmech= (1-s)*(Pgf-Pgb);
 Tmech=Pmech/((1-s)*omega);
omega1=(1-s)*omega;
hold on
plot(Pmech,omega1)
hold on
xlabel('P mechanical')
ylabel('w rad/s')
end
```

5.2.4 The Matlab Program that changes of the current angle between the main and the auxiliary windings

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%The effect of alpha on the charaacteritec  %%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc
clear
%useful constant
f=50;
omega = pi*f;
 s=.05; % slip
R1=4.25;
X1=3.6;
Xm=86.38;
R2=3;
X2=3.6;

%winding voltage
for n=0:.005:pi
Vm=220;
Va=205*exp(n*j);
magVa=abs(Va)

alpha=180*angle(Va)/3.14
% finf the forword(Vf) and back(Vb) word voltag
Vf=0.5*(Vm-j*Va);
Vb=0.5*(Vm+j*Va);
magVf=abs(Vf);
angleVf=angle(Vf);
magVb=abs(Vb);
angleVb=angle(Vb);

%the caculation of the input forword impedence of the motor
```

```
Zforward=R1+j*X1 +j*Xm*(R2/s+j*X2)/(j*Xm+(R2/s+j*X2));

% the forword current
If=Vf/Zforward;
magIf=abs(If);
angleIf=angle(If);

%the caculation of the input backword impedence of the motor
Zback=R1+j*X1 +j*Xm*(R2/(2-s)+j*X2)/(j*Xm+(R2/(2-s)+j*X2));

% the backword current
Ib=Vb/Zback;
magIb=abs(Ib);
angleIb=angle(Ib);


%wiinding current

Im =If+Ib;
Ia=j*(If-Ib);
magIm=abs(Im);
angleIm=angle(Im);
magIa=abs(Ia);
angleIa=angle(Ia);
Power = abs(abs(Va)*magIa)+abs(abs(Vm)*magIm);
realIm = real(Im);
imagnIm =imag(Im);
realIa = real(Ia);
imagnIa =imag(Ia);
IL=abs(realIm) +j*abs(imagnIm) +abs(realIa) +j*abs(imagnIa) ;

magIL=abs(IL);

% The power calculation

% the forward pwoer
```

```
Pgf=2*(real(Vf*conj(If))-R1*magIf^2);

%the backword power

Pgb =2*(real(Vb*conj(Ib))-R1*magIb^2);

%mech power
Pmech= (1-s)*(Pgf-Pgb);


Tmech=Pmech/((1-s)*omega);
omega1=(1-s)*omega;
eff=abs(Pmech)/Power
hold on
plot(alpha,eff)
hold on

xlabel('alpha [degre ]')
ylabel('eff')
title('motor eff')
end
```

5.3 Experimental Results

5.3.1 Pulse Width Modulation Signals (PWM)

The following figures show the PWM signal taken from the matlab. Where the first signal appears on the oscilloscope shows how the width of the pulse increase in sinusoidal function .

The second signal shown is for one pair of the IGBT's that work together, it shows that the signal is turned on for 180 dg and turned off for 10 dg.

The third waveform shows the gate signals taken for one inverter; the gate signals for positive and negative sides of the output sinusoidal.

Figure 5.13 : PWM Signals (Gates Signals)

5.3.2 Output Voltage of the Inverter

The two figures show the output waveform of the inverter, it is an ac wave and can be considered sinusoidal.

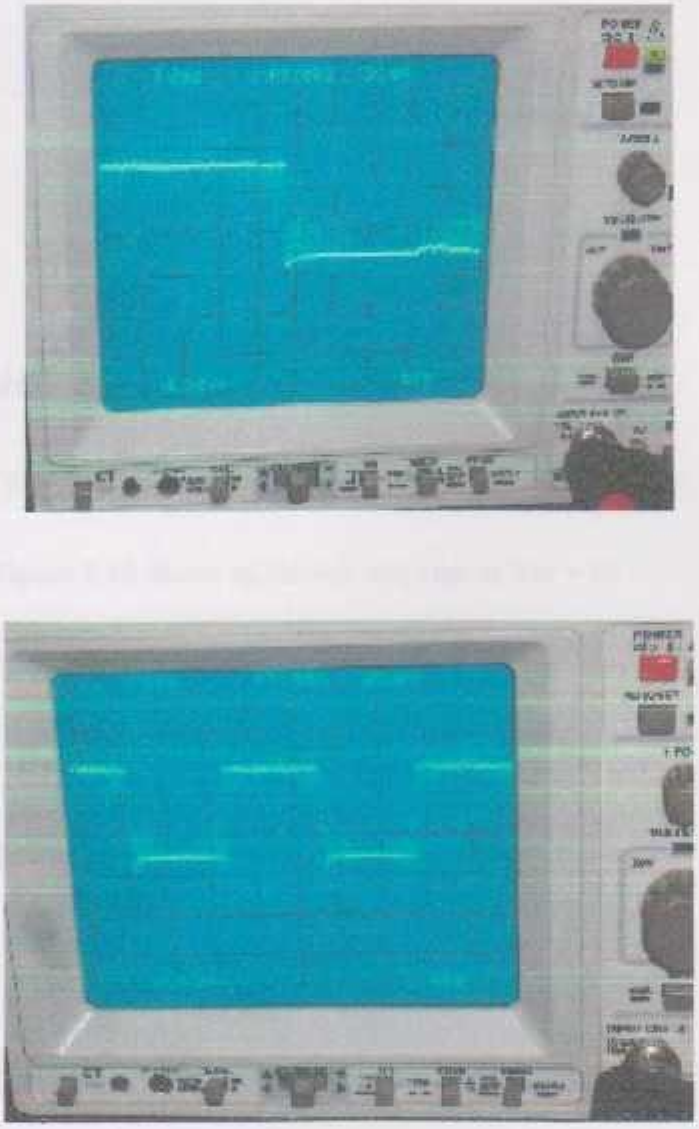


Figure 5.14 : Inverter Waveforms

5.3.3 Dynamic behaviour of the motor

The following curves reresent the dynamic behaviour of the motor in starting and breaking. When the motor is ocrated at 85V, it neds about 2 seconds to reach the synchronous speed, and it needs 1 second at 170V.

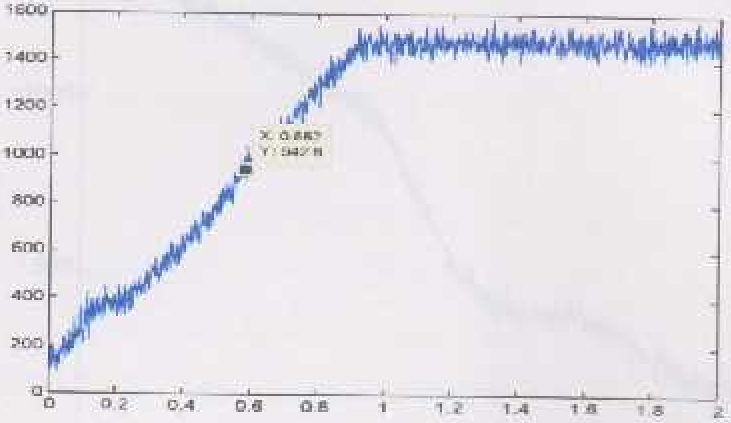


Figure 5.15 Motor speed step response at Vm = 85

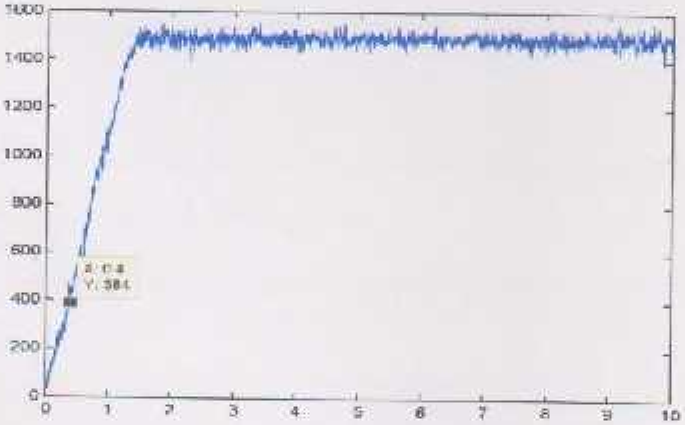


Figure 5.16 Motor speed step response at Vm = 170

The curve below shows that the motor needs about 10 seconds to stop when dynamic breaking is applied on it.

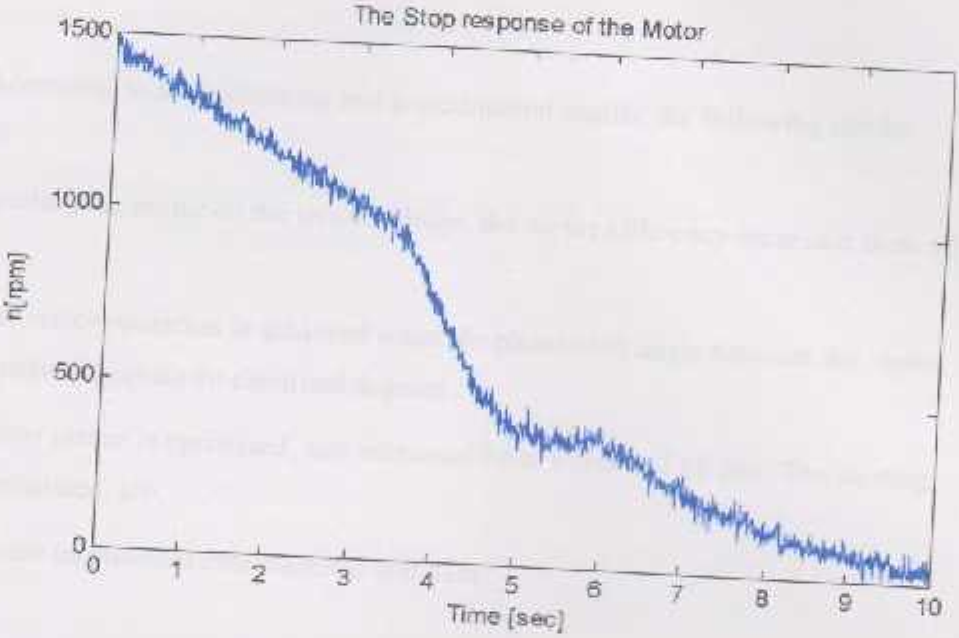


Figure 5.17 Motor speed response at breaking

CHAPTER SIX

Conclusions And Recommendations

6.1 Conclusions

According to the simulation and experimental results, the following can be concluded

1 .By operating the motor on the two windings, the motor efficiency increased from 65% to 70%.

2. The best motor operation is achieved when the phase shift angle between the motor windings currents equals 90 electrical degrees .

3 The motor torque is optimized, and increased from 5 Nm to 7.68 Nm .The starting torque is optimized, too.

4. The motor mechanical characteristic still hard.

6.2 Recommendations

1. The motor could be driven and controlled using microcontroller in order to be applicable packaged drive system.
2. The converter can be designed consisting of three arms rather than four.

Appendix A

A.1 Testing Single-Phase Motors

The methods to determine the winding resistances of the main, R_{mw}, and the auxiliary winding, R_{aw}, are not discussed in this section because we can use any method that can accurately determine the resistances of these windings such that the DC test. The other equivalent circuit parameters of a single-phase induction motor can be determined performing the blocked-rotor and the no-load tests.

A.1.1 Blocked-Rotor Test

The blocked-rotor test is performed with the rotor held at standstill by exciting one winding at a time while the other winding is left open. The test arrangement with the auxiliary winding open is shown in **Figure A.1**. The test is performed by adjusting the applied voltage until the main winding carries the rated current. Since the slip at standstill in either direction is unity, the rotor circuit impedance is usually much smaller than the magnetization reactance. Therefore, for the blocked-rotor test we can use the approximate equivalent circuit of the main winding without the magnetization reactance, as depicted in Figure A.2.

(a) Auxiliary Winding Open

Let V_{bm}, I_{bm}, and P_{bm} be the measured values of the applied voltage, the main-winding current, and the power supplied to the motor under blocked-rotor condition.

The magnitude of the input impedance is

$$Z_{bm}=\frac{V_{bm}}{I_{bm}} \tag{A.1}$$

The total resistance in the circuit is

$$R_{bm}=\frac{P_{bm}}{I^{2}_{bm}} \tag{A.2}$$

Thus, the total reactance is

$$X_{bm}=\sqrt{Z^{2}_{bm}-R^{2}_{bm}} \tag{A.3}$$

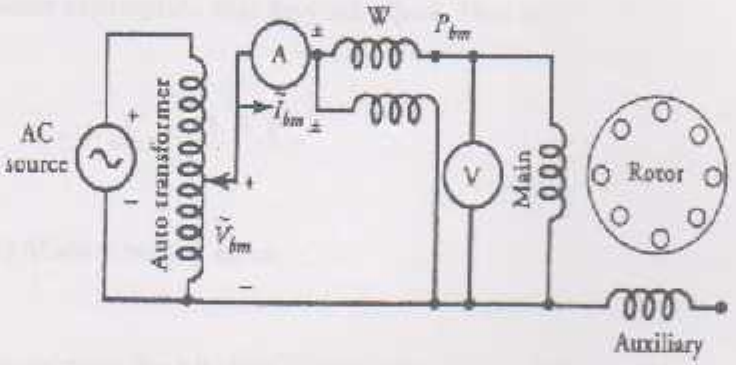


Figure A.1 Experimental setup for blocked-rotor test with auxiliary winding open.

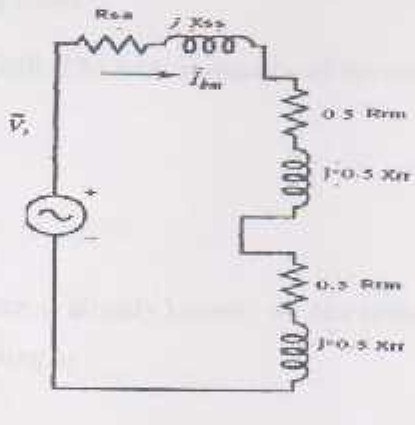


Figure A.2 Approximate equivalent circuit as viewed from the main winding under blocked-rotor condition.

From the approximate equivalent circuit (*Figure* A.2), we have

$$R_{bm} = R_{sm} + R_{rm} \qquad \text{(A.4)}$$

and $X_{bm} = X_{sm} + X_{rm}$ (A.5)

Since the main-winding resistance is already known, the rotor resistance at standstill, from **Eq. (A.3)**, is

$$R_{rm} = R_{bm} - R_{sm} \qquad \text{(A.6)}$$

To separate the leakage reactance's of the main winding and the rotor, we once again make the same assumption that they are equal. That is,

$$X_{sm} = X_{rm} = 0.5X_{bm} \qquad \text{(A.7)}$$

(b) Main winding open

We can also perform the blocked-rotor test by exciting the auxiliary winding with the main winding open. Let Iba' *Vba,* and *I,a* be the power input, the applied voltage, and the current in the auxiliary winding when

and the rotor is at standstill. The total resistance of the auxiliary winding can now be computed as

$$R_{ba} = \frac{P_{ba}}{I^2_{ba}} \qquad \text{(A.8)}$$

Since the rotor winding resistance is already known, we can compute the rotor resistance as referred to the auxiliary winding as

$$R_{ra} = R_{ba} - R_{sa} \qquad \text{(A.9)}$$

We can now determine the a-ratio, the ratio of effective turns in the auxiliary winding to the main winding, by the square root of the ratio of the rotor resistance as viewed from the auxiliary winding to the value of the rotor resistance as viewed from the main winding. Thus,

$$a=\sqrt{\frac{R_{ra}}{R_{rm}}} \tag{A.10}$$

A.1.2 No-Load Test with Auxiliary Winding Open

In the three-phase induction motor operating under no load, we neglected the copper loss in the rotor circuit because it was assumed to be very small. In fact, we considered the rotor branch an open circuit because of very low slip at no load. In a single-phase motor running on main winding only, the no-load slip is considerably higher than that for a three-phase motor. If we still assume that the slip under no load is almost zero and replace the rotor circuit of the forward branch with an open circuit under no load, the error introduced in the calculation of the motor parameters based upon this test is somewhat greater than that for the three- phase motor. Making such an assumption, however, does simplify the equivalent circuit of the main winding under no load with auxiliary winding open. Such an equivalent circuit is given in Figure A.3 .
Let *VflL*, *'InL'* and V*nL* be the measured values of the rated applied voltage, the current, and the power intake by the motor under no-load condition. Then the no-load impedance is

$$Z_{nl}=\frac{V_{nl}}{I_{nl}} \tag{A.11}$$

The equivalent resistance under no load is

$$R_{nl}=\frac{P_{nl}}{I^{2}_{nl}} \tag{A.12}$$

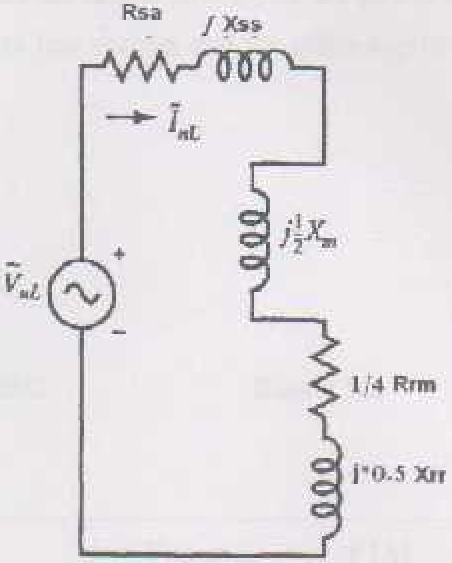


Figure A.3 Approximate equivalent circuit as referred to the main winding under no- load condition $(s = 0)$.

Hence, the no-load reactance is

$$X_{nl} = \sqrt{Z^2_{nl} - R^2_{nl}} \qquad \text{(A.13)}$$

However, from the equivalent circuit (Figure 10.15), we have

$$X_{nl} = X_{ss} + 0.5X_m + 0.5X_r$$

Since $X_r = X_{ss} = 0.5X_{bm}$

$$X_1 + 0.5X_2 = .0.75X_{bm}$$

Thus, from **Eq. A.13**, the magnetization reactance is

$$X_m = 2X_{nl} - 1.5X_{bm} \qquad \text{(A.14)}$$

Finally, the rotational loss is

$$P_r = P_{nl} - I^2_{nl}(R_1 + 0.25R_2) \qquad \text{(A.15)}$$

All the parameters of a single-phase induction motor are now known. Using these parameters we can now compute the torque developed, the power input, the power output, the winding currents, the line current, and the efficiency of the motor at any slip.

Test Results

Rsa =4.25Ω **Rsm = 3Ω**

	Power	I [A]	V [V]
No load	210	5	220
Block rotor main open	18.1	1.5	19.3
Auxiliary open	277	6.8	63.7

Table A.1 The motor test results

A.2 Test Calculations

From auxiliary Winding Open Test

$Z_{bm} = 63.7/6.8 = 9.37\ \Omega$

$Rbm = 277 /(6.8)2 = 6\ \Omega$

$Xbm = \sqrt{((9.37)^2 - 6^2)} = 7.2\ \Omega$

$Xss = Xrr = 0.5 * 7.2 = 3.6\Omega$

$Rrn = Rbm - Rm = 6 - 3 = 3\ \Omega$

From Main Winding Open Test

$Z_{ba} = 19.3 / 1.5 = 12.87\ \Omega$

$R_{ba} = 18.1/1.52 = 7.84\ \Omega$

$Rra = 7.84 - 4.25 = 3.6\ \Omega$

$a = \sqrt{(3.4/2.95)} = 1.07$

From No Load Test

$ZnL = 220/5 = 44\ \Omega$

$RnL = 210/5^2 = 8.4\ \Omega$

$XnL = \sqrt{(44^2 - 8.4^2)}\ \Omega = 43.2\ \Omega$

$Xm = 2*43.2 = 86.4\ \Omega$

$Protatnal = 210 - 5^2*(3+0.25*3) = 116.25$ Watt

Appendix B

IGBT Data Sheet

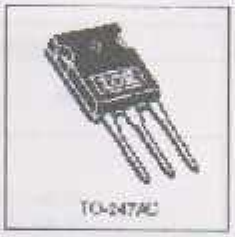
Features

- Standard: Optimized for minimum saturation voltage and low operating frequencies (< 1kHz)
- Generation 4 IGBT design provides tighter parameter distribution and higher efficiency than Generation 3
- Industry standard TO-247AC package
- Generation 4 IGBT's offer highest efficiency available
- IGBT's optimized for specified application conditions
- Designed to be a "drop-in" replacement for equivalent industry-standard Generation 3 IR IGBT's

$V_{CES} = 600V$

$V_{CE(on)}$ typ. $= 1.28V$

@$V_{GE} = 15V$, $I_C = 41A$



	Parameter	Max.	Units
V_{CES}	Collector-to-Emitter Breakdown Voltage	600	V
I_C @ $T_C = 25°C$	Continuous Collector Current	70	A
I_C @ $T_C = 100°C$	Continuous Collector Current	41	
I_{CM}	Pulsed Collector Current ①	140	
I_{LM}	Clamped Inductive Load Current ②	140	
V_{GE}	Gate-to-Emitter Voltage	± 20	V
E_{ARV}	Reverse Voltage Avalanche Energy ③	20	mJ
P_D @ $T_C = 25°C$	Maximum Power Dissipation	200	W
P_D @ $T_C = 100°C$	Maximum Power Dissipation	78	
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to + 150	°C
	Soldering Temperature, for 10 seconds	300 (0.063 in. (1.6mm) from case)	
	Mounting torque, 6-32 or M3 screw.	10 lbf•in (1.1N•m)	

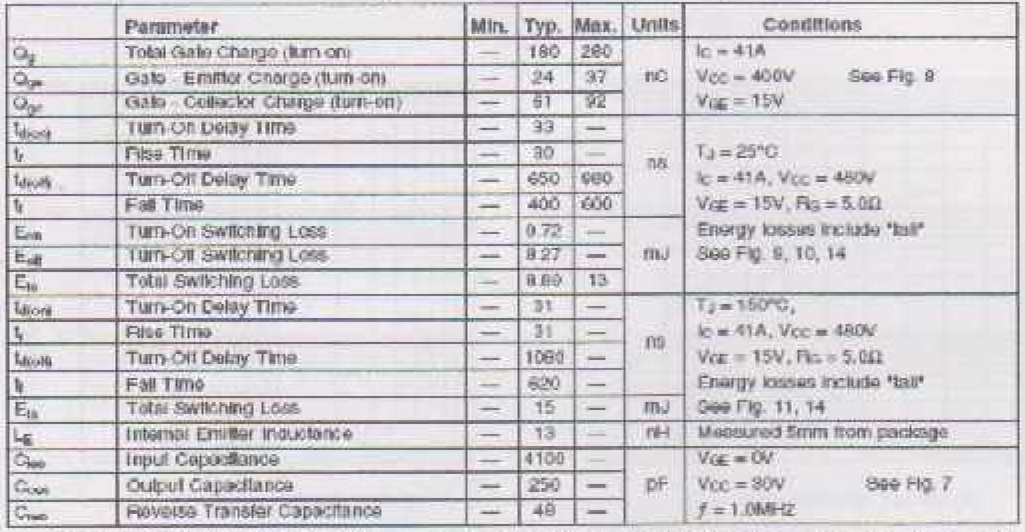
Table (B.1) Absolute Maximum Ratings

	Parameter	Typ.	Max.	Units
$R_{θJC}$	Junction-to-Case	—	0.64	°C/W
$R_{θCS}$	Case-to-Sink, Flat, Greased Surface	0.24	—	
$R_{θJA}$	Junction-to-Ambient, typical socket mount	—	40	
Wt	Weight	6.0 (0.21)	—	g (oz)

Table(B.2) Thermal Resistance

	Parameter	Min.	Typ.	Max.	Units	Conditions
$V_{(BR)CES}$	Collector-to-Emitter Breakdown Voltage	600	—	—	V	$V_{GE} = 0V$, $I_C = 250\mu A$
$V_{(BR)ECS}$	Emitter-to-Collector Breakdown Voltage ④	18	—	—	V	$V_{GE} = 0V$, $I_C = 1.0A$
$\Delta V_{(BR)CES}/\Delta T_J$	Temperature Coeff. of Breakdown Voltage	—	0.75	—	V/°C	$V_{GE} = 0V$, $I_C = 1.0mA$
$V_{CE(ON)}$	Collector-to-Emitter Saturation Voltage	—	1.28	1.36	V	$I_C = 41A$ $V_{GE} = 15V$ See Fig.2, 5
		—	1.62	—		$I_C = 60A$
		—	1.28	—		$I_C = 41A$, $T_J = 150°C$
$V_{GE(th)}$	Gate Threshold Voltage	3.0	—	6.0		$V_{CE} = V_{GE}$, $I_C = 250\mu A$
$\Delta V_{GE(th)}/\Delta T_J$	Temperature Coeff. of Threshold Voltage	—	-9.3	—	mV/°C	$V_{CE} = V_{GE}$, $I_C = 250\mu A$
g_{fe}	Forward Transconductance ⑤	17	34	—	S	$V_{CE} = 100V$, $I_C = 41A$
I_{CES}	Zero Gate Voltage Collector Current	—	—	250	µA	$V_{GE} = 0V$, $V_{CE} = 600V$
		—	—	2.0		$V_{GE} = 0V$, $V_{CE} = 10V$, $T_J = 25°C$
		—	—	1000		$V_{GE} = 0V$, $V_{CE} = 600V$, $T_J = 150°C$
I_{GES}	Gate-to-Emitter Leakage Current	—	—	±100	nA	$V_{GE} = \pm 20V$

Table (B.3) Electrical Characteristics @ TJ = 25°C (unless otherwise specified)



	Parameter	Min.	Typ.	Max.	Units	Conditions
Q_g	Total Gate Charge (turn-on)	—	180	280	nC	$I_C = 41A$
Q_{ge}	Gate - Emitter Charge (turn-on)	—	24	37		$V_{CC} = 400V$ See Fig. 8
Q_{gc}	Gate - Collector Charge (turn-on)	—	61	92		$V_{GE} = 15V$
$t_{d(on)}$	Turn-On Delay Time	—	33	—	ns	$T_J = 25°C$
t_r	Rise Time	—	30	—		$I_C = 41A$, $V_{CC} = 480V$
$t_{d(off)}$	Turn-Off Delay Time	—	650	980		$V_{GE} = 15V$, $R_G = 5.0\Omega$
t_f	Fall Time	—	400	600		Energy losses include "tail"
E_{on}	Turn-On Switching Loss	—	0.72	—	mJ	See Fig. 9, 10, 14
E_{off}	Turn-Off Switching Loss	—	8.27	—		
E_{ts}	Total Switching Loss	—	8.89	13		
$t_{d(on)}$	Turn-On Delay Time	—	31	—	ns	$T_J = 150°C$,
t_r	Rise Time	—	31	—		$I_C = 41A$, $V_{CC} = 480V$
$t_{d(off)}$	Turn-Off Delay Time	—	1080	—		$V_{GE} = 15V$, $R_G = 5.0\Omega$
t_f	Fall Time	—	620	—		Energy losses include "tail"
E_{ts}	Total Switching Loss	—	15	—	mJ	See Fig. 11, 14
L_E	Internal Emitter Inductance	—	13	—	nH	Measured 5mm from package
C_{ies}	Input Capacitance	—	4100	—	pF	$V_{GE} = 0V$
C_{oes}	Output Capacitance	—	250	—		$V_{CC} = 30V$ See Fig. 7
C_{res}	Reverse Transfer Capacitance	—	48	—		$f = 1.0MHz$

Table(B.4) Switching Characteristics @ TJ = 25°C (unless otherwise specified)

_ Repetitive rating; VGE = 20V, pulse width limited by max. junction temperature. (See fig.(B. 13b)

_ VCC = 80%(VCES), VGE = 20V, L = 10µH, RG = 5.0Ω, (See fig.(B.13a)

_ Repetitive rating; pulse width limited by maximum junction temperature.

_ Pulse width ≤ 80µs; duty factor ≤ 0.1%.

_ Pulse width 5.0µs, single shot.

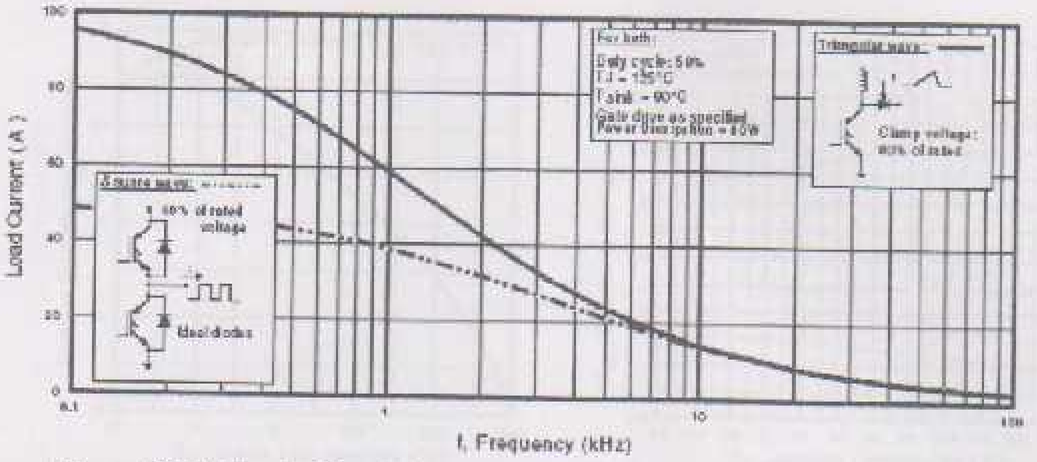
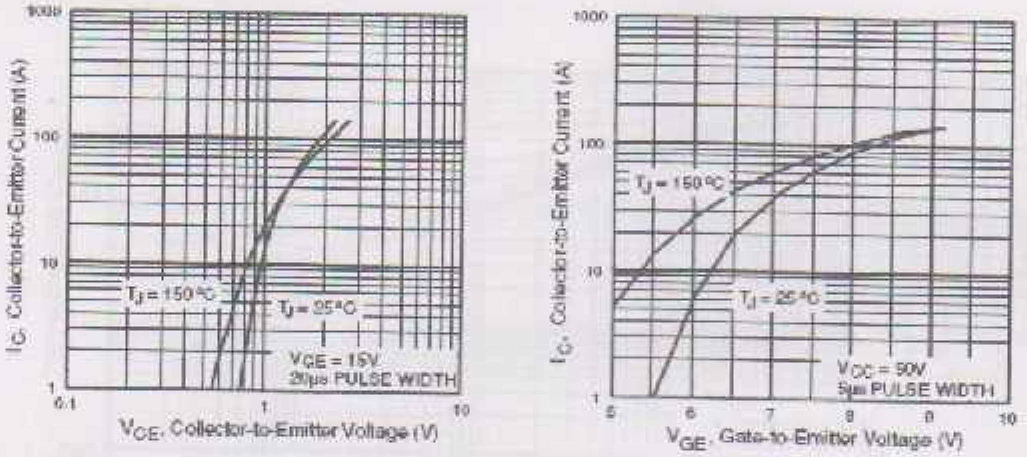


Figure (B.2)- Typical Load Current vs. Frequency(Load Current = IRMS of fundamental)



Figure(B.3)a) Typical Output Characteristics **b)** - Typical Transfer Characteristics

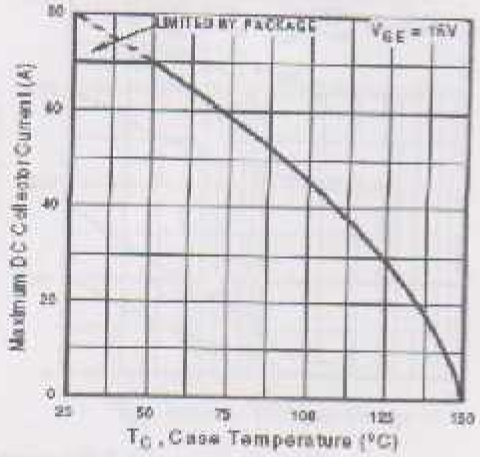


Figure (B.4) Maximum Collector Current vs. Case Temperature

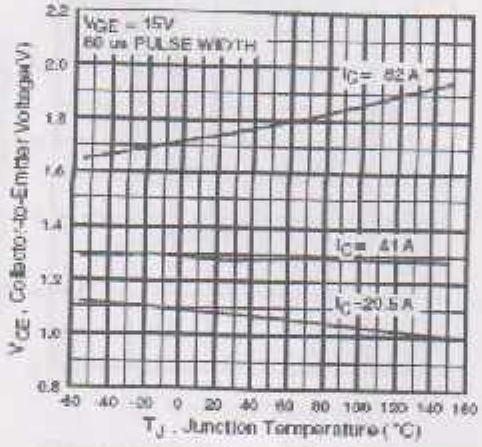


Figure (B.5) Typical Collector-to-Emitter Voltages. Junction Temperature

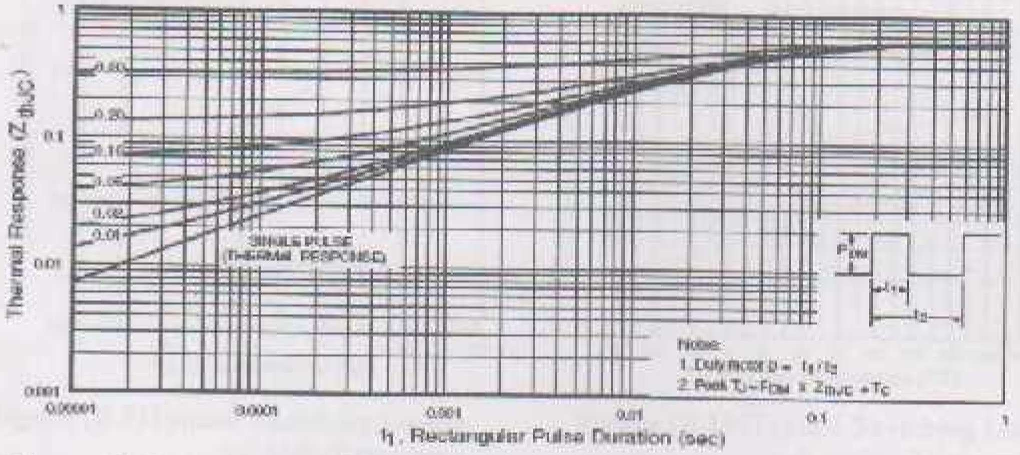


Figure (B.6) Maximum Effective Transient Thermal Impedance, Junction-to-Case

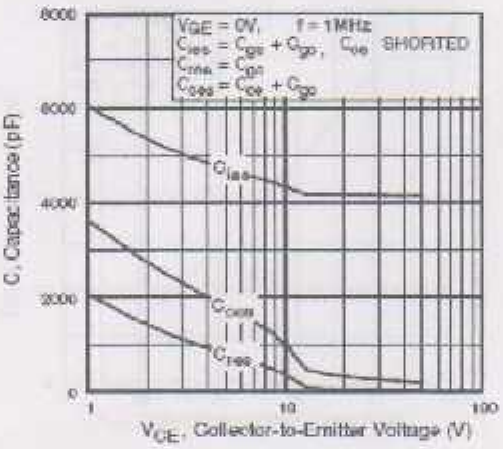


Figure (B.7)Typical Capacitance vs. Collector-to-Emitter Voltage

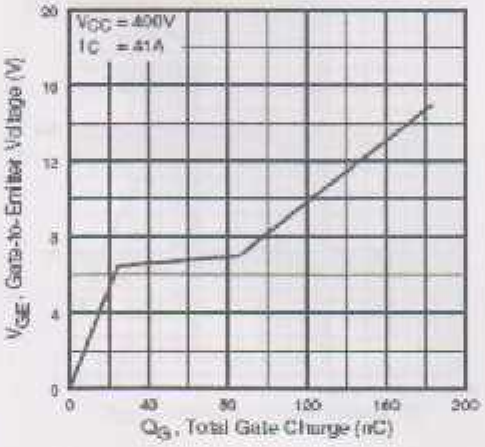


Figure (B.8)Typical Gate Charge vs. Gate-to-Emitter Voltage

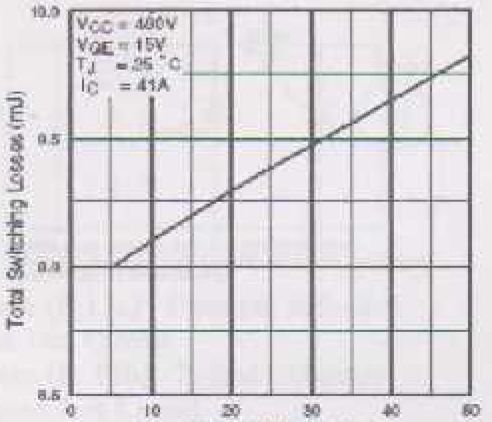


Figure (B.9)Typical Switching Losses vs. Gate Resistance

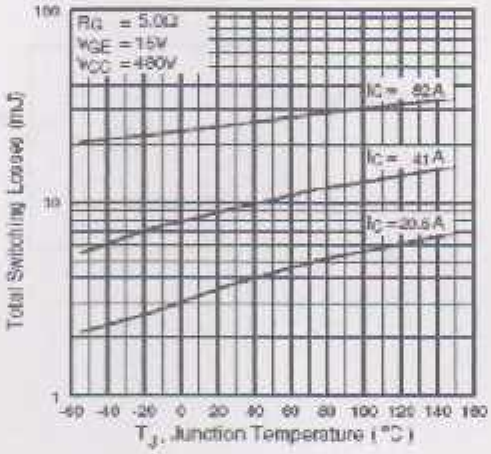


Figure (B.10)Typical Switching Losses vs Junction Temperature

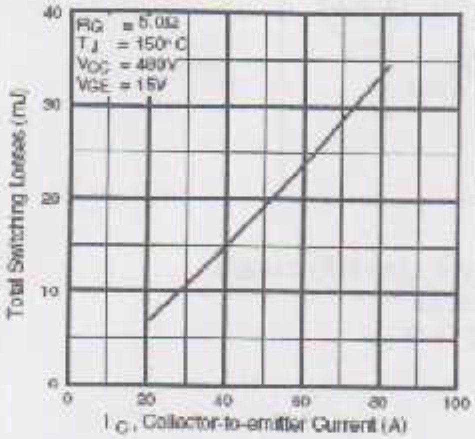


Figure (B.11) Typical Switching Losses vs. Collector-to-Emitter Current

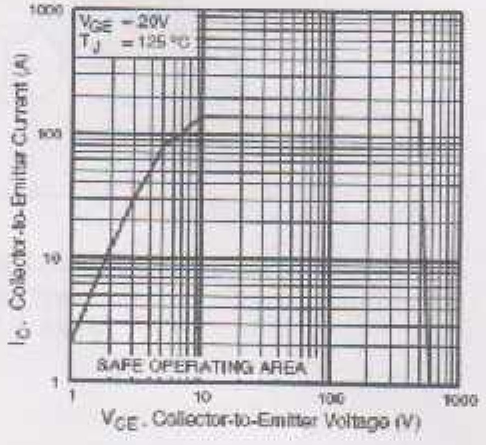
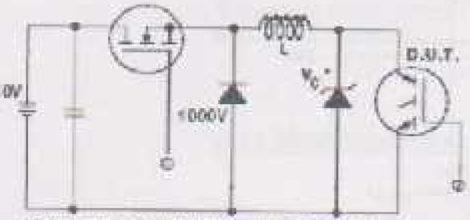


Figure (B.12)- Turn-Off SOA



* Driver same type as D.U.T.; Vc = 80% of Vce(max)
* Note: Due to the 50V power supply, pulse width and inductor will increase to obtain rated Id.

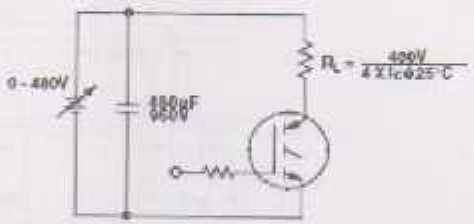


Figure (B.13a) - Clamped Inductive Load Test Circuit

Figure (B. 13b) - Pulsed Collector Current Test Circuit

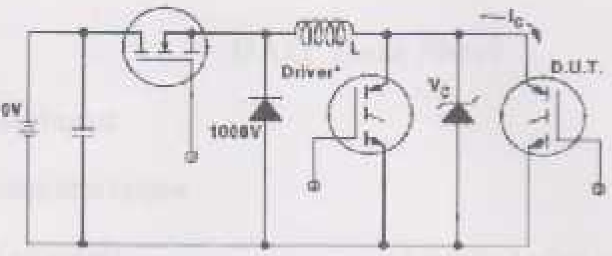


Figure (B.14a) - Switching Losses Test Circuit
* Driver same type
as D.U.T., VC = 480V

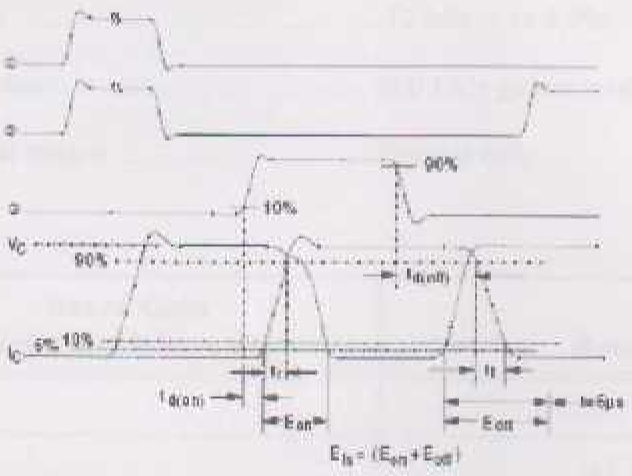
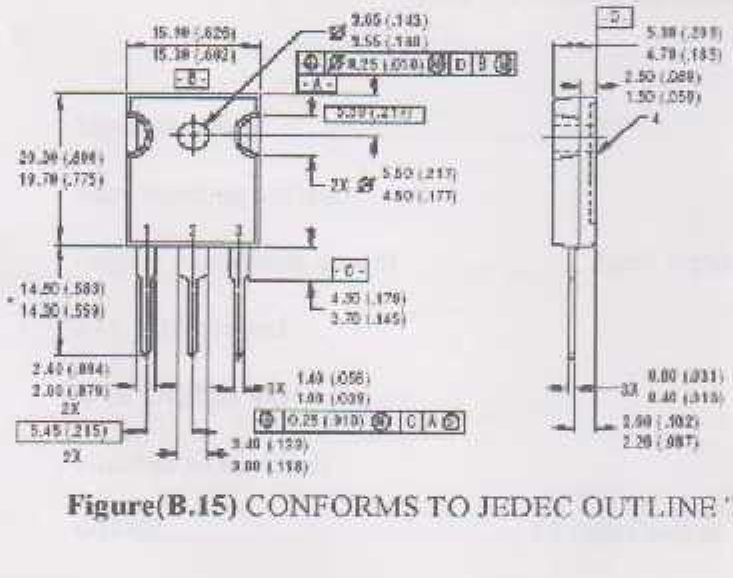


Figure (B. 14b) - Switching Loss Waveforms

Case Outline and Dimensions — TO-247AC



NOTES:
1 DIMENSIONS & TOLERANCING PER ANSI Y14.5M, 1982.
2 CONTROLLING DIMENSION : INCH.
3 DIMENSIONS ARE SHOWN MILLIMETERS (INCHES).
4 CONFORMS TO JEDEC OUTLINE TO-247AC.

LEAD ASSIGNMENTS
1 - GATE
2 - COLLECTOR
3 - EMITTER
4 - COLLECTOR

* LONGER LEADED (20mm) VERSION AVAILABLE (TO-247AD) TO ORDER ADD "-E" SUFFIX TO PART NUMBER

Figure(B.15) CONFORMS TO JEDEC OUTLINE TO-247AC (TO-3P)

Appendix C

DAQ Data Sheet

C.1 Analog Input

Input Characteristics

Number of channels .... 16 single-ended or 8 differential

(software-selectable per channel)

Type of ADC.. Successive approximation

Resolution .... 12 bits, 1 in 4,096

Sampling rate .... 200 kS/s guaranteed

Input signal ranges .... Bipolar only

Board Gain (Software-Selectable)	Range
0.5	±10 V
1	±5 V
10	±500 mV
100	±50 mV

Table C1 Analog input gain

Input coupling ....DC

Max working voltage

(signal + common mode) .... Each input should remain within

+11 V of ground

C .2 Digital I/O

Number of channels

6025E.. 32 input/output

6023E and 6024E........................... 8 input/output

Compatibility .... TTL/CMOS

DIO<0..7>

Digital logic levels

Level	Min	Max
Input low voltage	0 V	0.8 V
Input high voltage	2 V	5 V
Input low current (V_{IL} = 0 V)	—	–320 µA
Input high current (V_{IH} = 5 V)	—	10 µA
Output low voltage (I_{OL} = 24 mA)	—	0.4 V
Output high voltage (I_{OH} = 13 mA)	4.35 V	—

Table C.2 The voltage level

50 kΩ pull up to +5 VDC

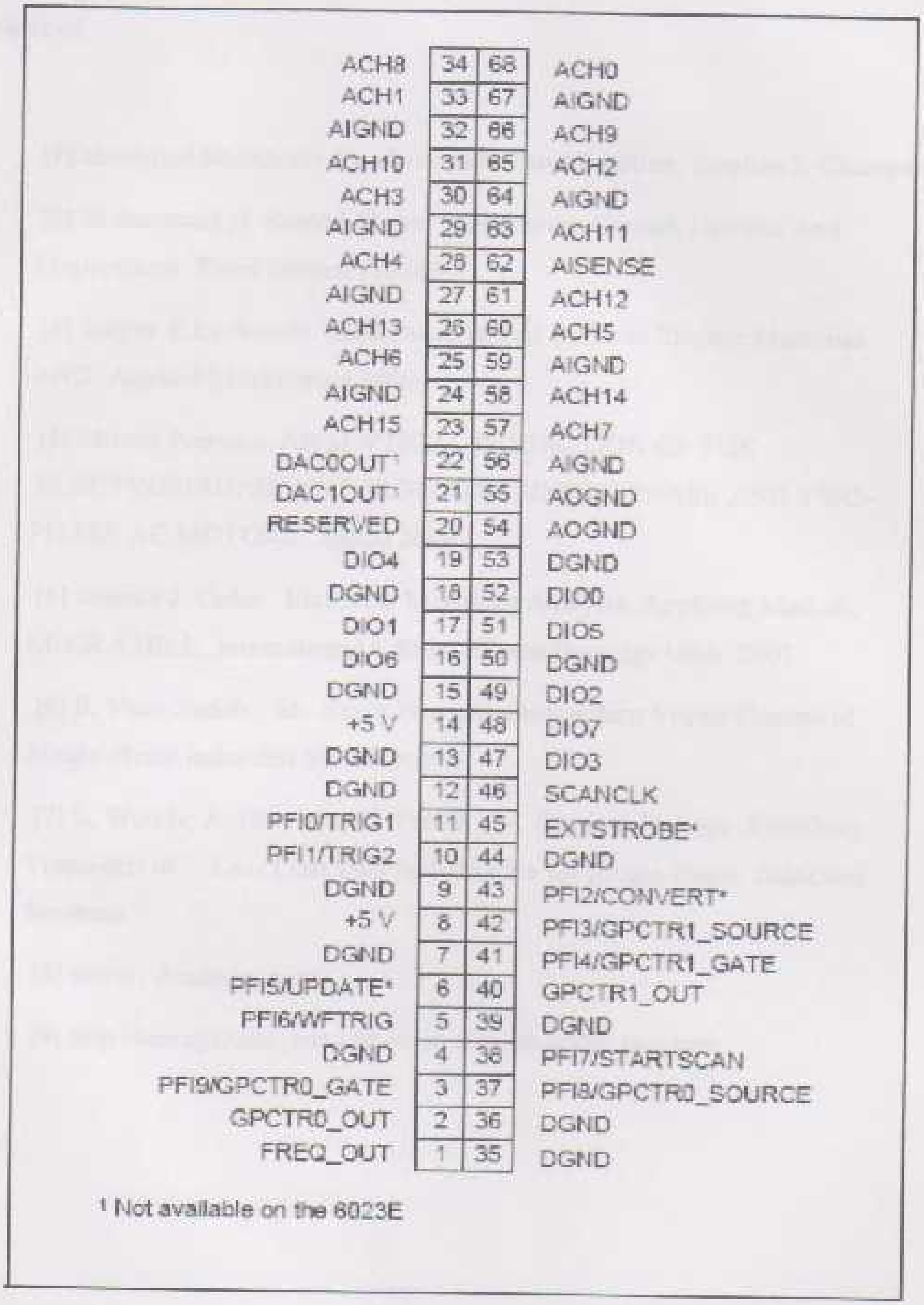
Data transfers .... Programmed I/O

PA<0..7>,PB<0..7>,PC<0..7>

Digital logic levels

Level	Min	Max
Input low voltage	0 V	0.8 V
Input high voltage	2.2 V	5 V
Input low current (V_{IL} = 0 V, 100 kΩ pull up)	—	–75 µA
Input high current (V_{IH} = 5 V, 100 kΩ pull up)	—	10 µA
Output low voltage (I_{OL} = 2.5 mA)	—	0.4 V
Output high voltage (I_{OH} = 2.5 mA)	3.7 V	—

Table C. 3 Digital logic levels



ACH8	34	68	ACH0
ACH1	33	67	AIGND
AIGND	32	66	ACH9
ACH10	31	65	ACH2
ACH3	30	64	AIGND
AIGND	29	63	ACH11
ACH4	28	62	AISENSE
AIGND	27	61	ACH12
ACH13	26	60	ACH5
ACH6	25	59	AIGND
AIGND	24	58	ACH14
ACH15	23	57	ACH7
DAC0OUT[1]	22	56	AIGND
DAC1OUT[1]	21	55	AOGND
RESERVED	20	54	AOGND
DIO4	19	53	DGND
DGND	18	52	DIO0
DIO1	17	51	DIO5
DIO6	16	50	DGND
DGND	15	49	DIO2
+5 V	14	48	DIO7
DGND	13	47	DIO3
DGND	12	46	SCANCLK
PFI0/TRIG1	11	45	EXTSTROBE*
PFI1/TRIG2	10	44	DGND
DGND	9	43	PFI2/CONVERT*
+5 V	8	42	PFI3/GPCTR1_SOURCE
DGND	7	41	PFI4/GPCTR1_GATE
PFI5/UPDATE*	6	40	GPCTR1_OUT
PFI6/WFTRIG	5	39	DGND
DGND	4	38	PFI7/STARTSCAN
PFI9/GPCTR0_GATE	3	37	PFI8/GPCTR0_SOURCE
GPCTR0_OUT	2	36	DGND
FREQ_OUT	1	35	DGND

[1] Not available on the 6023E

Figure C. 1 The pins port of the DAQ

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