PALESTINE POLYTECHNIC UNIVERSITY

COLLEGE OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

GRADUATION PROJECT REPORT

DESIGN AND CONTROL OF THREE-PHASE BRUSHLESS SENSORLESS DC MOTOR

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ABSTRACT

Brushless DC (BLDC) motors are widely used in many application such as hard disk and CD drive, robots, fans and pumps.....etc, this referred to their advantages that have it, such as simple construct, good performance, reliability and high speed

In this project we aim to study the construction and principle of operation of three phase brushless DC motor, design the excitation circuit (p. magnet rotor) and armature circuit, replace the mechanical position sensor with back EMF electronic circuit applied the (PC) as controlling unit of the motor, and finally we aim to implement this design and compare with two phase (BLDCM)

The signal obtained from the tachogenerator is processed by an 8085 microprocessor-based system through an A/D converter. The 8085 microprocessor is the main control device (controller). It contains the comparison circuit of the closed loop system.

The converter is used in our project is an inverter that takes a D.C voltage as input and the output is pulsating voltages for the three phases individually. The D.C voltage is obtained from a single-phase uncontrolled rectifier with a D.C filtration to obtain pure dc voltage for the converter.

The programming language required to program the microprocessor-based system that works as a controller is the low-level language C++ language.

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CHAPTER ONE

INTRODUCTION

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INTRODUCTION

1.1General outlooks:

General brushed dc motors have a great importance in our live and can also be used in closed-loop control system and applications. Unlike the other types of motors, a brush motor does not require any additional electronic driver to operate. Connect a power supply across the brush terminals and the motor will go.

This level of simplicity is achieved through mechanical commutation. The commutator on a brush motor can be thought of as a multi-position switch. The commutator has multiple contacts each wired in series to a group of windings on the armature. The contact angle of the brushes on the commutator determine which windings are excited which in turn controls the electrical phase angle of the armature. The brush contact angle is phased to produce maximum torque for a given electrical input. This is similar to the commutation function performed by the electronics in a brushless D.C. motor. The disadvantage of a brush motor is its limited life. The sliding electrical contact between the commutator and brush is subject to wear. In vacuum, this wear is accelerated and must be considered in every application. Typically brush life in vacuum is on the order of 50-200 hours,and they need a continuous maintenance.

Brushless dc motor is the solution for these limitations. Brushless dc motor provide us a very high speeds, say from 3,000 rpm extended to 10,000 rpm, this because no brushes used and so no direct friction with the rotor. These high speeds enable us using these motors in many applications, for example hard disk drives which need a very high speed reaches 10000rpm.

A brushless DC motor is simply normal DC motor turned inside out, which means that the coil is on the outside part (stationary part) and the magnets set are fixed on the inside (rotational part) as well shown in fig.(1.1) . One of the main advantages of these motors is that there is no mechanical contact between the stator and rotor presented by the absence of Brush set. The stator consists of several coils producing total magnetic flux leads to electromagnetic torque acting on the rotor causing it to rotate. Three phases are usually used creating six different ways (switching combinations) to let current run through the coils. A microcontroller frequently redirects the current leading to a fast-changing magnetic field turning the rotor.

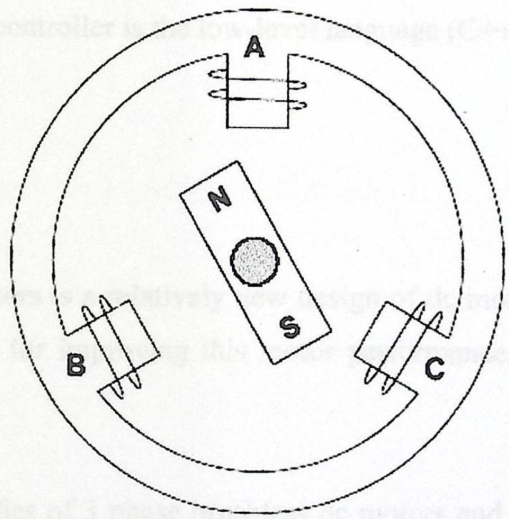

Fig. (1.1): Three-phase BLDC motor.

In this project we will built up a three phase brushless dc motor, and deign its closed loop control system using the 8085 microprocessor controller, and also we will use photo cell sensor for detecting the rotor position in addition to the sensorless method.

This project is very important for many applications which need high speeds, such as hard disk , medical applications, robots, home appliances (air conditioners, refrigerators, washing machines), and industrial applications (pumps and ventilators), etc…

A PWM signal is generated that needed for converter to feed the motor with variable voltage. The converter used is an inverter that takes a D.C voltage as input and the output is pulsating voltages for the three phases as six step ,in each step there are two phases are excited and the third is unexcited .

The programming language required to program the microprocessor-based system that works as a controller is the low-level language (C++ language).

1.2 Previous studies:

Brushless dc motors is a relatively new design of dc motors so, the studies in this field is continuous for improving this motor performance, designs and control circuits.

The previous studies of 3 phase brushless dc motors and its control system by sensors are very much, but by sensorless are little, so we searched for these studies and found the following:

- ✓ power pulse group :

They show an ordinary 3 phase motor and using back EMF sensing and they showed an ordinary equations and they didn't do any thing for control any type of BDCM , but they only compare theoretically between the advantages of the three types (one phase, two phase, and three phase) of BDCM. [5].

- ✓ Faulhaber group :

They studied show the construction of the three phase dc motor; they described the principle of operation, the sensor unit, and its application.

- ✓ Remote Laboratory for a Brushless DC Motor :

Worked by 3 persons [1] they design new drive of brushless dc motor using microprocessor system of a 3 phase brushless dc motor.

- ✓ Fundamentals of electric drive :

Its a book in which the author show study of unipolar and bipolar 3 phase brushless dc motor and its drive ,the book shoes the application of the Brushless dc motor in sensor case .

1.3 Estimated cost:

The project device requirements are microprocessor, the encoder and sensing unit ,six MOSFETS, 22 pieces of rectangular magnets, push bottoms, lamps and switches , IC comparators ,Isolation circuit, protection circuits, 24 volt power supply , 5 volt power supply , 6high power diodes,. the sensorless circuit components, adhesive for agglutinating the magnets on the rotor, and steel bar which weight is 6kg.

There are some other costs for the project including rewinding the sartor, special personal computer, printer, transportation, information sources, computing and designing programs lathes, millings, cutting tools, and other services costs. According to these requirements, our project is estimated to cost more than $750.

1.4 Project Contents.

This chapter talks about the general idea of our project and its advantages, and its applications. Also, it contains reviews of the previous studies about the brushless DC motors.

Chapter two talks about theoretical background of the project.. It also gives the general explanations for the project devices; and contains comparing study between brushless DC motors and other motors.

Chapter three is the theoretical design concepts of the three -phase brushless DC motor and the closed loop speed control system, and It contains the project objectives and the general block diagram and explains how the project works.

Chapter four explains the motor design, and motor calculations, hardware design of the power circuits and converter used for the motor, and the controller as a design of the microprocessor-based system.

Chapter five is the software design of the microprocessor-based system using the C++ language to make programs for the closed-loop systems of the three-phase brushless motor speed control. It contains the general programming algorithms and flow charts.

Chapter six models the motor mathematically and analyzes the results and curves of the motor characteristics that is gotten from the experiments and tests performed on our motor.

Chapter seven bases the conclusion and the future works and recommendations. It lists the points we results out and how this project may be improved in future, in addition of some suggested projects to be done in future.

CHAPTER TWO

THEORETICAL BACKGROUND

CHAPTER TWO

THEORETICAL BACKGROUND

2.1 Introduction:

Conventional DC motors are highly efficient and their characteristics make them usable in variable speed applications. However, their only drawback is that they need a commutator and brushes which are subject to wear and require maintenance. When the functions of commutator and brushes were implemented by solid-state switches, maintenance-free motors were realized. These motors are now known as brushless DC motors.

In this chapter, the basic structures drive circuits, fundamental principles, steady state characteristics, and the applications of brushless DC motors will be discussed.

2.2 The advantages of BLDC motor compared to brush DC motors:

1 Better speed versus torque characteristics
2 High dynamic response
3 High efficiency
4 Long operating life
5 Noiseless operation
6 Higher speed ranges

2.3 Applications:

Brushless dc motors are widely used in various applications. For example BDCM used in Laser printer, Hard disk drives and CD/DVD drive, Heating, ventilation and air conditioning, Refrigerators, Medical equipment ,Robotics ,Fans and Pumps

2.4 Equivalent Circuit and General Equations:

The per phase equivalent circuit of three phase brushless dc motors is shown in Fig. (2.1), the induced voltage of the motor is calculated by the following equation

$$e = \left(\frac{d\lambda_m}{dt}\right) \times m \qquad \text{......... (2.1)}$$

where λ is the flux linkage of stator winding per phase due to the permanent magnet.

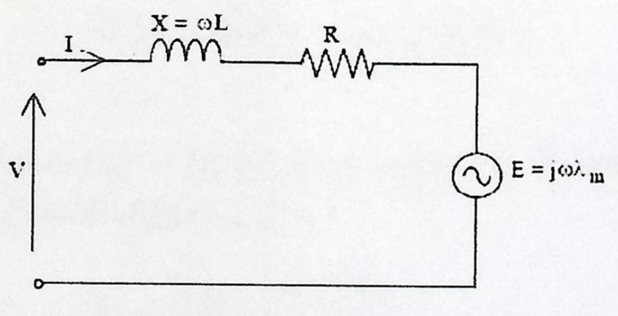

Fig. (2.1): steady state equivalent circuit per phase

For steady state conditions, assuming v and e are sinusoidal at frequency ω, the equivalent circuit becomes as shown in Fig.(2.1), where X=ωL, and V, I, E, and λm are phasors with rms amplitudes.

$$X = \omega L \qquad \text{......... (2.2)}$$

$$E = j\omega\lambda m \qquad \text{......... (2.3)}$$

The steady state circuit equation can be written as:

$$V = E + (R + j\omega L) \qquad \text{......... (2.4)}$$

For a maximum mechanical power at a given speed, I and E are in phase. This also gives maximum torque/ampere (minimum current / Nm). A brushless dc motor has position feedback from the rotor via back EMF sensing. To keep a particular angle between V and E, since E is in phase with rotor position, and V is determined by the inverter supply to the motor. Assuming that wL<<R, when I is in phase with E, V will also be in phase with E. Thus the circuit can be analyzed using magnitudes of E, V, and I, as if it was a dc circuit.

But first note that when E and I are in phase, the motor mechanical power output (before friction, windage, and iron losses) i.e. the electromagnetic output power is:

$$Pem = m|E||I| = m\omega|\lambda m||I| \qquad \text{......... (2.5)}$$

where m is the number of phases, |E|, |I|, and |λm| are the amplitudes of phasor E, I, and λm, The electromagnetic torque is:

$$T_{em} = \frac{P_{em}}{\omega_r} = \frac{m.|I||\lambda_m|}{\omega_r} \qquad \text{......... (2.6)}$$

where ωr = 2ω/p is the rotor speed in Rad/s, and p the number of poles.

$$T_{em} = \frac{(mp|\lambda_m||I|)}{2} \qquad \text{......... (2.7)}$$

The actual shaft output torque is:

$$T_{load} = T_{em} - T_{loss} \qquad \text{......... (2.8)}$$

Where T_{loss} is the total torque due to friction, windage, and iron losses.

And in terms of rotor speed:

$$E = \frac{(p\omega_r I\lambda_m)}{2} \qquad \text{......... (2.9)}$$

2.5 Performance of Brushless DC Motor.

The voltage equation can be simplified in algebraic form as:

$$Va = E_g + Ra.Ia \qquad \text{......... (2.10)}$$

Substituting relations (2.7) and (2.9), we obtain:

$$Va = C\phi\omega_r + Ia.Ra \qquad \text{......... (2.11)}$$

and

$$\omega r = \frac{Va}{(C\phi)} - \frac{Ra.T_{em}}{(C\phi)^2} \qquad \text{......... (2.12)}$$

Where:

C: is the motor constant and its unit is (V.s / Wb)

Φ: is the air gap magnetic flux (Wb).

2.6 Efficiency.

Efficiency is defined as the ratio of the output power and input power, i.e.

$$\eta = \left(\frac{P_{out}}{P_{in}}\right) \times 100\,\% \qquad \text{......... (2.13)}$$

where $P_{in} = Va * Ia$, and $P_{out} = T_{load} * \omega_r$

In term of the power flow,

$$P_{in} = P_{cu} + P_{Fe} + P_{mec} + P_{out} \qquad \text{......... (2.14)}$$

where:

$P_{cu} = m*Ra*Ia^2$ is the copper loss due to windings resistance.

P_{Fe} is the iron loss due to hysterics and eddy currents.

P_{mec} is the mechanical losses due to windage and friction.

2.7 Controlling a BLDC Motor:

Two parameters of a normal DC motor are very easy to control, the speed and the direction. To control the speed, we must vary the input voltage.

To change the direction, simply reverse the polarity. The speed is often controlled with pulse width modulation,

2.8 Project Main Elements.

2.8.1 MOSFET:

We used the MOSFT transistor in power circuit because of its characteristics. It is used as power switch and it has very high speed to turn on and off. Also, it rates very high currents reaches 50A.

2.8.2 Isolation Circuits:

Optical isolator is a device that uses a short optical transmission path to accomplish electrical isolation between elements of a circuit. The optical path may be air or a dielectric waveguide. The transmitting and receiving elements of an optical isolator may be contained within a single compact module.

The optical isolator has many functions, such as the dispatching of a signal, message, or other form of information; The propagation of a signal, message, or other form of information by any means, such as by telegraph, telephone, radio, television, or facsimile via any medium, coaxial cable, microwave, optical fiber, or radio frequency, in communications systems, a series of data units, such as blocks, messages, or frames; The transfer of electrical power from one location to another via conductors.

An optical isolator uses a short optical transmission path to accomplish electrical isolation between elements of a circuit. So, it is necessary for using in the motor system and control circuit to isolate the elements of the system and protect it from high current that damage the control circuit.

Stability is another advantage of isolation circuit. It is needed to accurately monitor motor in high noise motor control environments, providing for smoother control.

In various types of motor control applications, high accuracy and linearity are paramount, under transient conditions. So, we must use isolation circuit between motor and control circuit, between control circuit and microprocessor, between microprocessor and power circuit.

2.8.3 Photo-Cell Sensor:

Photosensitive elements are versatile tools for detecting light. They exceed the sensitivity of the human eye to all the colors of the spectrum and operate in the ultraviolet and entrained regions.

2.8.4 Tachogenerator:

An electromechanical generator is a device capable of producing electrical power from mechanical energy. When not connected to a load resistance, generators will generate voltage roughly proportional to shaft speed. With precise construction and design, generators can be built to produce very precise voltages for certain ranges of shaft speeds, thus making them well-suited as measurement devices for shaft speed in mechanical equipment.

A generator specially designed and constructed for this use is called a tachometer or tachogenerator as shown in fig. (2.2).

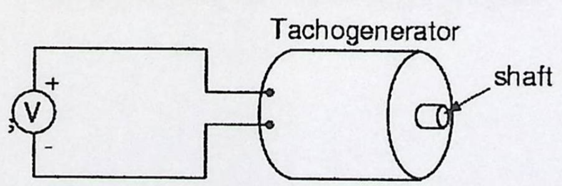

Fig. (2.2): Tachogenerator diagram

By measuring the voltage produced by a tachogenerator, you can easily determine the rotational speed of whatever it's mechanically attached to. One of the more common voltage signal ranges used with tachogenerators is 0 to 10 volts. Obviously, since a tachogenerator cannot produce voltage when it's not turning, the zero cannot be "live" in this signal standard. Tachogenerators can be purchased with different "full-scale" (10 volt) speeds for different applications

2.9Analog-to-Digital (A/D) Converter.

The A/D conversion is a process in which an analog signal is represented by equivalent binary states. A/D converters use the successive-approximation technique to perform the conversion.

Figure (2.2) shows a block diagram of the 8-bit A/D converter. It has one input line for an analog signal and eight output lines for digital signals.

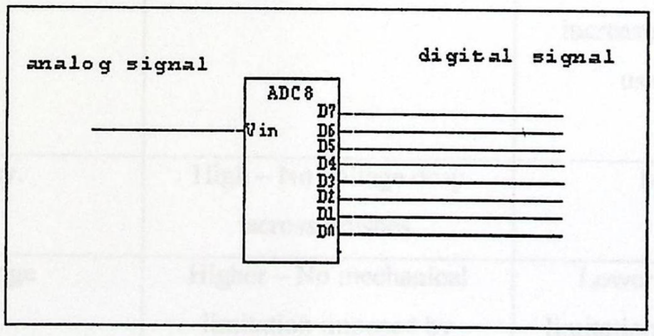

Fig. (2.3): A/D Converter block diagram

2.10 Comparing between BLDC motors and other motors:

We will show in Table (2.1) the comparing between BLDC and brushed motors.

Feature	BLDC Motor	Brushed DC Motor
Commutation	Electronic commutation based on Hall position sensors and back EMF.	Brushed commutation.
Life	Longer.	Shorter.
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load.	Moderately flat – At higher speeds, brush friction increases, thus reducing useful torque.
Efficiency.	High – No voltage drop across brushes	Moderate.
Speed Range	Higher – No mechanical limitation imposed by Brushes/commutator.	Lower – Mechanical limitations by the brushes.
Cost of Building	Higher – Since it has permanent magnets, building costs are higher.	Low
Control.	Complex and expensive	Simple and inexpensive.

Output Power/ Frame Size	High – Reduced size due to superior thermal Characteristics. Because BLDC has the windings on the stator, which is connected to the case, the heat Dissipation is better.	Moderate/Low – The heat produced by the armature is dissipated in the air gap, thus increasing the temperature in the air gap and limiting specs on the Output power/frame size.

Table (2.1) comparing BLDC motors to brushed DC motors

And we will show in table (2.2) the comparing between BLDC motors and induction motor

Feature	BLDC Motor	Induction Motor
Speed/Torque Characteristics	Flat – Enables operation at all speeds with Rated load.	Nonlinear – Lower torque at lower speeds
Output Power/ Frame Size	High – Since it has permanent magnets on the rotor, smaller size can be achieved for a given output power.	Moderate – Since both stator and rotor have windings, the output power to size is lower than BLDC.
Starting Current	Rated – No special starter circuit required.	Approximately up to seven times of rated – Starter Circuit rating should be carefully selected. Normally Uses a Star-Delta starter.
Slip	No slip is experienced between stator and rotor Frequencies.	The rotor runs at a lower frequency than stator by slip frequency and slip increases with load on the Motor.

Table (2.2) comparig BLDC motors to induction motors

CHAPTER THREE

DESIGN CONCEPTS

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DESIGN CONCEPTS

3.1 Project Objectives:

In this project we aim to study the construction and principle of operation of three phase brushless DC motor, design the excitation circuit (p. magnet rotor) and armature circuit, use the mechanical position sensor (hall sensor), use back EMF electronic circuit to detect the rotor position. Then we will compare between two methods, apply the (PC) as controlling unit of the motor, and finally we aim to implement this design and compare with two phase (BLDCM).

3.2 Control of a 3-Phase BLDC Motor:

There are two methods to control of the motor, the first one is by back EMFs signals (sensorless case), and the other by photo cell sensor (sensor case)

3.2 .1 Sensor-less Operation of a 3-Phase BLDC Motor:

3.2.1.1 Why we applied sensorless control ?

BLDC motors require electronic control; Some BLDC motors use Hall Effect sensors to provide absolute position sensing. This result need more wires,higher cost and reliability reduction, Sensorless control eliminates the need of Hall Effect sensors, using the back-EMF (electromotive force) of the motor to detect the rotor position; Sensorless control is essential for low-cost variable speed applications such as fans and pumps. Refrigerator and air conditioning compressors also require sensorless control when using BLDC motors.

3.2.1.2 What is back EMF?

When a BLDC motor rotates, each winding generates a voltage known as back Electromotive Force or back EMF, which opposes the main voltage supplied to the windings according to Lenz's Law. The polarity of this back EMF is in opposite direction of the energized voltage.

Back EMF depends mainly on three factors:

- Angular velocity of the rotor
- Magnetic field generated by rotor magnets
- The number of turns in the stator windings

3.2.1.3 The Commutation of Three Phase BLDC Motor:

A 3-Phase Inverter is used to perform the electronic commutation.The operation of Commutation produces the rotating magnetic field developed in the stator. The principal structure of the 3-Phase inverter with motor is shown in fig (3.1)

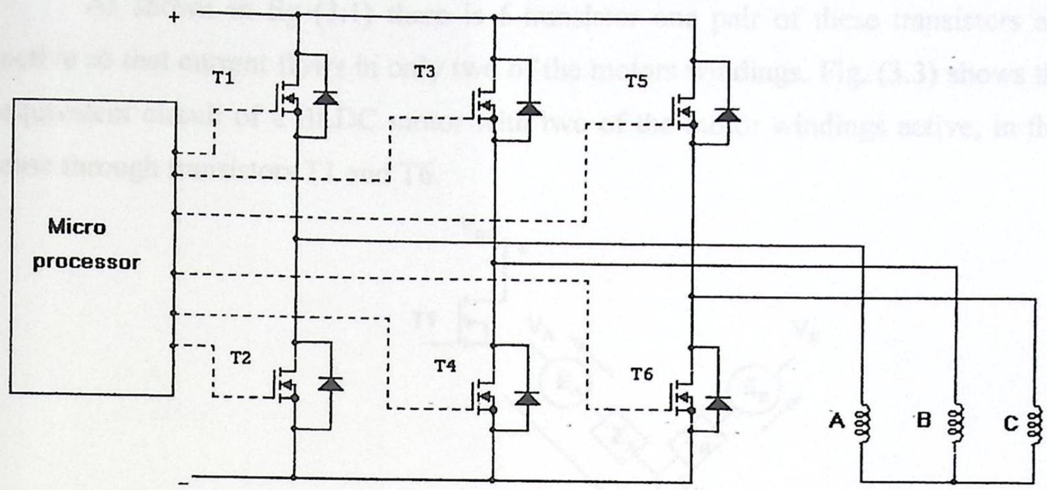


Fig. (3.1): Three-Phase Inverter and motor connections

The circuit contains 6 transistors connected to the high and low side of the DC supply. T1, T3 and T5 are the high side transistors and T2, T4 and T6 are the low side transistors of the circuit. To create the rotating magnetic field in the stator the commutation sequence of the transistors and the resultant motor terminal voltages are shown in fig. (3.2)

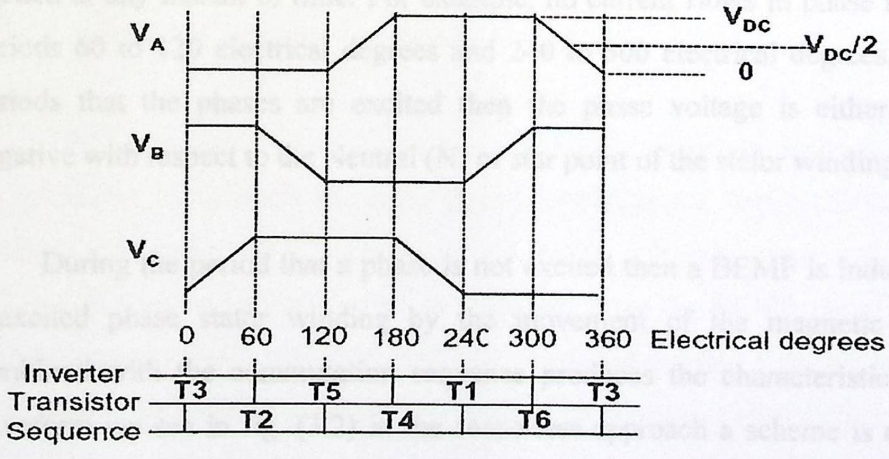


Fig. (3.2): Motor Commutation sequence

As shown in fig (3.1) there is 6-transistor one pair of these transistors are active so that current flows in only two of the motors windings. Fig. (3.3) shows the equivalent circuit of a BLDC motor with two of the motor windings active, in this case through transistors T1 and T6.

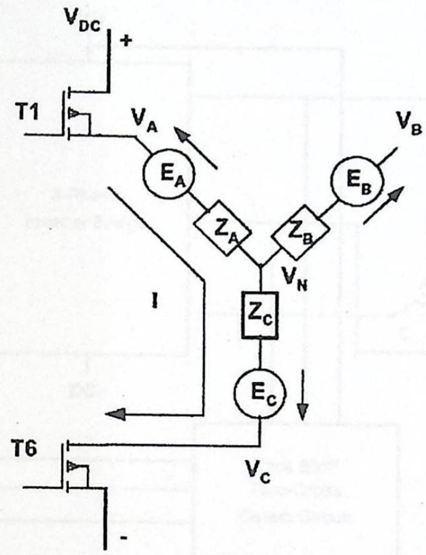


Fig. (3.3): BLDC Motor Equivalent circuit with two phases active

We can see from fig. (3.2) and (3.3) that only two of the three motor phases are excited at any instant of time. For example, no current flows in phase B during the periods 60 to 120 electrical degrees and 240 to 300 electrical degrees. During the periods that the phases are excited then the phase voltage is either positive or negative with respect to the Neutral (N) or star point of the stator windings.

During the period that a phase is not excited then a BEMF is induced into the unexcited phase stator winding by the movement of the magnetic rotor. This combined with the commutation sequence produces the characteristic trapezoidal waveform we see in fig. (3.2) in the sensorless approach a scheme is employed to detect the point at which the BEMF voltage in the unexcited phase crosses zero (VN). In order to use this point to derive the switching sequence, this point has to be phase shifted by 30 degrees.

At the instant of the zero crossing of the BEMF waveform on the unexcited phase, the terminal voltage is equal to the neutral voltage VN. When the BEMF voltage for each phase crosses zero then, Vx = VN = VDC/2 (where X = A, B or C).

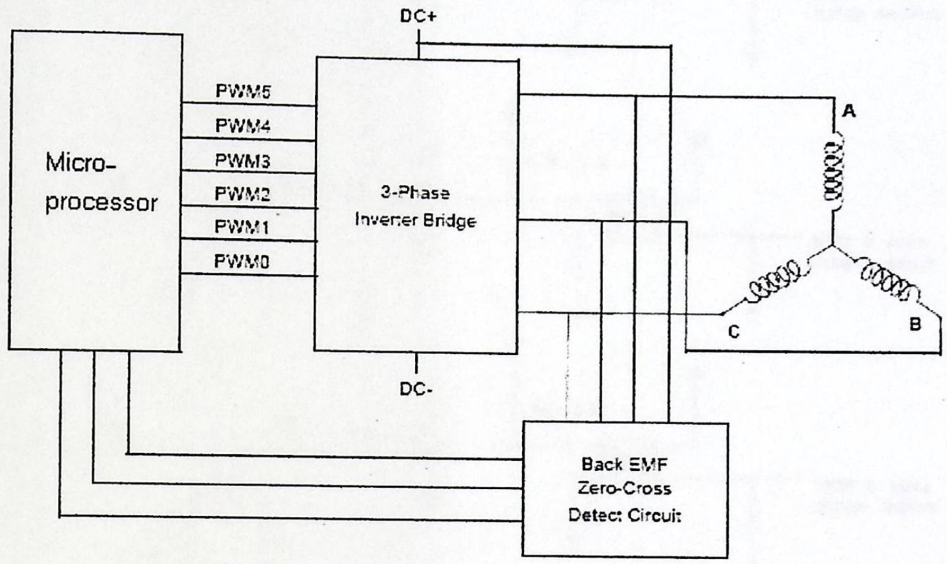


Fig. (3.4) Block diagram of sensorless control

3.2.1.4 Back EMF Sensing (sensorless) Circuit:

The circuit that we should use in our project to detect the zero crossing point is shown in Fig. (3.5), where the motor terminal voltages are stepped down to the input range of the comparator IC by resistors Rd and Rf. These resistors and the capacitor Cf used as filter to remove the PWM frequency from the BEMF signal. The filtered BEMF signals VfA, VfB and VfC are then fed to the positive inputs of the comparator. To enable the BEMF voltages to be compared with (VN), a virtual star point is created by the three resistors Rs. This voltage is fed to the negative input of the comparator. The comparator outputs are then fed to the inputs of the micro controller.

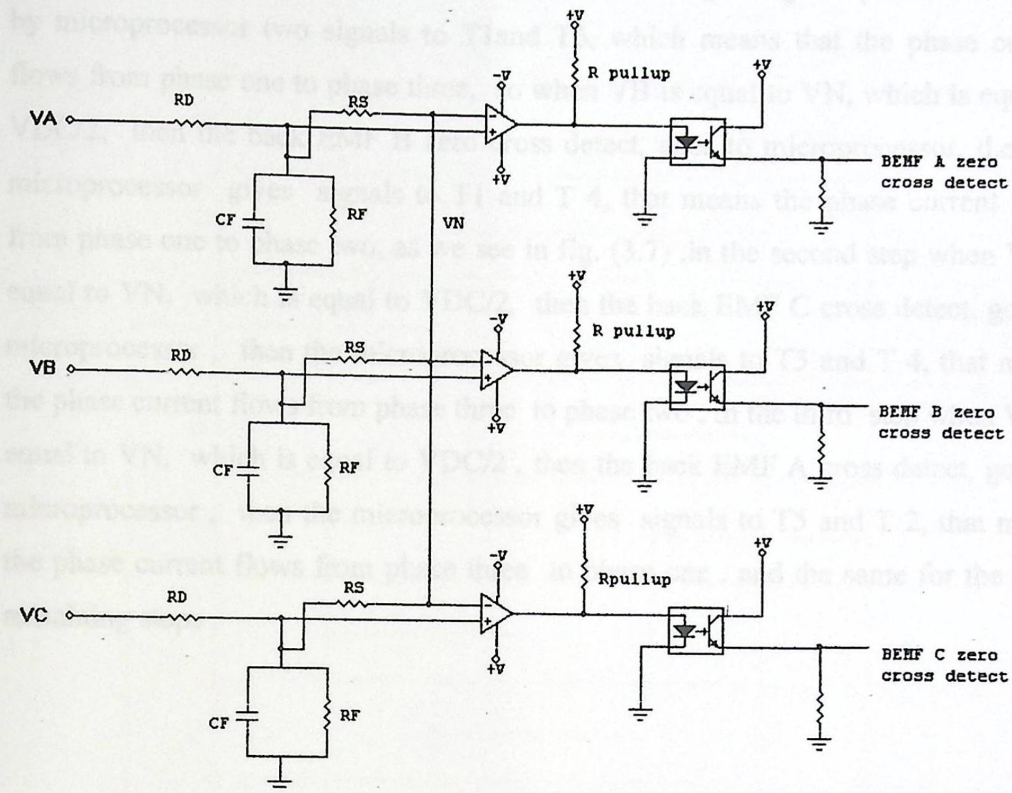


Fig. (3.5): BEMF Zero crossing detection circuit

Typically, a Brushless dc motor is driven by a three-phase inverter, which is called, Six-step commutation. The conducting interval for each phase is 120^0, by electrical angle. The commutation phase sequence is like AB-AC-BC-BA-CA-CB. Each conducting stage is called one step

3.2.1.5 How does the system work?

As we see in fig. (3.5).,there are three outputs from sensorless circuit, back EMF A zero cross detect , back EMF B zero cross detect, and back EMF C zero cross detect, Each signal goes to microprocessor, then the microprocessor gives it signals to the inverter transistors. From fig. (3.6) we can see there are six step of inverter, each step is 60^0 electrical degrees ,in the beginning of operation ,we give by microprocessor two signals to T1and T6, which means that the phase current flows from phase one to phase three, so when VB is equal to VN, which is equal to VDC/2, then the back EMF B zero cross detect, goes to microprocessor, then the microprocessor gives signals to T1 and T 4, that means the phase current flows from phase one to phase two, as we see in fig. (3.7) ,in the second step when VC is equal to VN, which is equal to VDC/2, then the back EMF C cross detect, goes to microprocessor , then the microprocessor gives signals to T5 and T 4, that means the phase current flows from phase three to phase two , in the third step when VA is equal to VN, which is equal to VDC/2 , then the back EMF A cross detect, goes to microprocessor , then the microprocessor gives signals to T5 and T 2, that means the phase current flows from phase three to phase one , and the same for the three remaining steps .

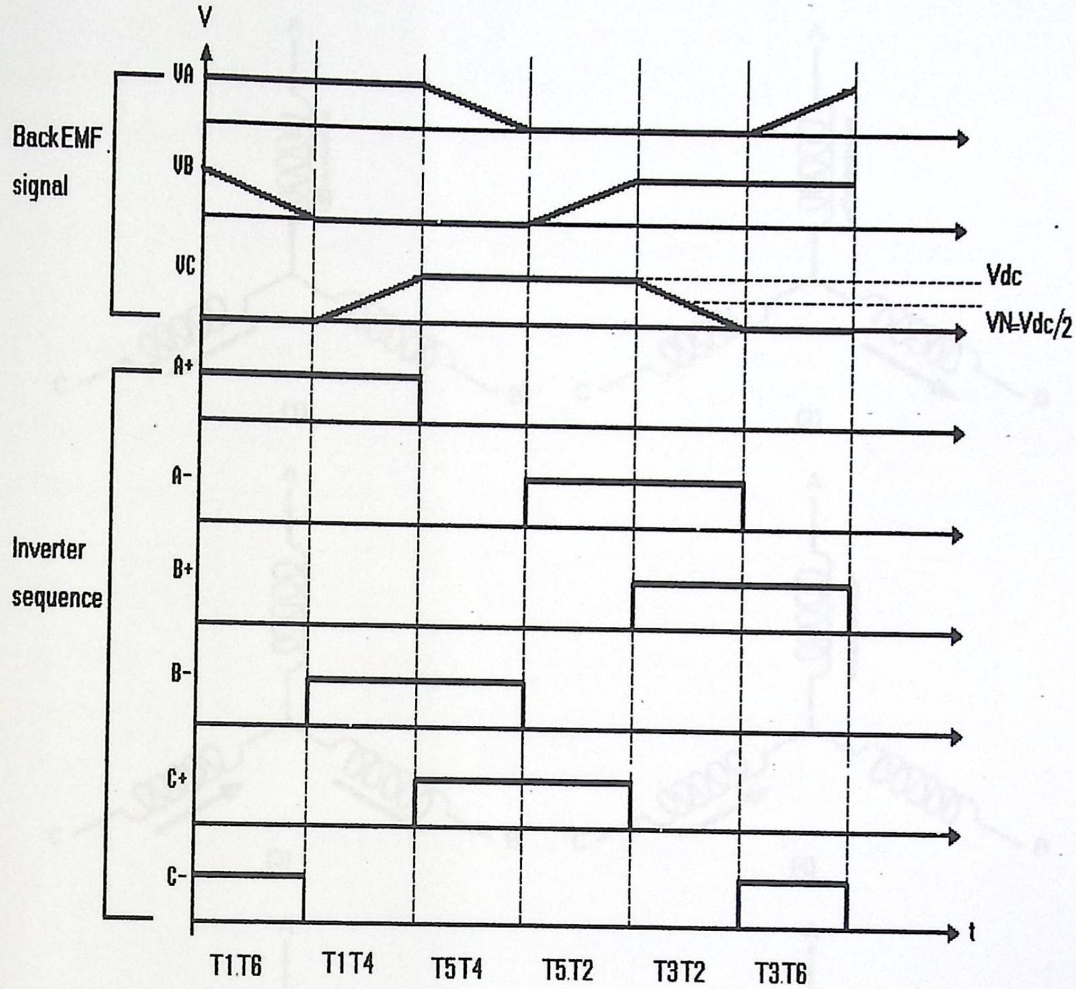


Fig. (3.6): back EMF signal and inverter sequence

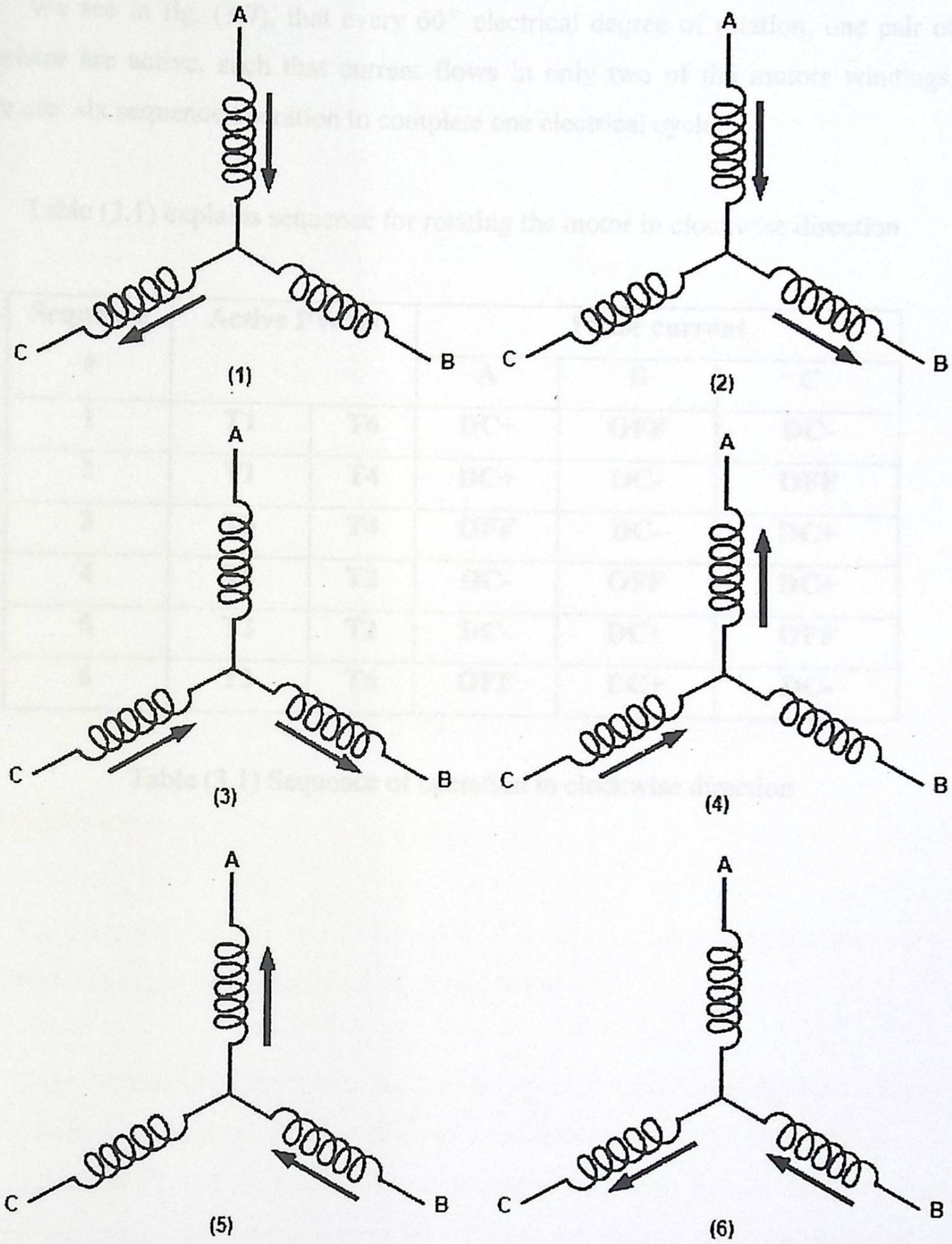


Fig (3.7) Winding energized sequence with respect to back EMF

We see in fig. (3.7), that every 60^0 electrical degree of rotation, one pair of transistor are active, such that current flows in only two of the motors windings, there are six sequence operation to complete one electrical cycle.

Table (3.1) explains sequence for rotating the motor in clockwise direction

Sequence #	Active PWMs		Phase current		
			A	B	C
1	T1	T6	DC+	OFF	DC-
2	T1	T4	DC+	DC-	OFF
3	T5	T4	OFF	DC-	DC+
4	T5	T2	DC-	OFF	DC+
5	T3	T2	DC-	DC+	OFF
6	T3	T6	OFF	DC+	DC-

Table (3.1) Sequence of operation in clockwise direction

To reverse the direction of three phase BLDCM we replace one of three phases to anther one.

Table (3.2) explains sequence for rotating the motor in counter-clockwise direction

Sequence #	Active PWMs		Phase current		
			A	B	C
1	T3	T6	OFF	DC+	DC-
2	T3	T2	DC-	DC+	OFF
3	T5	T2	DC-	OFF	DC+
4	T5	T4	OFF	DC-	DC+
5	T1	T4	DC+	DC-	OFF
6	T1	T6	DC+	OFF	DC-

Table (3.2) Sequence of operation in counter-clockwise direction

3.2.2 Sensor case:

The controller (microprocessor) each time accepts an input from the photo cell, and directly changes its output to the other sequences

In the beginning of operation, we give by microprocessor two signals to T1and T6.Then when the controller (microprocessor) accepts logic 1 from photocell, then it gives signals to T1 and T4 MOSFETs, at the same time, and these MOSFETs feed the first and third phase of the motor. When it accepts logic 0 from the photocell, it gives two signals to the T5 and T4 MOSFETs, which feed the third and second phase of the motor, with the same duration. And so in the other sequences which shown in the table (3.1) for the clockwise direction, and in the table (3.2) for the counter-clockwise direction.

3.3 General block diagram:

Our system is controlled by closed loop control system.

3.3.1Closed loop control system:

This system is used when the user needs to operate the motor with a load that needs constant speed and variable torque for some operations, only he calibrates the speed at the needed constant speed.

If the load increases on the motor for any additional load torque, then the speed will be the same or fixed at the calibrated speed unless the current increases over the maximum permissible current, i.e. the speed is compensated only if the current not exceeds the permissible current and if it exceeds it, then the system will not compensate the speed and will not increase the input voltage to obtain the compensation according to equation (2.11). Fig. (3.8) shows the block diagram of the closed loop control system.

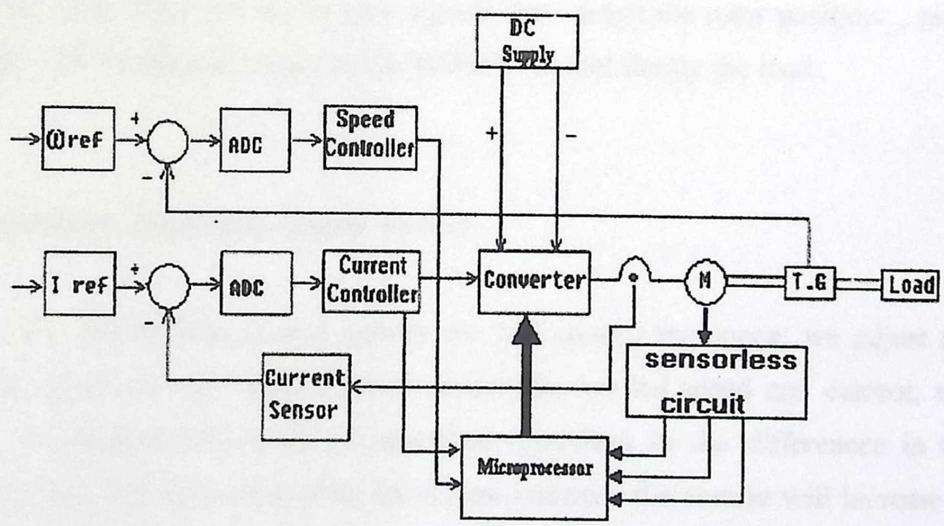


Fig. (3.8): closed loop control system

In the closed loop control system there is a feedback signal taken from the output (the speed) and then compared to a reference predetermined needed value, we used the tachogenerator to measure the actual speed. In addition to the current closed loop system which is very important here, because the speed maintained constant due to current increase and voltage increase as the load increase, these two closed loop control systems called cascaded control system in order to maintain our purpose (constant speed) and also to prevent the motor from high currents.

This system consists of following main components, the microprocessor which contain the controller, Vref and Iref, generating circuit, two comparators , DC supply which gives us the dc needed voltage, the converter which called inverter, which used for generating the needed phase voltages from the DC supply, three phase brushless dc motor , current controller which we used it to prevent current from reach to unallowed level , Tachogenerator which is the speed sensor, which enables us to compare the actual speed with the reference speed , back EMF processing unit which we use to give signals that detect the rotor position , pulse modeling unit which give pulses to the MOSFETs , and finally the load .

3.3.2 How does closed loop system works?

In this closed loop control system we will control the speed; we adjust the reference values at some values, which means the needed speed and current, and manage to maintain this speed of operation regardless in the differences in the applied torque. We know that when the torque increase, the current will increase to reach to unallowed level, then the motor will be brake down, and the system will be become unresponse , so we used the feed back signal that taken from output of the converter to prevent current from reach to unallowed level, then the system remains in the response state , This applied by comparing the actual speed and actual current with our required speed and current continuously.

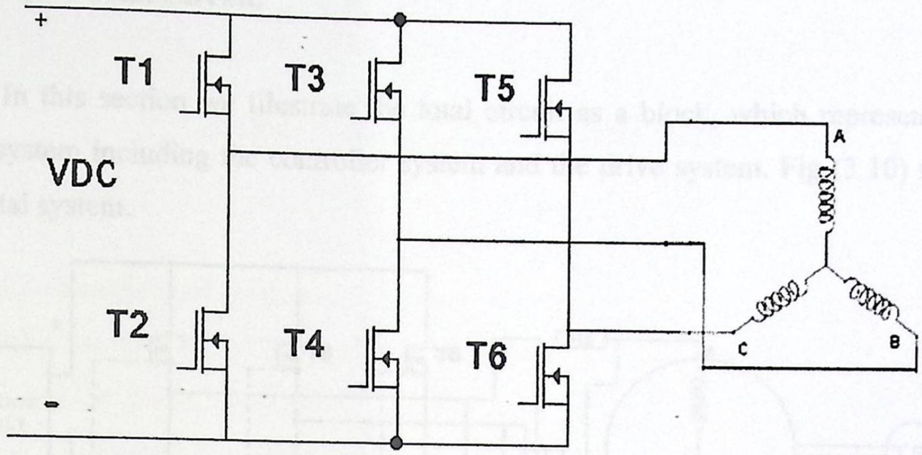


Fig. (3.9): Converter circuit

The feedback signal is taken from the tachogenerator which gives us a voltage proportional to actual speed. And we take feedback signal from output of the converter and compared this value with the reference value.

Feedbacks signals is an analog signal, and the controller (microprocessor) only accepts the digital form of signal, so we convert this feedback signal into a digital form, using analog to digital converter (AD converter) which converts this voltage and current into a hexadecimal value, which represents the actual speed and actual current, this feedback value taken to the controller (microprocessor)

Then the microprocessor subtracts the reference value from the feedback value, the resultant of this operation is the error value (represents error voltage).

3.4 Project Total Circuit.

In this section we illustrate the total circuit as a block, which represents the total system including the controller system and the drive system. Fig (3.10) shows the total system.

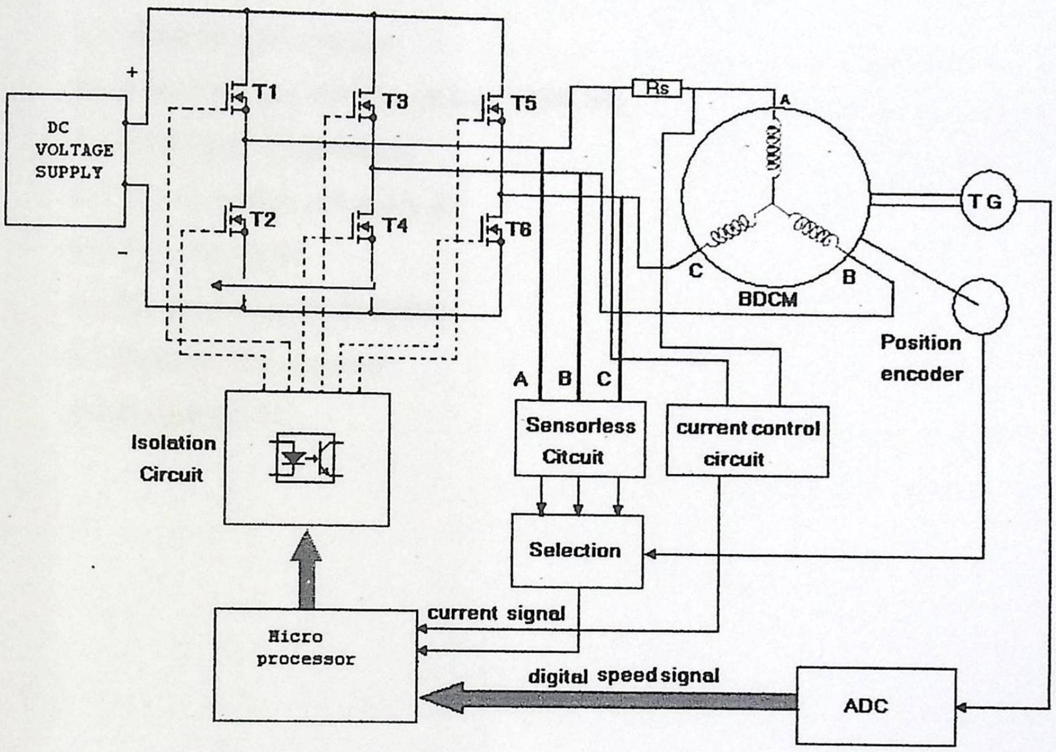


Fig. (3.10): Total circuit as blocks

CHAPTER FOUR

HARDWARE SYSTEM DESIGN

CHAPTER FOUR

HARDWARE SYSTEM DESIGN

In this chapter we will give the hardware system design and how we used the hardware components, power and control components in our system and why we used these components.

4.1 Brushless DC Motor:

We used this type of motor, three phases brushless DC motor, because it gives high speeds, reduces the cost, as known each BDCM needs detection of rotor position circuit, an inverter circuit, and control circuit.

4.2 Construction of three phases (BDCM):

Our 3-phase brushless DC motor consists of:

1) Motor frame, this house contains the iron stator laminated sheets which is surrounds the stator phases.
2) Bearing houses: and here we have two bearing houses in both motor faces.
3) Bearings: the internal diameter of these bearings is 8mm and the outside diameter is 11mm.
4) Stator.
5) Rotor.

Figure (4.1) shown the parts of the motor which we used in our project

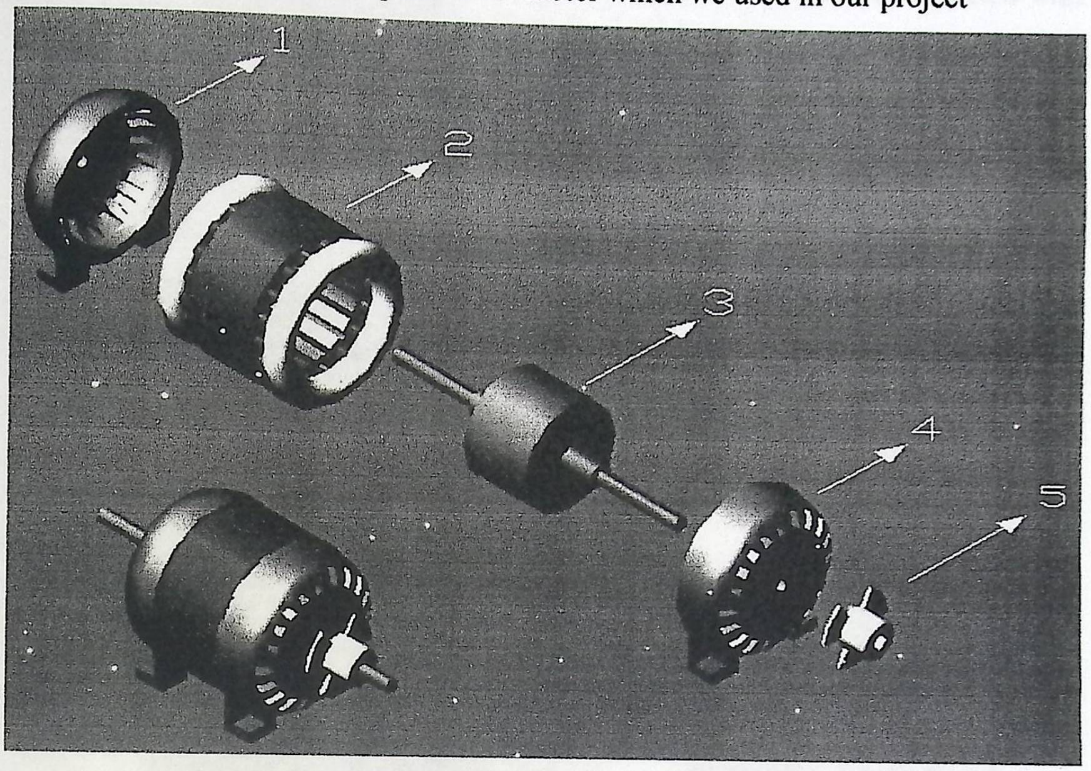


Fig. (4.1) the parts of the motor, 1- Back cover 2-Stator 3- Rotor 4-Front cover 5-Revolving shutter

BLDC motors are a type of synchronous motor. This means that magnetic field generated by the stator and the magnetic field generated by the rotor rotates at the same frequency. BLDC motors do not experience the "slip" that is normally seen in induction motors.

4.2.1Stator:

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery as shown in Fig (4.2). Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner. Most BLDC motors have three Stator windings connected in star connection. Each of these windings is constructed with several coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings is distributed over the stator periphery to form an even numbers of poles

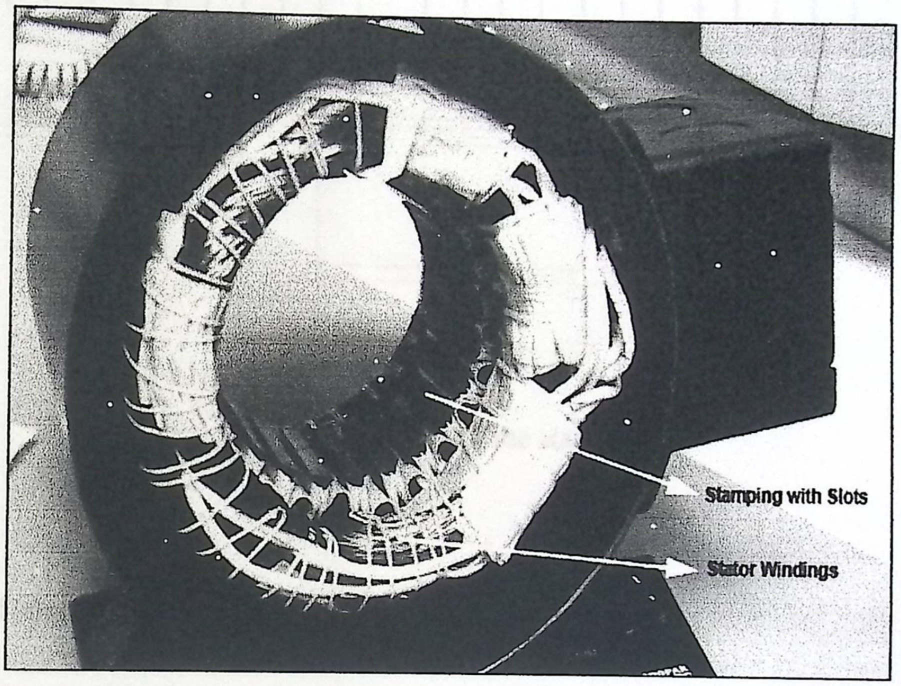


Fig (4.2) Stator of BLDCM

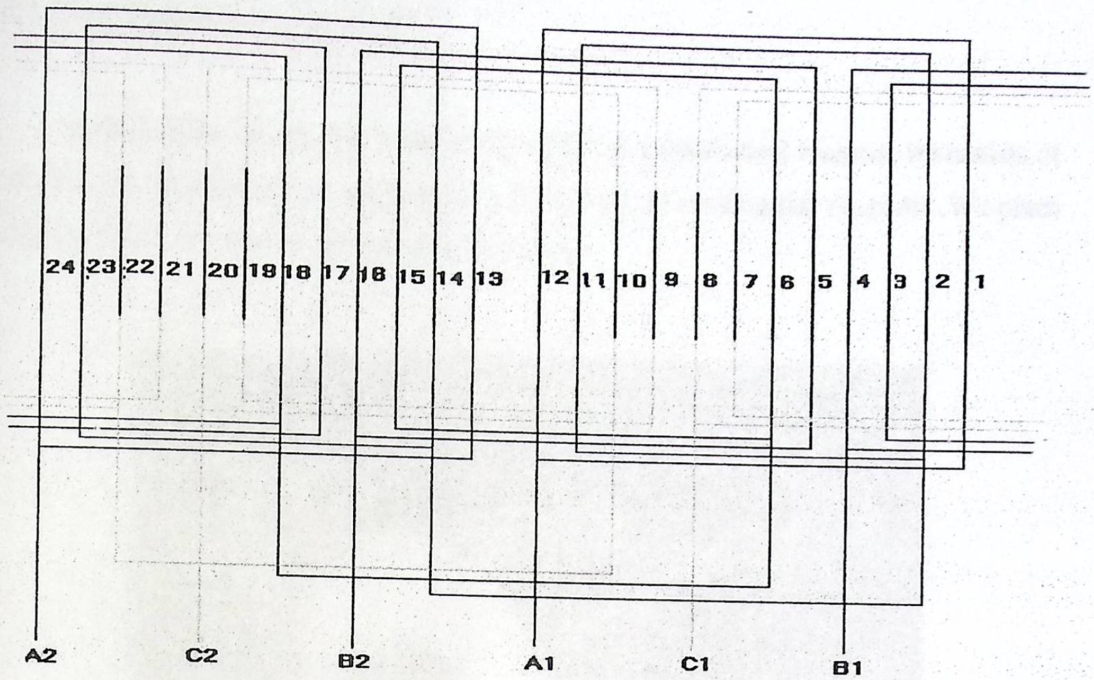


fig.(4.3) Windings of the stator

number of slots (S)=24.

number of poles (P)=2.

winding pitch (Yu)=1-12.

phase pitch (Yph)=1-5.

number of windings(N) =90 turns

The diameter of wire is 0 .7 mm.

and we connect the windings as start to start .

4.2.2 Permanent magnet rotor:

In this motor the exciter is the rotor, which is a permanent magnet, it consists of twenty two magnets, these magnets are on the form of rectangular magnets .We place them on the rotor surface as shown in fig (4.4).

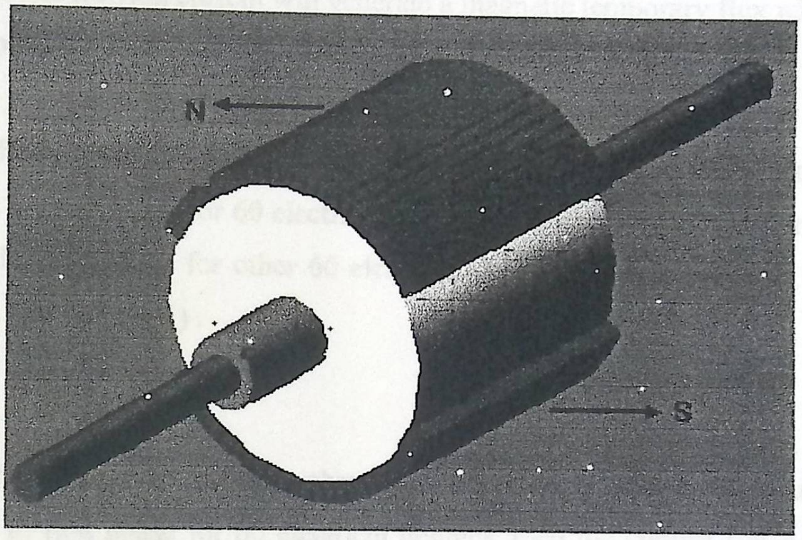


Fig (4.4) Rotor with permanent magnets

Eleven of these magnets perform a north pole and the others performs a south pole, and they are mounted on an iron box to construct a cylindrical shape. The magnets we used are of the type NdFeB permanent magnet. At room temperature NdFeB has the highest energy product of all commercially available magnets. The high remanence and coercivity permit marked reductions in motor frame size for the same output compared with motors using ferrite magnets..

4.3 Principle of operation:

When we apply the first phase with a voltage then it flows a current from this phase to second phase for 60 electrical degrees, then the current flows from first phase to the third phase for other 60 electrical degrees., phase one must be fed (by sensorless circuit signal) . the current value is proportional to voltage applied on this phase, and this flowing current will generate a magnetic temporary flux which affects the rotor pole, at this moment the rotor will repel and it will rotate.

At the moment the rotor reaches the second phase then it flows a current from this phase to third phase for 60 electrical degrees, then the current flows from second phase to the first phase for other 60 electrical degrees., phase two must be fed (by sensorless circuit signal) .

At the moment the rotor reaches the third phase then it flows a current from this phase to first phase for 60 electrical degrees, then the current flows from third phase to the second phase for other 60 electrical degrees., phase three must be fed (by sensorless circuit signal) .

As the phase voltages increased then the current increased and so the resulting magnetic flux increased (until it reaches the saturation value), as the flux increased then the pole repelling will be greater and so the speed of rotation will be higher.

When the rotor rotate then its flux also rotates, this flux is a changing flux for the fixed position relative to stator and so there will be a changing flux applied to the unexcited phase, so an induced voltage will be generated in this unexcited phase, this induced voltage called back electromotive force (back e.m.f).

As the motor speed increases, then the back e.m.f increases and this phenomenon can be used for controlling motor speed without using any sensor.

4.4 Motor design calculations:

We wish to design a brushless DC motor that produces a torque of 0.159 Nm. Then we will size this motor and compute the air gap flux density. To do this we applied the design steps and the design equations of motors.

First we will estimate the rotor volume according to the equation:

$$TRV = T / Vr$$
$$= T / (\Pi * rr2 * L) \qquad \text{............ (4.1)}$$

Where:

TRV: torque per unit Rotor Volume.

T: needed torque.

Vr: rotor volume.

rr: rotor radius.

L: axial rotor length.

There is a table for TRV and shear stress values for some recommended motors and their applications. we will use torque to be 0.01 Nm, we computed the rotor volume as shown in table (4.1). And so we can find rotor radius from the same equation.

Also we need to compute the average shear stress at the rotor surface, consider one square unit area of the rotor surface, if the average shear stress is (σ) then the torque is given by:

$T = 2 * \Pi * rr2 * L * \sigma.$

$TRV = 2 * \sigma$

……… (4.2)

Where,

σ: average shear stress.

Then,

$\sigma = TRV / 2$

we have magnets on the form of regtangular shape and their remanent flux are $Br = 1.39\ T.$

Our magnets have a width (Wm) of 4 mm and a length (Lm) of 43mm, and 5mm thickness (ℓm).

So the pole area of the magnet (Am) is:

Am = Lm*Wm .... (4.3)

And also we need to compute the remanent flux:

Φr=Br*Am .... (4.4)

And the internal leakage permeance is given by:

$$P_{m0} = \frac{\mu_o \mu_{rec} A_m}{l_m}$$ ……. (4.5)

Where:

Pmo= is the internal leakage permeance.

μrec.: coil permeability

μ0: Air permeaplity.

ℓm=5mm (radial length, the magnet length in the direction of magnetization

These magnets are constructed in the rotor as shown in Fig (4.1). Let us compute the stator volume to determine the air gap value; the stator volume follows the rotor volume, for every rough estimation of overall size, a typical value of split ratio S (rotor/stator diameter ratio) can be used.

Then,

Vs = Vr / S2

Where, Vs is the stator volume.

From the stator volume, we can compute the effective stator radius rs.

Then the air gap was calculated. And so the internal stator radius (rs-in) is equal to rotor radius plus the air gap length. After that we computed the external radius of the stator (rs-out) by adding the effective radius to the internal radius.

And so we can compute Bg as follows.

The area of the air gap (Ag) is the area above the permanent magnet and it given by:

$$A_g = (\varphi)\left[(r) - \frac{g}{2}\right]L \qquad \text{........ (4.6)}$$

Where:

φ: The angle against or opposite to the area magnet which equals 105 degrees, note figure (4.1).

r: the radius from center to air gap average (r = 20.75mm).

L: axial length.

g :equivalent air gap length.

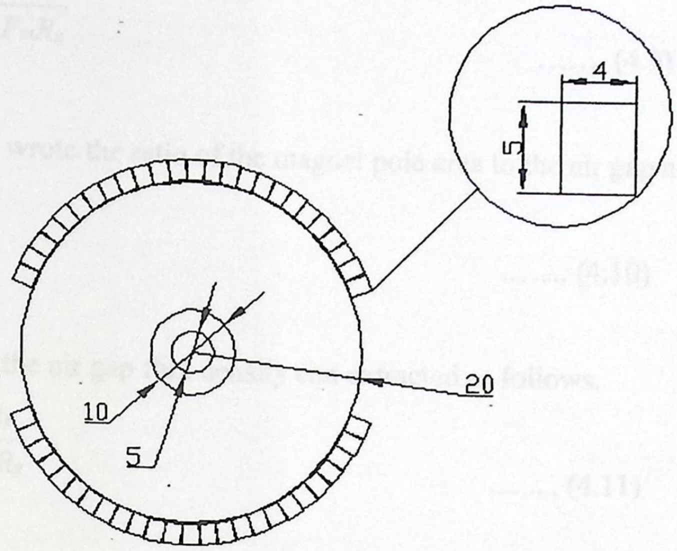


Fig. (4.5): Rotor cross section

Then we need to compute the air gap reluctance as the following relation.

$$R_g = \frac{g}{\mu_o A_g} \qquad \text{............. (4.7)}$$

Also, we need to calculate the internal permeance, and it given by:

Pm= Pmo(1+Pr1) ....(4.8)

Where Pr1 is the rotor leakage permeance, which represents the paths of magnet flux components that fail to cross the air gap and it's difficult to estimate it because the flux paths are not obvious. By practice it's founded that Pr1 has values 0.05 to 0.2, and assuming it to be 0.1.

Then we computed the MMF across the magnet to the MMF across the air gap as:

$$F_m = \frac{\Phi_r}{1 + P_m R_g}$$
.... (4.9)

Then we wrote the ratio of the magnet pole area to the air gap area as

$$c'\Phi = \frac{A_m}{A_g}$$
.... (4.10)

And then the air gap flux density can extracted as follows.

$$B_g = \frac{c'\Phi.Br}{1 + P_m R_g}$$
.... (4.11)

And then from this equation we computed the air gap flux.

Then the magnetic flux in the air gap is

Φg = Bg*Ag .... (4.12)

After that we determined the motor constant C,

C = (Z* P) / (2*Π*a) .... (4.13)

Where:

P: number of poles and here =2.

a: number of parallel paths and equal 2.

But Z = 2*N*Ć

Where,

N: number of turns per one coil, which equals to 96.

Ć: number of coils and here Ć = 2.

After that we compensated all the previous design equation in table (4.1).

Table (4.1): Motor design

Equation	Answer
V_r	54.008e-5 m^3
r_r	20 mm
S	0.77
r_s	25.75mm
G	1.5mm
r_s-*in*, r_s-*out*	21.5mm, 47.25mm
r (gap)	20.75mm
V_s	70.1e-6 m^3
A_m	172mm^2
Φ_r	0.239e-3 Wb
P_{mo}	432.064e-3 (Wb/At)
A_g	2246 e-6 m^2
R_g	0.53 e6At/Wb
P_m	475.27 e-3Wb/At
F_m	9.5 e-10 At
$c'\Phi$	0.07
B_g	0.69 T
Φ_g	0.0015598 Wb
Z	384 conductors
C	61.14 s/Wb
$C\Phi$	0.056 V.s

4.5 The Converter:

The converter used in our project consists of a DC supply and an inverter.

4.5.1 Inverter:

The inverter provides the required sequence of the phase voltages that operates the motor in both directions. In our project we mean by the inverter, the electronic power circuit which gives us the required DC pulses for the motor

This inverter consists of 6 transistors as shown in fig (4.6).

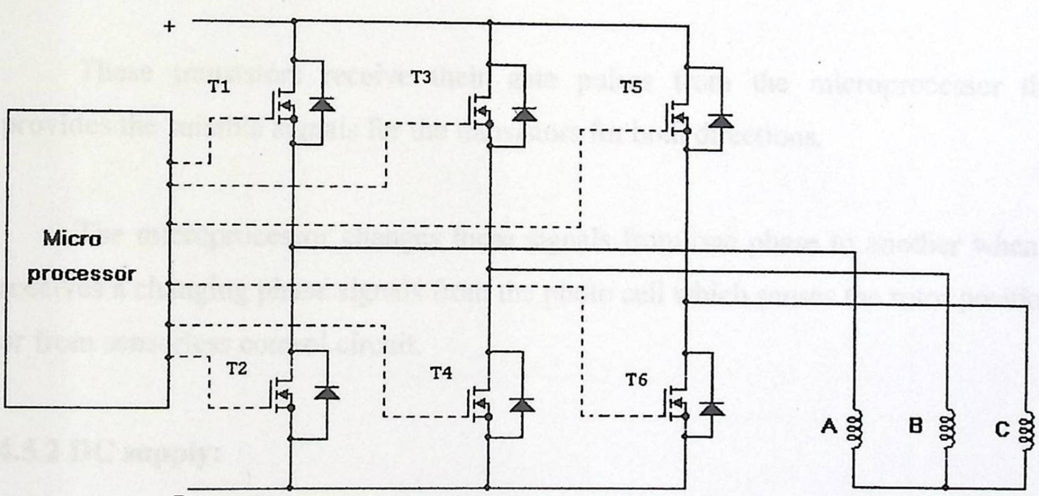


Fig (4.6): Inverter circuit.

Typically, a Brushless dc motor is driven by a three-phase inverter with, what is called, six-step commutation. The conducting interval for each phase is 120^0 by electrical angle. The commutation phase sequence is like AB-AC-BC-BA-CA-CB. Each conducting stage is called one step. Therefore, only two phases conduct current at any time, leaving the third phase unexcited.

The inverter should be commutated every 60o so that current is in phase with the back EMF. The commutation timing is determined by the rotor position, which can be detected by Hall sensors or estimated from motor parameters, i.e., the back EMF on the unexcited coil of the motor if it is sensorless system.

In brushless dc motor, only two out of three phases are excited at one time, leaving the third winding unexcited. The back EMF voltage in the unexcited winding can be measured to establish a switching sequence for commutation of power devices in the three-phase inverter.

These transistors receive their gate pulses from the microprocessor that provides the suitable signals for the transistors for both directions.

The microprocessor changes these signals from one phase to another when it receives a changing phase signals from the photo cell which senses the rotor position, or from sensorless control circuit.

4.5.2 DC supply:

We used this changing DC power supply to feed the motor through the inverter.

4.6 Inverter Signals Isolation.

Our inverter consists of 6 transistors for operating the designed brushless motor bidirectional rotation. 2 transistors for each phase are required .The transistors require signals to turn it on to conduct the current of each phase of the motor.

These signals come from the microprocessor system. They must be isolated from the power circuit (the inverter). The N-channel MOSFET needs a positive gate voltage applied between the gate and the source of the MOSFET without existing any resistance between the source and the ground of the gate voltage supply. So the load that is driven must be on the drain side of the MOSFET.

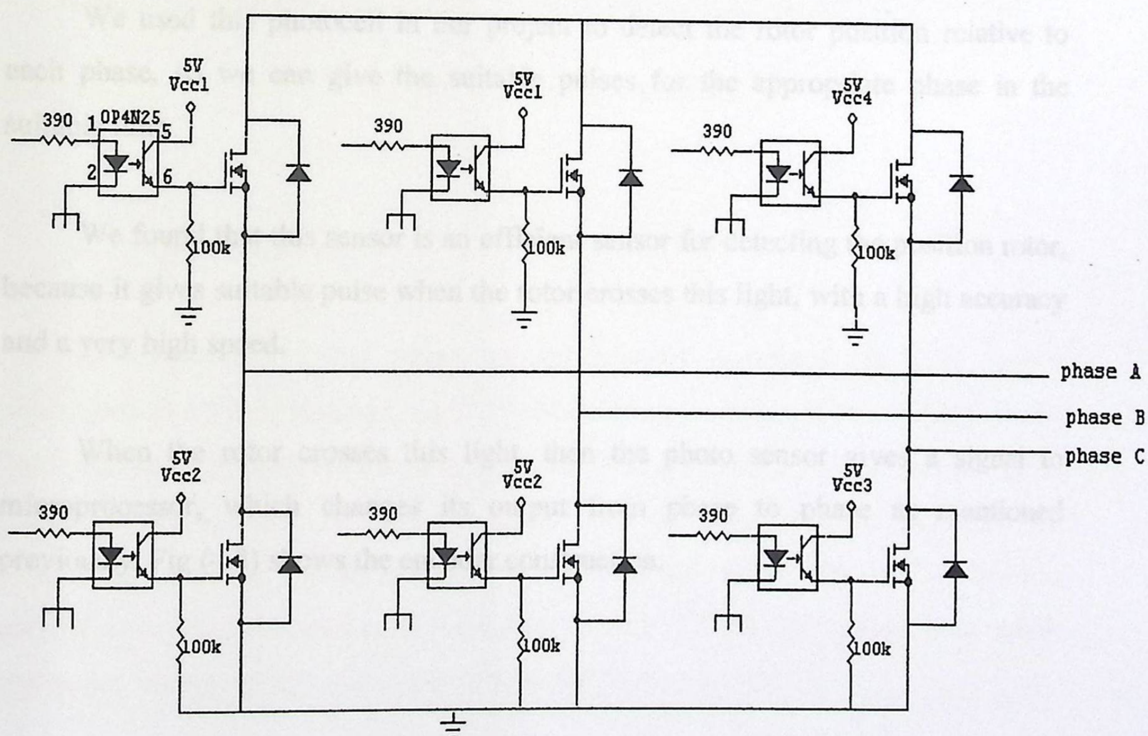


Fig (4.7): Isolation of power circuit

- When the power supply is disconnected from the motor, it works as a generator and it reverse the current. This reverse current may destroy the MOSFETs; we have connected for each MOSFET a reversing diode to pass the reverse current without letting it to pass through the MOSFETs.

- The inputs of the optocouplers come from the microprocessor system through a current-limiting resistor.

4.7 Special Components.

4.7.1 Photocell:

We used this photocell in our project to detect the rotor position relative to each phase, so we can give the suitable pulses for the appropriate phase in the suitable time.

We found that this sensor is an efficient sensor for detecting the position rotor, because it gives suitable pulse when the rotor crosses this light, with a high accuracy and a very high speed.

When the rotor crosses this light, then the photo sensor gives a signal to microprocessor, which changes its output from phase to phase as mentioned previously. Fig (4.8) shows the encoder construction.

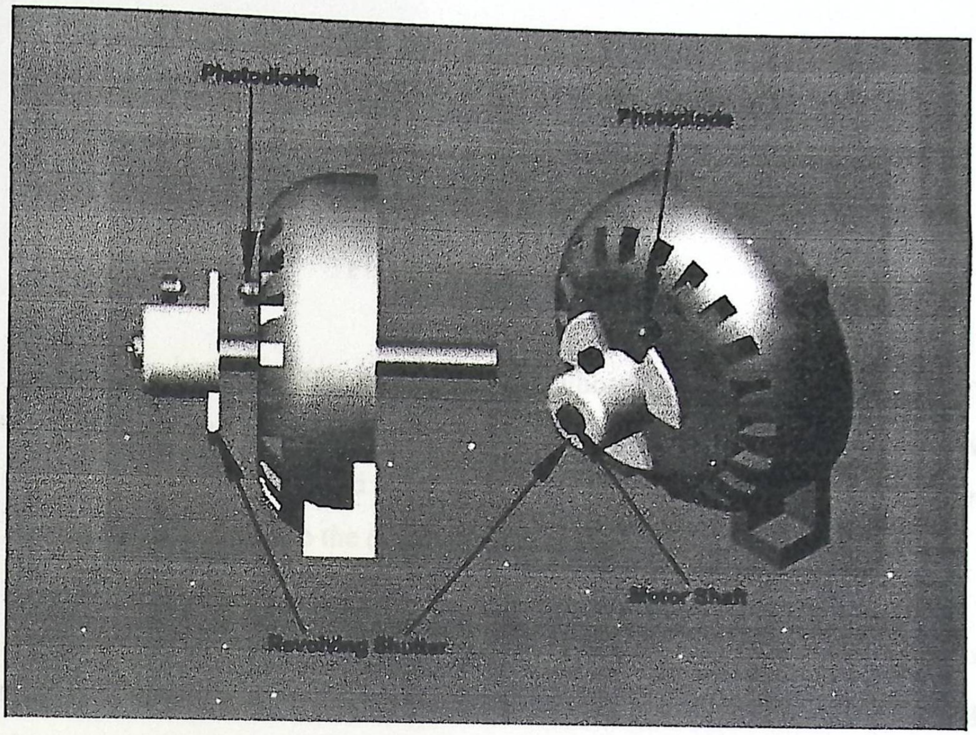


Fig (4.8): Encoder construction

4.7.2 Opto-isolators:

An opt-coupler (also called an opt-isolator) combines an LED and a photodiode in a single package. Fig (4.9) shows an opt coupler. It has an LED on the input side and a photodiode on the output side. The left source voltage and the series resistor set up a current through the LED. Then the light from the LED hits the photodiode, and this sets up a reverse current in the output circuit. This reverse current produces a voltage across the output resistor. The output voltage then equals the output supply voltage minus the voltage across the resistor.

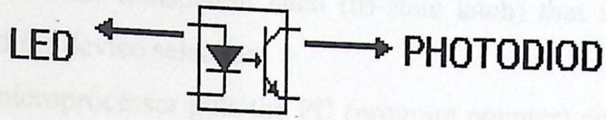


Fig (4.9): Opto-coupler

When the input voltage is varying, the amount of light is fluctuating. This means that the output voltage is varying in step with the input voltage. This is why the combination of an LED and a photodiode is called an opto coupler The device can couple an input signal to the output circuit.

The key advantage of an opto coupler is the electrical isolation between the input and output circuits. With an opto coupler, the only contact between the in put and the output is a beam of light. Because of this, it is possible to have an insulation resistance between the two circuits in the thousands of Meg ohms. Isolation like this is useful in high-voltage applications in which the potentials of the two circuits may differ by several thousand volts.

The aim function of it is connection between the microprocessor-based components and power circuit.

4.7.3 Microprocessor:

The microprocessor is a multipurpose, programmable logic device reads binary instructions from an EPROM memory as a program and processes data according to those instructions and provides results as output. The 8085 microprocessor has its low order address bus multiplexed with the 8-bit data bus. They are demultiplexed by using a compatible octal transparent latch (tri-state latch) that save the low order address to be used for device selection.

The 8085 microprocessor puts the PC (program counter) contents into the 16-bit address bus for a small duration. At the same time it sends a high signal on the ALE (Address Latch Enable) line of the microprocessor. Then, it reads or writes from or into the data bus. ALE signal indicates that the data exists on the address/data bus is an address now. We take the ALE signal to enable the latch to store the low order address bus as shown in fig (4.10).

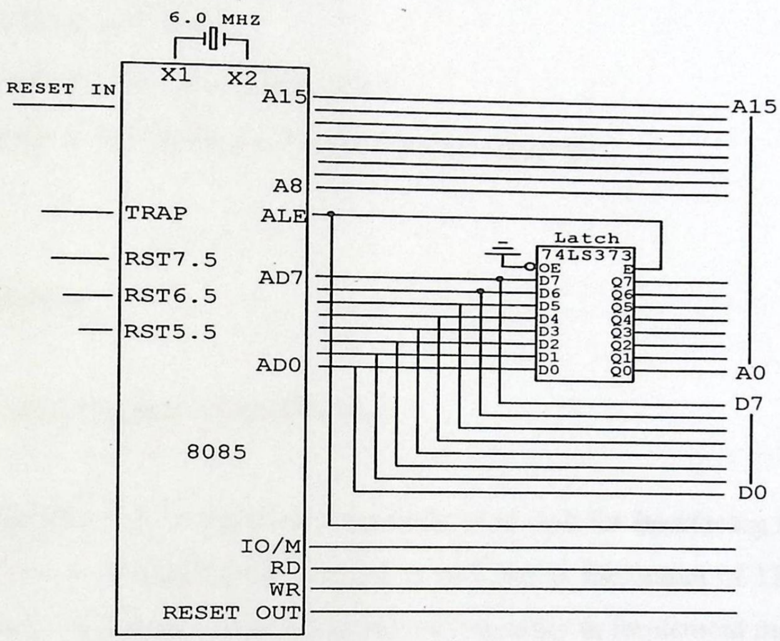


Fig (4.10): demultiplexing address/data bus

4.7.4 PC (Personal Computer)

The controller of the inverter or the pulse generator device to the switching device (MOSFETs) is a personal computer, and the software that used for this job is VISUAL C++ LANGUAGE, and the controller has the following characteristics at least:

- Pentium `I` computer 166MHz.
- RAM memory 32KB.
- Contain parallel port (printer port).
- Windows 95 or above to operate visual C language.

4.8 Parallel Port

4.8.1 Introduction to Parallel Port

The Parallel Port is the most commonly used port for interfacing home made projects. This port will allow the input of up to 9 bits or the output of 12 bits at any one given time, thus requiring minimal external circuitry to implement many simpler tasks. The port is composed of 4 control lines, 5 status lines and 8 data lines. It's found commonly on the back of your PC as a D-Type 25 Pin female connector. There may also be a D-Type 25 pin male connector. This will be a serial RS-232 port and thus, is a totally incompatible port.

4.8.2 Parallel Port Hardware Properties

Below is a table of the "Pin Outs" of the D-Type 25 Pin connector and the Centronics 34 Pin connector. The D-Type 25 pin connector is the most common connector found on the Parallel Port of the computer, while the Centronics Connector is commonly found on printers.

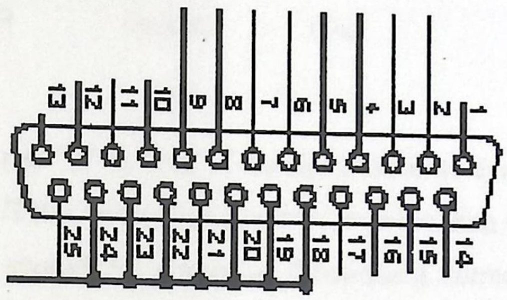


Fig (4.11): Parallel Port Pins

Table (4.2): Pin Assignments of the D-Type 25 pin Parallel Port Connector.

Pin No (D-Type 25)	Pin No (Centronics)	SPP Signal	Direction In/out	Register	Hardware Inverted
1	1	nStrobe	In/Out	Control	Yes
2	2	Data 0	Out	Data	
3	3	Data 1	Out	Data	
4	4	Data 2	Out	Data	
5	5	Data 3	Out	Data	
6	6	Data 4	Out	Data	
7	7	Data 5	Out	Data	
8	8	Data 6	Out	Data	
9	9	Data 7	Out	Data	
10	10	nAck	In	Status	
11	11	Busy	In	Status	Yes

12	12	Paper-Out / Paper-End	In	Status	
13	13	Select	In	Status	
14	14	nAuto-Linefeed	In/Out	Control	Yes
15	32	nError / nFault	In	Status	
16	31	nInitialize	In/Out	Control	
17	36	nSelect-Printer / nSelect-In	In/Out	Control	Yes
18 - 25	19-30	Ground	Gnd		

The above table uses "n" in front of the signal name to denote that the signal is active low. E.g. Error. If the printer has occurred an error then this line is low. This line normally is high, should the printer be functioning correctly. The "Hardware Inverted" means the signal is inverted by the Parallel card's hardware. Such an example is the busy line. If +5v (Logic 1) was applied to this pin and the status register read, it would return back a 0 in Bit 7 of the Status Register.

The output of the Parallel Port is normally TTL logic levels. The voltage levels are the easy part. The current you can sink and source varies from port to port. Most Parallel Ports implemented in ASIC, can sink and source around 12mA. However these are just some of the figures taken from Data sheets, Sink/Source 6mA, Source 12mA/Sink 20mA, Sink 16mA/Source 4mA, and Sink/Source 12mA. As you can see they vary quite a bit. The best bet is to use a buffer, so the least current is drawn from the Parallel Port.

4.8.3 Port Addresses

The Parallel Port has three commonly used base addresses. These are listed in table (4.3), below. The 3BCh base address was originally introduced used for Parallel Ports on early Video Cards. This address then disappeared for a while, when Parallel

Ports were later removed from Video Cards. They have now reappeared as an option for Parallel Ports integrated onto motherboards, upon which there configuration can be changed using BIOS.

LPT1 is normally assigned base address 378h, while LPT2 is assigned 278h. However this may not always is the case as explained later. 378h & 278h have always been commonly used for Parallel Ports. The lower case h denotes that it is in hexadecimal. These addresses may change from machine to machine.

Table (4.3): Port Addresses

Address	Notes:
3BCh - 3BFh	Used for Parallel Ports which were incorporated on to Video Cards - Doesn't support ECP addresses
378h - 37Fh	Usual Address For LPT 1
278h - 27Fh	Usual Address For LPT 2

4.8.4 How to Connect Circuits to Parallel Port

PC parallel port is 25-pin D-shaped female connector in the back of the computer. It is normally used for connecting computer to printer, but many other types of hardware for that port are available today.

Not all 25 are needed always. Usually you can easily do with only 8 output pins (data lines) and signal ground. I have presented those pins in the table below. Those output pins are adequate for many purposes.

Pin	function
2	D0
3	D1
4	D2

5	D3
6	D4
7	D5
8	D6
9	D7

Pins 18,19,20,21,22,23,24 and 25 are all ground pins.

Those data pins are TTL level output pins. This means that they put out ideally 0V when they are in low logic level (0) and +5V when they are in high logic level (1). In real world the voltages can be something different from ideal when the circuit is loaded. The output current capacity of the parallel port is limited to only few mill amperes.

4.8.5 How to Calculate Your Own Values to Send To Program

You have to think the value you give to the program as a binary number. Every bit of the binary number control one output bit. The following table describes the relation of the bits, parallel port output pins and the value of those bits.

Pin	1	2	3	4	5	6	7	8	9	14
Bit	C1	D0	D1	D2	D3	D4	D5	D6	D7	C2
Value	1	1	2	4	8	16	32	64	128	2

For example if you want to set pins 2 and 3 to logic 1 then you have to output value 1+2=3. If you want to set on pins 3,5 and 6 then you need to output value 2+8+16=26. In this way you can calculate the value for any bit combination you want to output.

CHAPTER FIVE

SOFTWARE SYSTEM DESIGN

5.1 Initializations

5.2 Determining the pins which we used as input and output

5.3 Calculating the hex codes required for each phase for both directions

5.4 Flow Chart of the System

CHAPTER FIVE

SOFTWARE SYSTEM DESIGN

5.1 Initializations:

Three-Phase Brushless DC Motor in our project is controlled in six steps of inverter as we mentioned previously in chapter three, this inverter feeds the motor phases in clockwise and counter clockwise directions operation. This inverter receives its signals from the parallel port of the microprocessor.

The microprocessor interchanges these signals from one step to another when it receives signal from the back EMF sensing circuit or from encoder of the sensor which senses the rotor position, and here, when the rotor is in the first phase region, then it outputs a hexadecimal code used to operate the first phase for a period of time until the back EMF signal or sensor signal received. Here the microprocessor changes its output to another code that operates the second phase until the other back EMF or sensor signal is received. Here the microprocessor changes its output to another code that operates the third phase until the other back EMF or sensor signal is received. And this operation is recurrence.

As we mentioned in the chapter four we used the parallel port to interfacing the power circuit of this project with microprocessor, and we know that the parallel port contains input and output pins. Pin (2-9) used as output of parallel port, and pin (10-13&15) used as input of parallel port.

In our project we used six output of parallel port to feed six transistors of the inverter with suitable signals, and we used five input of parallel port to feed the microprocessor with suitable signals from sensorless circuit or from sensor.

5.2 Determining the pins of parallel port which we used as input and output:

Table (5.1) shows the pins which we used in our project and its usage,

Table (5.1) the pins of parallel port which we used

Pin No	Direction	usage
2	OUT	To feed transistor #1
3	OUT	To feed transistor #3
4	OUT	To feed transistor #5
5	OUT	To feed transistor #6
6	OUT	To feed transistor #4
7	OUT	To feed transistor #2
10	IN	Switch for reverse direction
11	IN	Sensor signal
12	IN	Back EMF A zero cross detect
13	IN	Back EMF B zero cross detect
15	IN	Back EMF C zero cross detect

5.3 calculating the hex codes required for each phase for both directions:

Table (5.2) explains sequence for rotating the motor in clockwise direction

Table (5.2) sequence of operation in clockwise direction

Sequence #	Active PWMs		Phase current		
			A	B	C
1	T1	T6	DC+	OFF	DC-
2	T1	T4	DC+	DC-	OFF
3	T5	T4	OFF	DC-	DC+
4	T5	T2	DC-	OFF	DC+
5	T3	T2	DC-	DC+	OFF
6	T3	T6	OFF	DC+	DC-

Table (5.3) explains sequence for rotating the motor in counter-clockwise direction.

Table (5.3) sequence of operation in counter-clockwise direction

Sequence #	Active PWMs		Phase current		
			A	B	C
1	T5	T4	OFF	DC+	DC-
2	T1	T4	DC-	DC+	OFF
3	T1	T6	DC-	OFF	DC+
4	T3	T6	OFF	DC-	DC+
5	T3	T2	DC+	DC-	OFF
6	T5	T2	DC+	OFF	DC-

As we see in tables (5.2) and (5.3) there are six sequences of inverter for both directions and each sequence has especial code in programming of microprocessor.

Table (5.4) explains these sequences and their codes in binary and hex, for clockwise direction.

Table (5.4) codes of clockwise direction

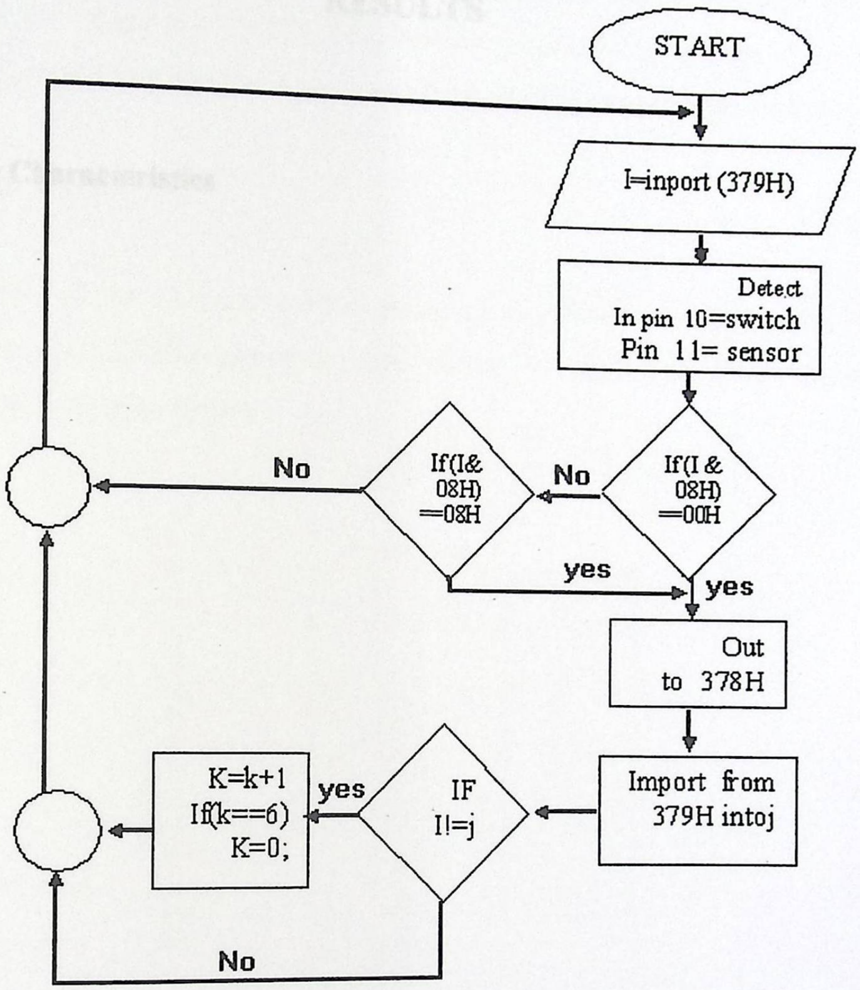
Sequence #	Active PWMs		binary	hex
1	T1	T6	0000 1001	09
2	T1	T4	0001 0001	11
3	T5	T4	0001 0100	14
4	T5	T2	0010 0100	24
5	T3	T2	0010 0010	22
6	T3	T6	0000 1010	0A

And table (5.5) explains these sequences and their codes in binary and hex, for counter clockwise direction.

Table (5.5) codes of counter clockwise direction

Sequence #	Active PWMs		binary	hex
1	T5	T4	0001 0100	14
2	T1	T4	0001 0001	11
3	T1	T6	0000 1001	09
4	T3	T6	0000 1010	0A
5	T3	T2	0010 0010	22
6	T5	T2	0010 0100	24

5.4 Flow chart of the system:



CHAPTER SIX

RESULTS

6.1 Motor Characteristics

6.1 Motor Characteristics.

This chapter shows the motor characteristics, we applied variable armuture voltage for the motor at 12 V,15V,24V. And we recorded the readings of the motor current (Ia), speed (w), and the input power (Pin) ,at different armature voltages.

6.1.1 Motor Curves:

We plotted the mechanical characteristics, the efficiency-torque curve, speed-torque curve, and Efficiency-output power curve, for the motor. These curves are shown in the following figures :

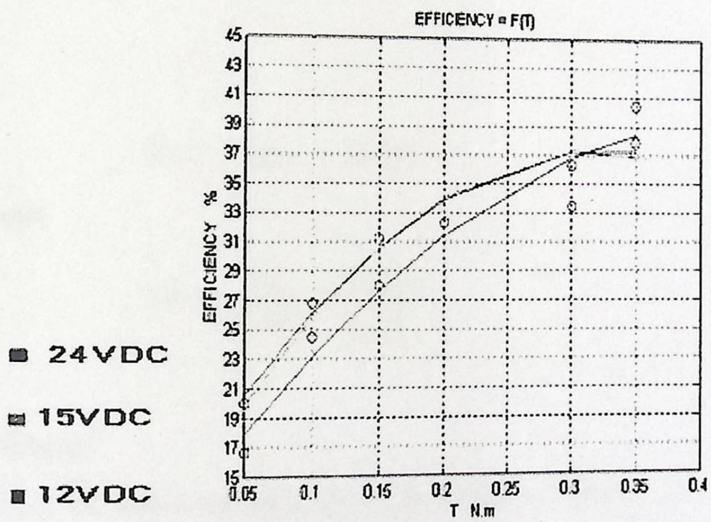


Fig. (6.1): Motor efficiency-torque curves at different voltages

$\eta\% = (Pout/ Pin)*100\%$

where $Pout = T. \omega$

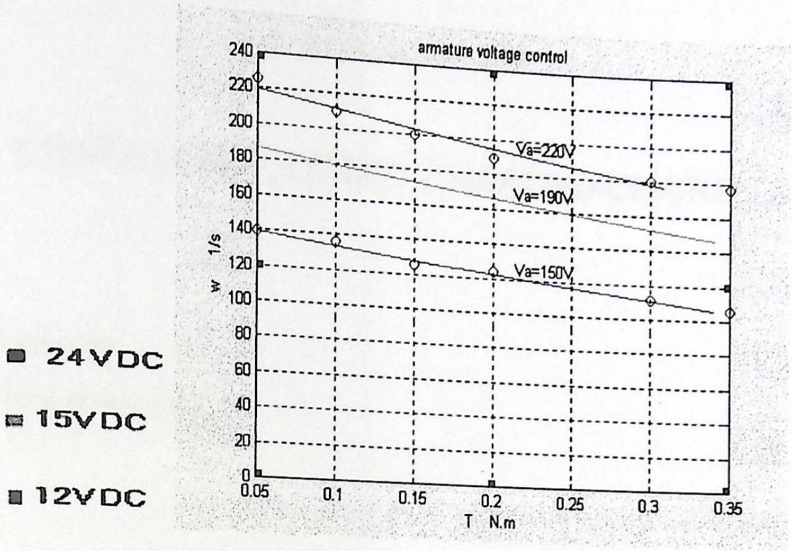


Fig. (6.2): Motor speed-torque curves at different voltages

$$Va = C\phi\omega_r + Ia.Ra$$

and

$$\omega r = \frac{Va}{(C\phi)} - \frac{Ra.T_{em}}{(C\phi)^2}$$

Where:

C: is the motor constant and its unit is (V.s / Wb)

Φ: is the air gap magnetic flux (Wb).

ω : The angular velocity of the Rotor.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

7.2 Recommendation

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this chapter we will represent the conclusion and summary of our project, the applications of brushless DC (BLDC) motors and drives have grown significantly in recent years in the appliance industry and the automotive industry.

We designed this brushless DC motor with a permanent magnet rotor design. This design eliminates the rotor excitation losses and minimizes the rotor volume.

Sensorless operation method is a very efficient method for detecting the rotor position. The brushless DC motor needs a position sensor which detects the rotor angular position. So, we designed and constructed a sensorless circuit to avoid using sensor and to get a great accuracy in determining the rotor position. We operated the project by the two methods, using the sensor and the sensorless circuit.

The inverter which we used in our project provides the required sequence of the phase voltages that operates the motor in both directions. This inverter consists of six transistors, and these transistors receive its pulses from the microprocessor that provides the suitable signals for these transistors for both directions. We designed this inverter with a very special isolation circuits that first isolate the signals from the microprocessor system, and second, avoid using multiple power supplies for the transistors gates of the inverter.

The microprocessor-based system provides digital communication for the signals that control the project's analog circuits. That is a great solution for the limitations of the time response of the speed and current control systems.

Through our project we find that the brushless DC motors are widely used in much application such as Hard disk drives and CD/DVD drive, heating, ventilation and air conditioning, Refrigerators, Medical equipment, Robotics, Fans and Pumps.

This widely used is referred to the many advantages that it have, such as low cost, simplicity, reliability, good performance, high speed.

We used the microprocessor which is a very efficient controller, in this system because it replaces instead of a very complex control circuit and also it saves a lot of money by reducing a number of hardware devices.

We will focus in our project how back EMF detecting the rotor position and the advantages of using this method such as reduce cost and increase the reliability.

7.2 Recommendations.

Finally, we recommend the next researcher generations the following.

1. New machine design is an alternate solution to sensorless operation. Some research is going on to add the special sensing winding to the machine to indicate the rotor position. There are no Hall-type sensors; therefore the system is robust.

The microprocessor-based system provides digital communication for the signals that control the project's analog circuits. That is a great solution for the limitations of the time response of the speed and current control systems.

Through our project we find that the brushless DC motors are widely used in much application such as Hard disk drives and CD/DVD drive, heating, ventilation and air conditioning, Refrigerators, Medical equipment, Robotics, Fans and Pumps.

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We used the microprocessor which is a very efficient controller, in this system because it replaces instead of a very complex control circuit and also it saves a lot of money by reducing a number of hardware devices.

We will focus in our project how back EMF detecting the rotor position and the advantages of using this method such as reduce cost and increase the reliability.

7.2 Recommendations.

Finally, we recommend the next researcher generations the following.

1. New machine design is an alternate solution to sensorless operation. Some research is going on to add the special sensing winding to the machine to indicate the rotor position. There are no Hall-type sensors; therefore the system is robust.

2. The design of BLDC motor is not standardized yet. Optimized design of the BLDC motor that achieves higher efficiency with lower cost is desirable.

3. Continuing the studies of the 3-phase brushless DC motors for improving the values of the torque, speed and motor volume.

REFERENCES

1. Gobal K. Dubey, Fundamentals of electrical drive, Narosa Publishing House, Newdelhy, 1995.

2. Ramesh S. Gaonkar, Microprocessor Architecture, Programming and Application with 8085, Prentice-Hall, Newgercy, USA, 1999.

3. Malvino, Electronic Principles, Mc Graw-Hill Book Co., Singapore, 1993.

4. George McPherson, Robert D. Larame, An Introduction to Electrical Machines and Transformers, John Wiley and Sons, New York, USA, 1990.

5. http://www.PowerPulse.com/

6. http://www.ewh.ieee.org/

7. http://www.st.com/

APPENDICES

1. APPENDIX A: SOFTWARE PROGRAMS.
2. APPENDIX B: MAGNET PROPERTIES.
3. APPENDIX C: MOTOR AND CONTROLLER FIGURES.
4. APPENDIX D: CHIPS DATA SHEETS

APPENDIX A

SOFTWARE PROGRAMS

1. **Sensorless control method**
2. **sensor control method**

1. Sensorless control method :

```
<include<dos.h
<include<stdio.h#
<include<conio.h#
<include <math.h#
<include <dos.h#
define b 0x378#
define in 0x379#

()main
}
;int i=0x00,k=0,x=0x00
(;;)for
}

;(i=inport(in
;x=i&0x08
switch(x)            //Pin 10=Switch
}
case 0x00:   //CW
(if (x!=i&0x08
;k=0
(switch(k
}
;case 0:outport(b,0x09);break
;case 1:outport(b,0x11);break
;case 2:outport(b,0x14);break
;case 3:outport(b,0x24);break
;case 4:outport(b,0x22);break
;case 5:outport(b,0x0A);break
{

;k++
(if(k==6
;k=0
;break
case 0x08:        //CCW
(if (x!=i&0x08
;k=0
(switch(k
}
;case 3:outport(b,0x0A);break
;case 4:outport(b,0x22);break
;case 5:outport(b,0x24);break
;case 0:outport(b,0x14);break
;case 1:outport(b,0x11);break
;case 2:outport(b,0x09);break
{
;k++
(if(k==6
;k=0
```

```
;break
{
;(delay(6000
{
;(outport(b,0x00
{
```

2. sensor control method:

```
#include<dos.h>
#include<stdio.h>
#include<conio.h>
#include <math.h>
#define b 0x378
#define in 0x379
main()
 {
 int i=0x00,j=0x00,k=0,x=0x00;
 for(;;)
  {

   i=inport(in);
   x=i&0x08;
   switch(x)              //Pin 10=Switch,Pin 11=Sensor
    {
    case 0x00:   //CW
     if (x!=i&0x08)
      k=0;
     switch(k)
      {
      case 0:outport(b,0x09);break;
      case 1:outport(b,0x11);break;
      case 2:outport(b,0x14);break;
      case 3:outport(b,0x24);break;
      case 4:outport(b,0x22);break;
      case 5:outport(b,0x0A);break;
      }
     j=inport(in);
     if(i!=j)
      {
      ++k;
      if(k==6)
       k=0;
      }
      break;
   case 0x08:        //CCW
    if (x!=i&0x08)
     k=0;
    switch(k)
     {
     case 3:outport(b,0x0A);break;
     case 4:outport(b,0x22);break;
     case 5:outport(b,0x24);break;
     case 0:outport(b,0x14);break;
     case 1:outport(b,0x11);break;
     case 2:outport(b,0x09);break;
     }
    j=inport(in);
    if(i!=j)
```

```
        {
        ++k;
        if(k==6)
         k=0;
        }
        break;
      }

    }
    outport(b,0x00);
}
```

Matlab simulation:

Program: $\eta = f(T)$:

```
M1=[20,26.8,31.3,33.4,36.3,37.9];
M2=[19.2,27.1,30.6,33.4,37.2,37.1];
M3=[16.7,24.5,28,32.3,33.5,40.4];
T=[0.05,0.1,0.15,0.2,0.3,0.35];
polyfit(T,M1,1)
polyfit(T,M2,1)
polyfit(T,M3,1)
f1=(-220.6190*Q+143.6119*T+13.9957);
f2=(-251.1429*Q+157.3000*T+12.6514);
f3=(-148.8571*Q+127.8429*T+11.8629);
plot(T,f1,T,f2,T,f3,T,M1,'bo',T,M2,'go',
     T,M3,'ro');grid;
```

Program: $\omega = f(T)$:

```
w1=[225.1,209.4,200,189.5,180.1,176.9];
w2=[188.5,179.1,169.6,164.4,152.9,146.6];
w3=[139.3,136.1,125.6,123.6,111,105.8];
T=[0.05,0.1,0.15,0.2,0.3,0.35];
polyfit(T,w1,1)
Polyfit(T,w2,1)
polyfit(T,w3,1)
f3=(-0.0087 *w3+1.2611);
f2=(-0.0073*w2+1.4113);
f1=(-0.0061*w1+1.3877);
plot(f1,w1,f2,w2,f3,w3,T,w1,'bo',T,w2,'go',
     T,w3,'ro');grid;
```

APPENDIX B

MAGNET PROPERTIES

The B-H hysteresis loop of a hard permanent magnet material:

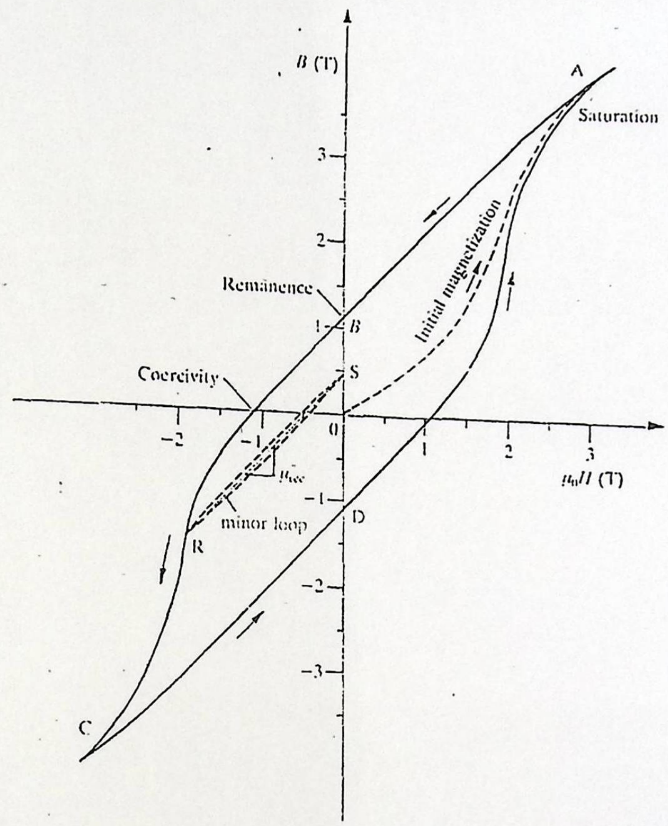
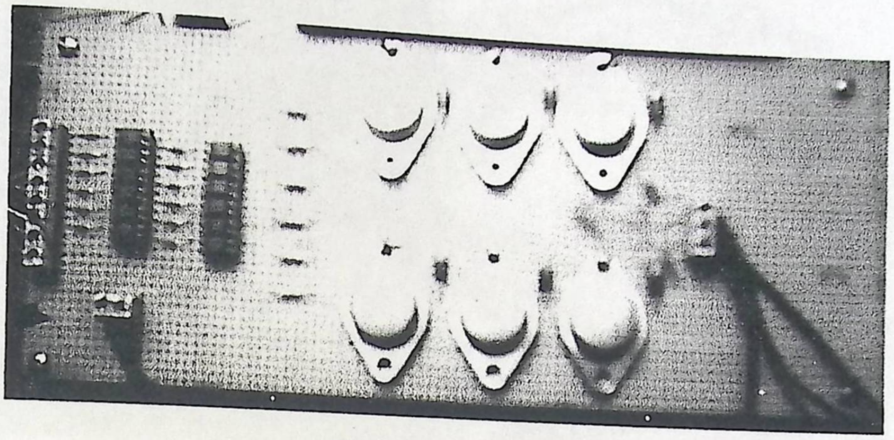


Table 3.1. Magnet properties

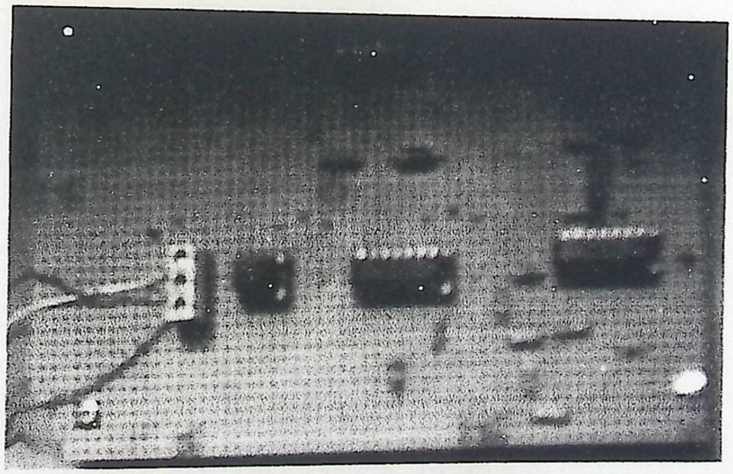
Property	Units	Alnico 5–7	Ceramic	Sm_2Co_{17}	NdFeB
B_r	T	1.35	0.405	1.06	1.12
$\mu_0 H_c$	T	0.074	0.37	0.94	1.06
$(BH)_{max}$	MGOe	7.5	3.84	26.0	30.0
μ_{rec}		1.9	1.1	1.03	1.1
Specific gravity		7.31	4.8	8.2	7.4
Resistivity	$\mu\Omega$ cm	47	$> 10^4$	86	150
Thermal expansion	$10^{-6}/°C$	11.3	13	9	3.4
B_r temperature coefficient	%/°C	−0.02	−0.2	−0.025	−0.1
Saturation H	kOe	3.5	14.0	>40	>30

APPENDIX C
MOTOR AND CONTROLLER FIGURES

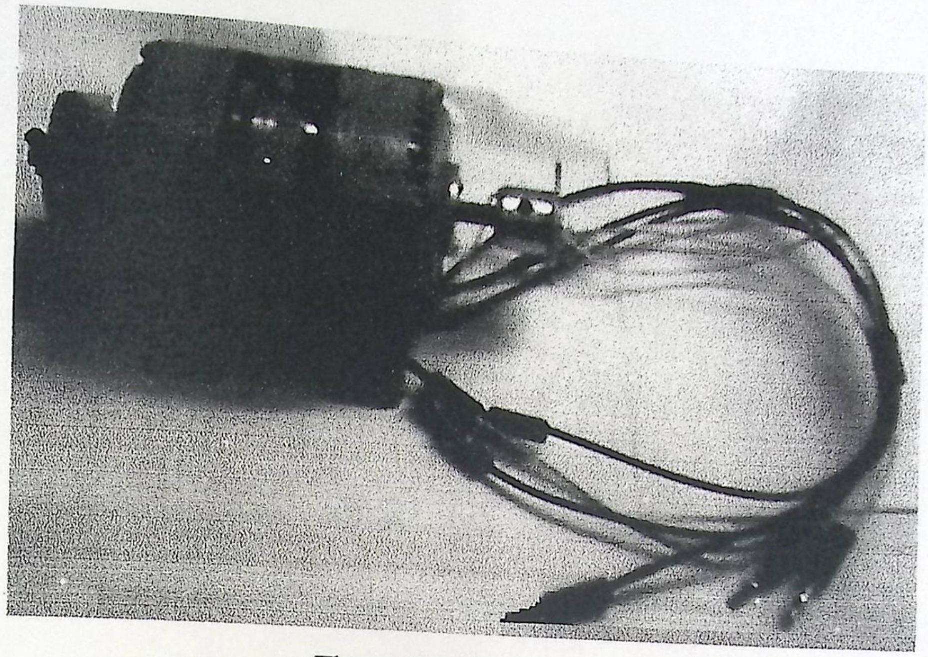
Motor and Control System Figures:



Three phase inverter



Sensorless circuit



Three phase BLDC motor

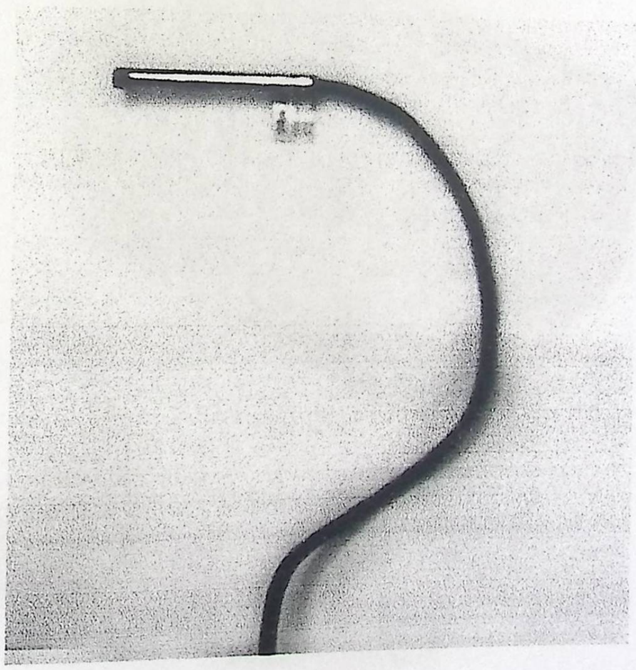
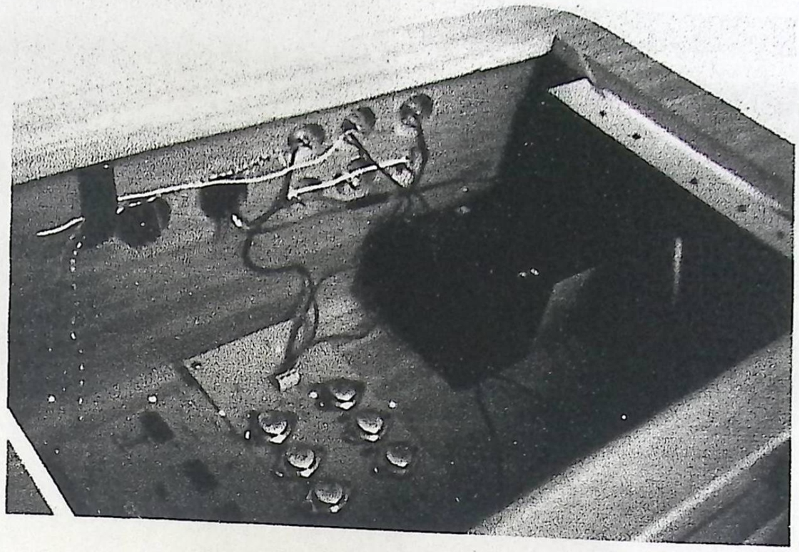
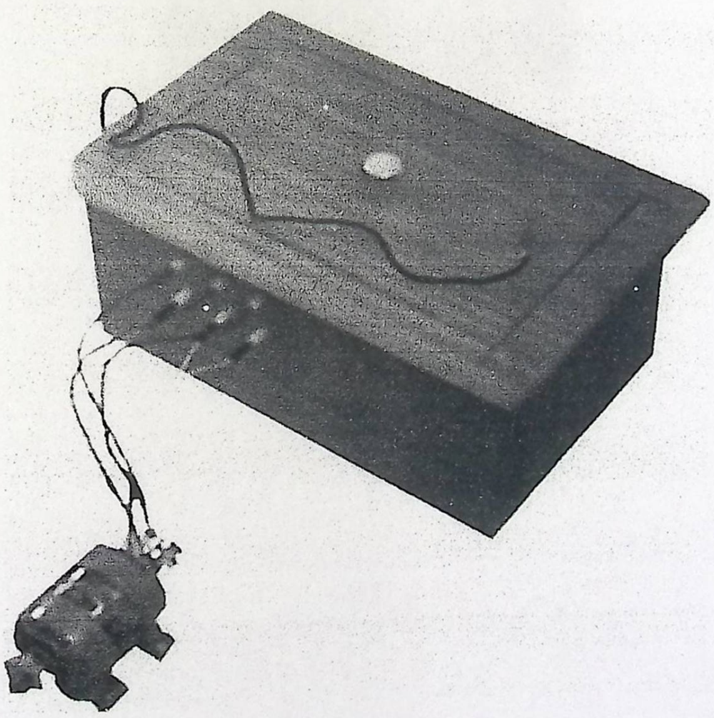


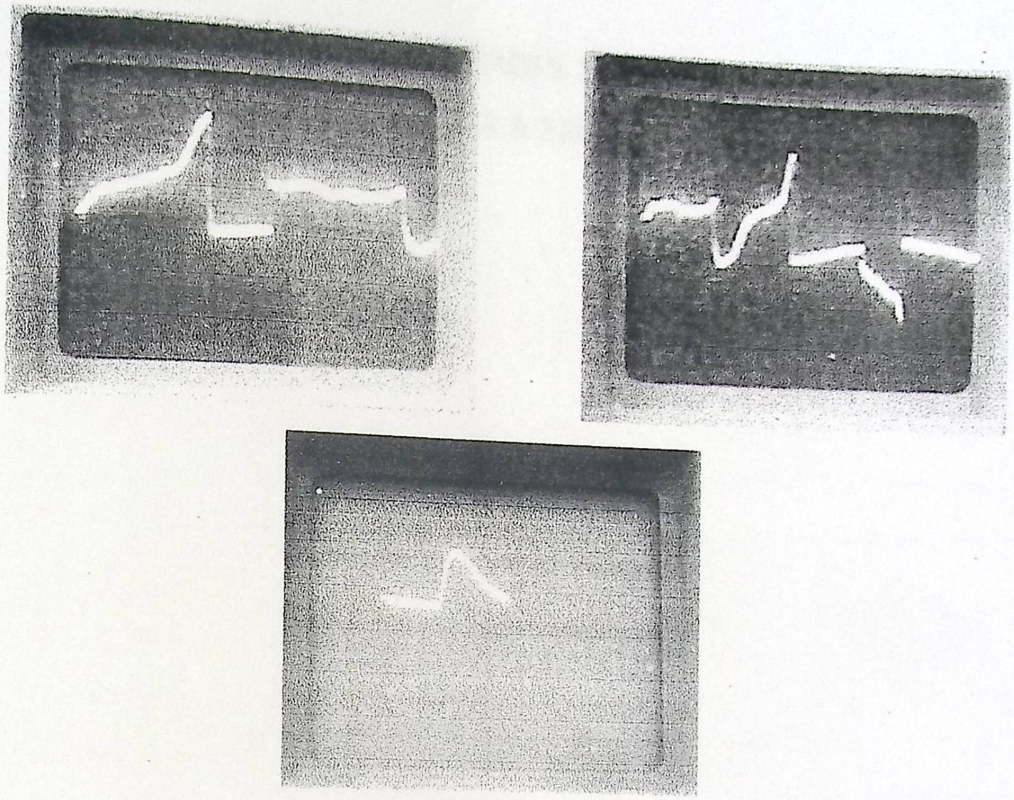
Photo cell sensor



System over all



Box of the project



Current waveforms

APPENDIX D

CHIPS DATA SHEETS

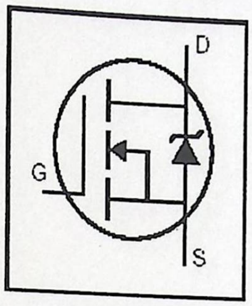
International
IOR Rectifier

PD - 94004A

IRFP260N

HEXFET® Power MOSFET

- Advanced Process Technology
- Dynamic dv/dt Rating
- 175°C Operating Temperature
- Fast Switching
- Fully Avalanche Rated
- Ease of Paralleling
- Simple Drive Requirements



V_{DSS} = 200V

$R_{DS(on)}$ = 0.04Ω

I_D = 50A

Description

Fifth Generation HEXFETs from International Rectifier utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit, combined with the fast switching speed and ruggedized device design that HEXFET Power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications.

The TO-247 package is preferred for commercial-industrial applications where higher power levels preclude the use of TO-220 devices. The TO-247 is similar but superior to the earlier TO-218 package because of its isolated mounting hole.

TO-247AC

Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	50	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	35	
I_{DM}	Pulsed Drain Current ①	200	
P_D @ T_C = 25°C	Power Dissipation	300	W
	Linear Derating Factor	2.0	W/°C
V_{GS}	Gate-to-Source Voltage	±20	V
E_{AS}	Single Pulse Avalanche Energy②	560	mJ
I_{AR}	Avalanche Current①	50	A
E_{AR}	Repetitive Avalanche Energy①	30	mJ
dv/dt	Peak Diode Recovery dv/dt ③	10	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to +175	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torque, 6-32 or M3 srew	10 lbf•in (1.1N•m)	

Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	0.50	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	0.24	—	
$R_{\theta JA}$	Junction-to-Ambient	—	40	

International
IOR Rectifier

PD - 94004A

IRFP260N

HEXFET® Power MOSFET

- Advanced Process Technology
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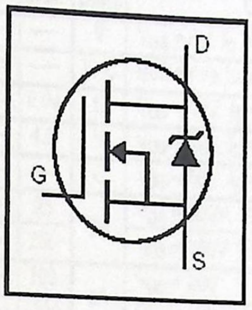
- 175°C Operating Temperature
- Fast Switching
- Fully Avalanche Rated
- Ease of Paralleling
- Simple Drive Requirements



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Description

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TO-247AC

Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	50	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	35	
I_{DM}	Pulsed Drain Current ①	200	
P_D @T_C = 25°C	Power Dissipation	300	W
	Linear Derating Factor	2.0	W/°C
V_{GS}	Gate-to-Source Voltage	±20	V
E_{AS}	Single Pulse Avalanche Energy②	560	mJ
I_{AR}	Avalanche Current①	50	A
E_{AR}	Repetitive Avalanche Energy①	30	mJ
dv/dt	Peak Diode Recovery dv/dt ③	10	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to +175	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torque, 6-32 or M3 srew	10 lbf•in (1.1N•m)	

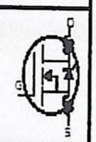
Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	0.50	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	0.24	—	
$R_{\theta JA}$	Junction-to-Ambient	—	40	

IRFP260N

International
IOR Rectifier

Electrical Characteristics @ $T_J = 25°C$ (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Conditions
$V_{(BR)DSS}$	Drain-to-Source Breakdown Voltage	200	—	—	V	$V_{GS} = 0V$, $I_D = 250\mu A$
$\Delta V_{(BR)DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	—	0.26	—	V/°C	Reference to 25°C, $I_D = 1mA$
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	—	—	0.04	Ω	$V_{GS} = 10V$, $I_D = 28A$ ④
$V_{GS(th)}$	Gate Threshold Voltage	2.0	—	4.0	V	$V_{DS} = V_{GS}$, $I_D = 250\mu A$
g_{fs}	Forward Transconductance	27	—	—	S	$V_{DS} = 50V$, $I_D = 28A$ ④
I_{DSS}	Drain-to-Source Leakage Current	—	—	25	μA	$V_{DS} = 200V$, $V_{GS} = 0V$
		—	—	250		$V_{DS} = 160V$, $V_{GS} = 0V$, $T_J = 150°C$
I_{GSS}	Gate-to-Source Forward Leakage	—	—	100	nA	$V_{GS} = 20V$
	Gate-to-Source Reverse Leakage	—	—	-100		$V_{GS} = -20V$
Q_g	Total Gate Charge	—	—	234	nC	$I_D = 28A$
Q_{gs}	Gate-to-Source Charge	—	—	38		$V_{DS} = 160V$
Q_{gd}	Gate-to-Drain ("Miller") Charge	—	—	110		$V_{GS} = 10V$ ④
$t_{d(on)}$	Turn-On Delay Time	—	17	—	ns	$V_{DD} = 100V$
t_r	Rise Time	—	60	—		$I_D = 28A$
$t_{d(off)}$	Turn-Off Delay Time	—	55	—		$R_G = 1.8\Omega$
t_f	Fall Time	—	48	—		$V_{GS} = 10V$ ④
L_D	Internal Drain Inductance	—	5.0	—	nH	Between lead, 6mm (0.25in.) from package 
L_S	Internal Source Inductance	—	13	—		and center of die contact
C_{iss}	Input Capacitance	—	4057	—	pF	$V_{GS} = 0V$
C_{oss}	Output Capacitance	—	603	—		$V_{DS} = 25V$
C_{rss}	Reverse Transfer Capacitance	—	161	—		$f = 1.0MHz$

Source-Drain Ratings and Characteristics

	Parameter	Min.	Typ.	Max.	Units	Conditions
I_S	Continuous Source Current (Body Diode)	—	—	50	A	MOSFET symbol showing the integral reverse p-n junction diode. 
I_{SM}	Pulsed Source Current (Body Diode)①	—	—	200		
V_{SD}	Diode Forward Voltage	—	—	1.3	V	$T_J = 25°C$, $I_S = 28A$, $V_{GS} = 0V$ ④
t_{rr}	Reverse Recovery Time	—	268	402	ns	$T_J = 25°C$, $I_F = 28A$
Q_{rr}	Reverse Recovery Charge	—	1.9	2.8	μC	$di/dt = 100A/\mu s$ ④
t_{on}	Forward Turn-On Time	Intrinsic turn-on time is negligible (turn-on is dominated by L_S+L_D)				

Notes:

① Repetitive rating; pulse width limited by max. junction temperature.

② Starting $T_J = 25°C$, $L = 1.5mH$, $R_G = 25\Omega$, $I_{AS} = 28A$.

③ $I_{SD} \le 28A$, $di/dt \le 486A/\mu s$, $V_{DD} \le V_{(BR)DSS}$, $T_J \le 175°C$

④ Pulse width $\le 400\mu s$; duty cycle $\le 2\%$.

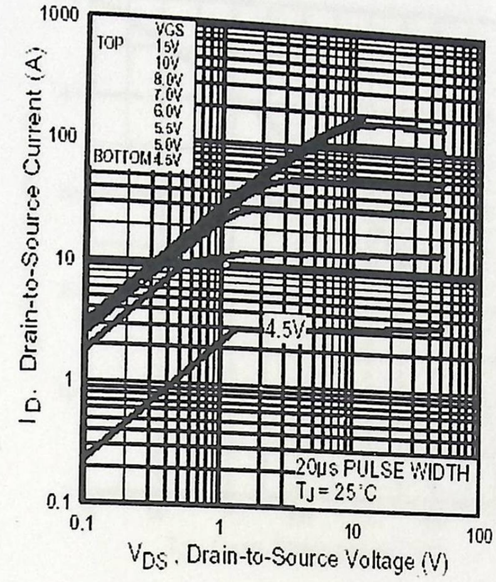


Fig 1. Typical Output Characteristics

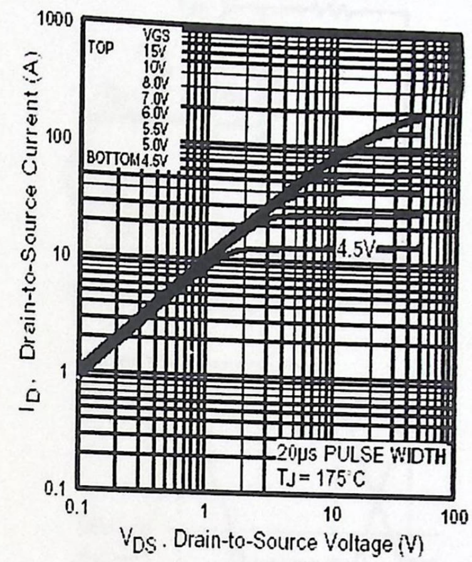


Fig 2. Typical Output Characteristics

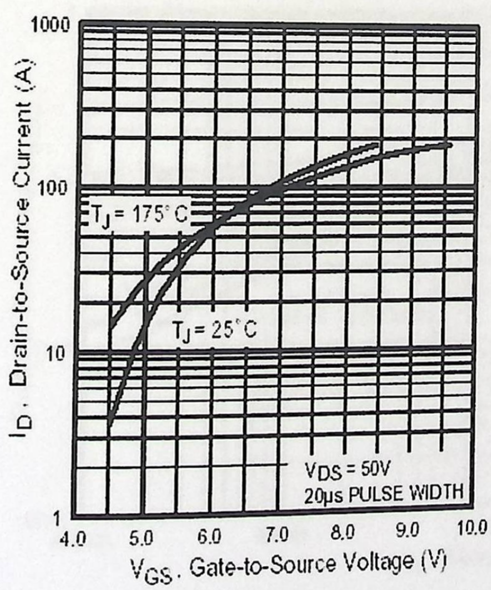


Fig 3. Typical Transfer Characteristics

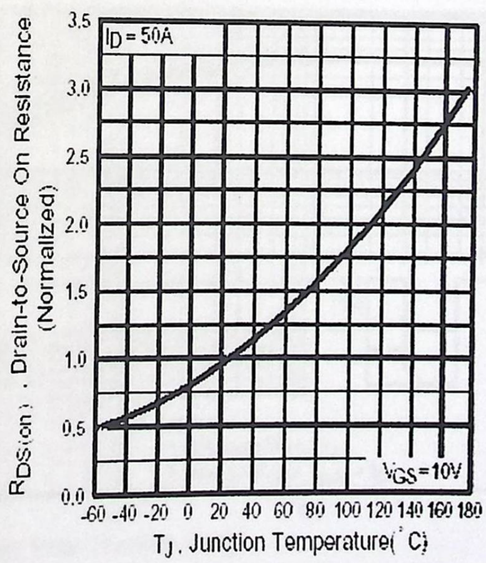


Fig 4. Normalized On-Resistance Vs. Temperature

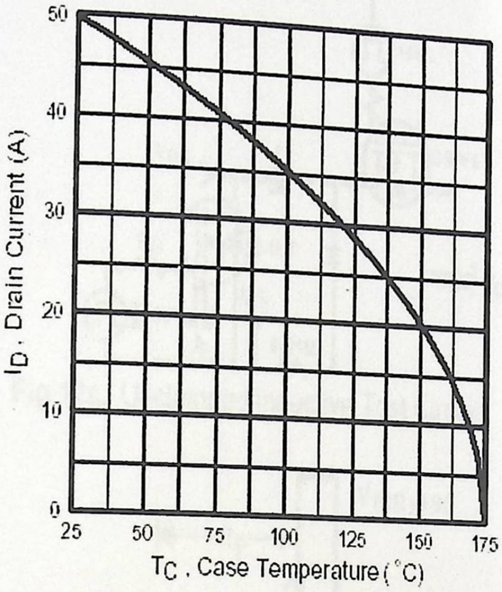


Fig 9. Maximum Drain Current Vs. Case Temperature

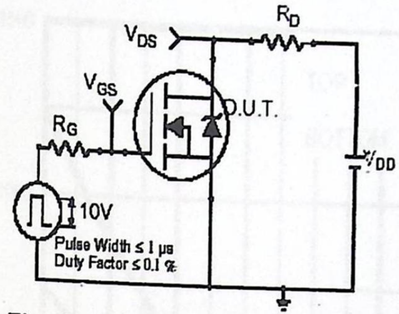


Fig 10a. Switching Time Test Circuit

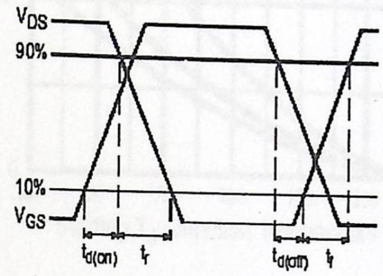


Fig 10b. Switching Time Waveforms

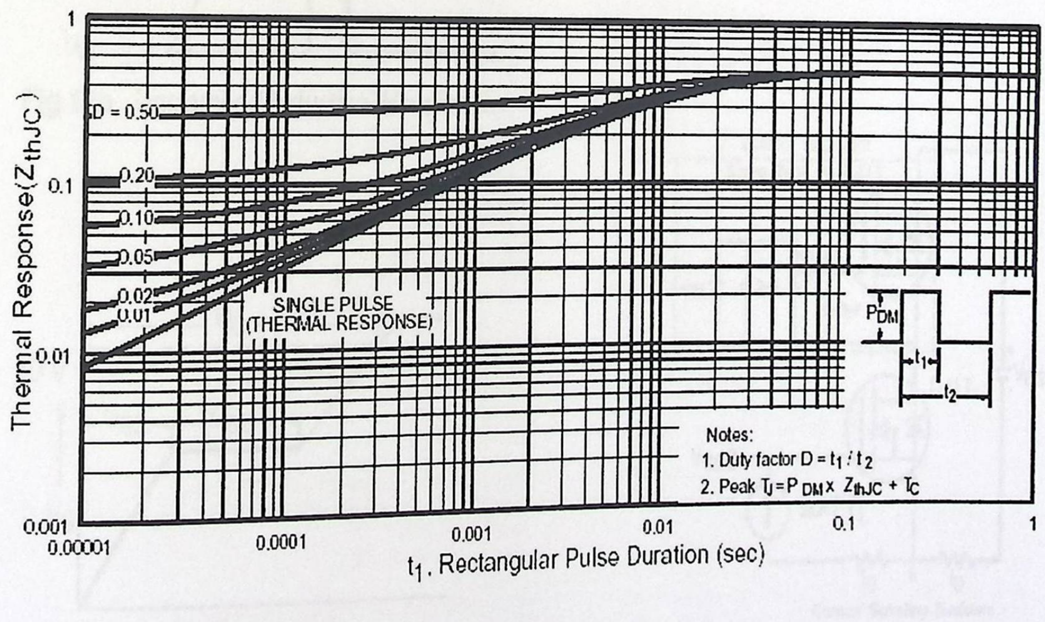


Fig 11. Maximum Effective Transient Thermal Impedance, Junction-to-Case

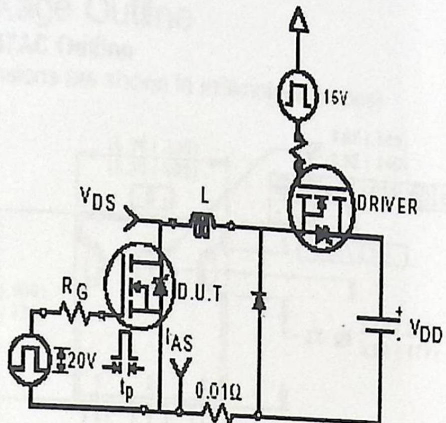


Fig 12a. Unclamped Inductive Test Circuit

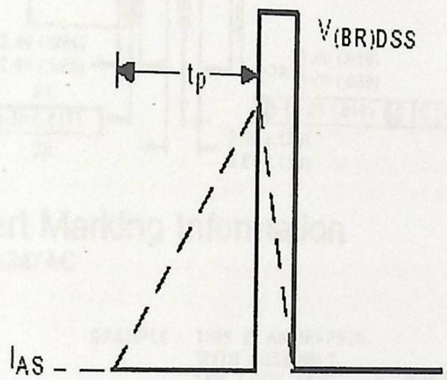


Fig 12b. Unclamped Inductive Waveforms

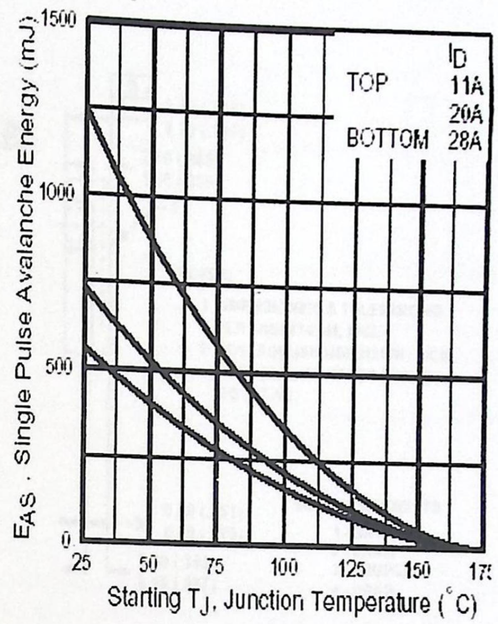


Fig 12c. Maximum Avalanche Energy Vs. Drain Current

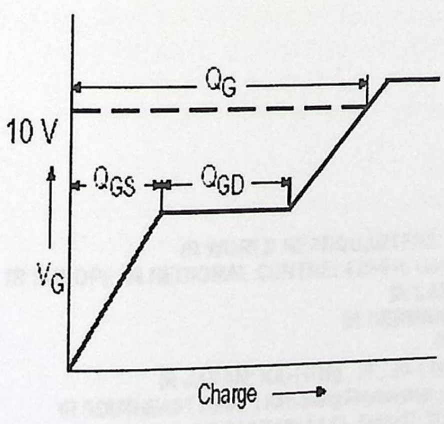


Fig 13a. Basic Gate Charge Waveform

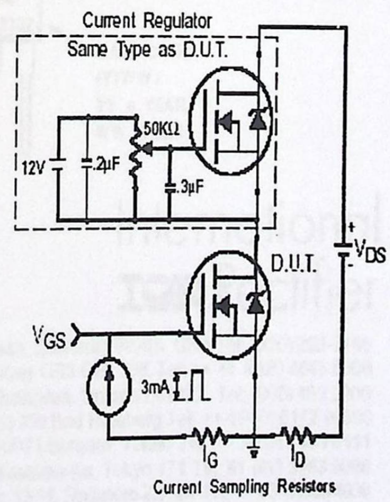


Fig 13b. Gate Charge Test Circuit

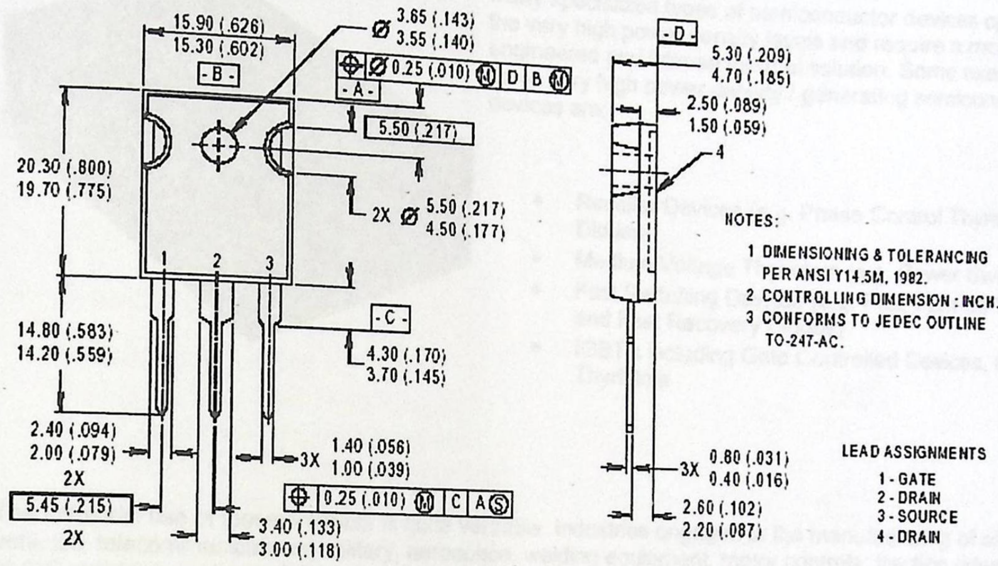
IRFP260N

International
IOR Rectifier

Package Outline

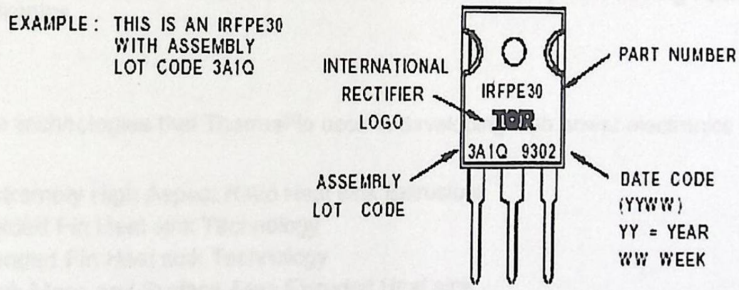
TO-247AC Outline

Dimensions are shown in millimeters (inches)



Part Marking Information

TO-247AC

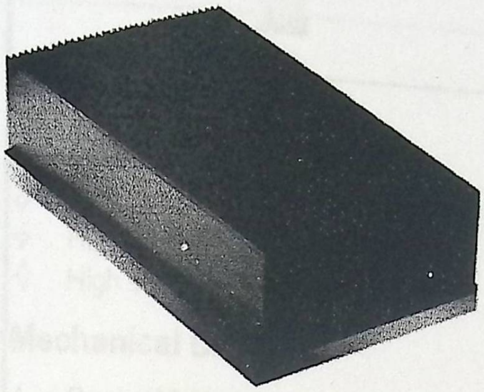


International
IOR Rectifier

IR WORLD HEADQUARTERS: 233 Kansas St., El Segundo, California 90245, USA Tel: (310) 252-7105
IR EUROPEAN REGIONAL CENTRE: 439/445 Godstone Rd, Whyteleafe, Surrey CR3 OBL, UK Tel: ++ 44 (0)20 8645 8000
IR CANADA: 15 Lincoln Court, Brampton, Ontario L6T3Z2, Tel: (905) 453 2200
IR GERMANY: Saalburgstrasse 157, 61350 Bad Homburg Tel: ++ 49 (0) 6172 96590
IR ITALY: Via Liguria 49, 10071 Borgaro, Torino Tel: ++ 39 011 451 0111
IR JAPAN: K&H Bldg., 2F, 30-4 Nishi-Ikebukuro 3-Chome, Toshima-Ku, Tokyo 171 Tel: 81 (0)3 3983 0086
IR SOUTHEAST ASIA: 1 Kim Seng Promenade, Great World City West Tower, 13-11, Singapore 237994 Tel: ++ 65 (0)838 4630
IR TAIWAN: 16 Fl. Suite D. 207, Sec. 2, Tun Haw South Road, Taipei, 10673 Tel: 886-(0)2 2377 9936

Data and specifications subject to change without notice. 10/00

High Power Heat Sinks



Many specialized types of semiconductor devices operate at the very high power density levels and require a more engineered and intense thermal solution. Some examples of these very high power density / generating semiconductor devices are:

- Rectifier Devices (e.g. Phase Control Thyristors and Diodes)
- Medium Voltage Thyristors (e.g. Power Switches)
- Fast Switching Devices (e.g. Fast Turn-off Thyristors and Fast Recovery Diodes)
- IGBT's including Gate Controlled Devices, GTO Thyristors

The industrial use of these products is quite versatile. Industries engaged in the manufacturing of electric vehicles, telecommunications, military, aerospace, welding equipment, motor controls, traction drive, and HVDC require a cooling solution specific to each design and ultimate power dissipation.

ThermaFlo develops efficient cooling solution for these industries using a methodology of applying standard product manufacturing technology and know-how towards developing a cooling solution for cooling high power electronics.

Some of the technologies that ThermaFlo uses in developing high power electronics cooling systems are:

- Extremely High Aspect Ratio Heat sink Extrusions
- Folded Fin Heat sink Technology
- Bonded Fin Heat sink Technology
- High Mass and Surface Area Extruded Heat sink
- Copper Heat sinks
- Integrated Heat Pipe and Heat Sink Solutions

To learn more about these and other technologies that can be used for developing high power cooling solutions, please contact ThermaFlo's Engineering Department today.

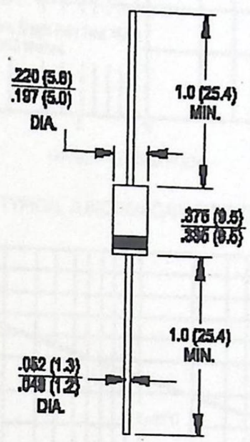
BY396 THRU BY399

3.0 AMPS. Fast Recovery Rectifiers

TSC

Voltage Range
100 to 800 Volts
Current
3.0 Amperes

DO-201AD



Dimensions in inches and (millimeters)

Features

- ✧ Low forward voltage drop
- ✧ High current capability
- ✧ High reliability
- ✧ High surge current capability

Mechanical Data

- ✧ Cases: Molded plastic
- ✧ Epoxy: UL 94V-0 rate flame retardant
- ✧ Lead: Axial leads, solderable per MIL-STD-202, Method 208 guaranteed
- ✧ Polarity: Color band denotes cathode end
- ✧ High temperature soldering guaranteed: 250°C/10 seconds/.375",(9.5mm) lead lengths at 5 lbs.,(2.3kg) tension
- ✧ Weight: 1.2 grams

Maximum Ratings and Electrical Characteristics

Rating at 25°C ambient temperature unless otherwise specified.
Single phase, half wave, 60 Hz, resistive or inductive load.
For capacitive load, derate current by 20%

Type Number	BY396	BY397	BY398	BY399	Units
Maximum Recurrent Peak Reverse Voltage	100	200	400	800	V
Maximum RMS Voltage	70	140	280	560	V
Maximum DC Blocking Voltage	100	200	400	800	V
Maximum Average Forward Rectified Current .375"(9.5mm) Lead Length @T_A = 55°C	3.0				A
Peak Forward Surge Current, 8.3 ms Single Half Sine-wave Superimposed on Rated Load (JEDEC method)	150				A
Maximum Instantaneous Forward Voltage @ 3.0A	1.2				V
Maximum DC Reverse Current @ T_A=25°C at Rated DC Blocking Voltage @ T_A=100°C	10 150				uA uA
Maximum Reverse Recovery Time (Note 1)	250				nS
Typical Junction Capacitance (Note 2)	60				pF
Operating Temperature Range T_J	-65 to +150				°C
Storage Temperature Range T_{STG}	-65 to +150				°C

Notes: 1. Reverse Recovery Test Conditions: I_F=0.5A, I_R=1.0A, I_{RR}=0.25A
2. Measured at 1 MHz and Applied Reverse Voltage of 4..0 Volts D.C.

RATINGS AND CHARACTERISTIC CURVES (BY396 THRU BY399)

FIG.1- MAXIMUM FORWARD CURRENT DERATING CURVE

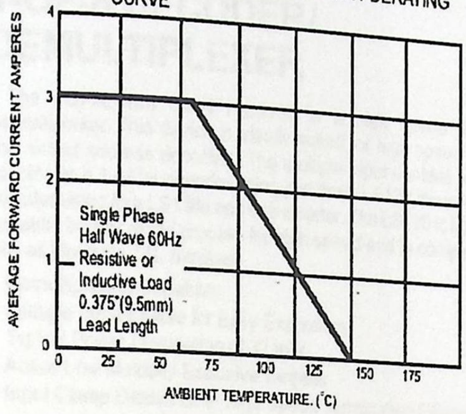


FIG.2- MAXIMUM NON-REPETITIVE PEAK FORWARD SURGE CURRENT

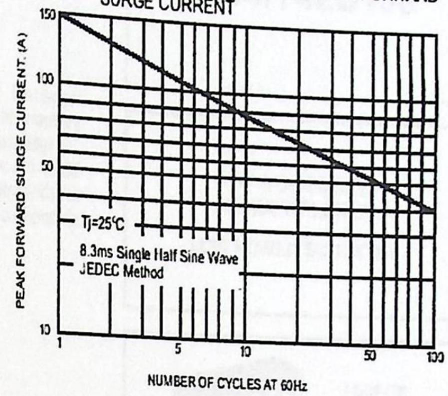


FIG.3- TYPICAL FORWARD CHARACTERISTICS

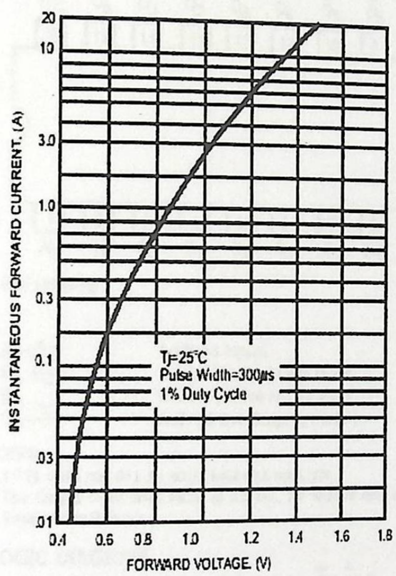


FIG.4- TYPICAL JUNCTION CAPACITANCE

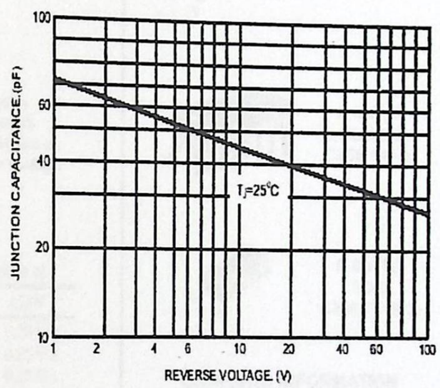
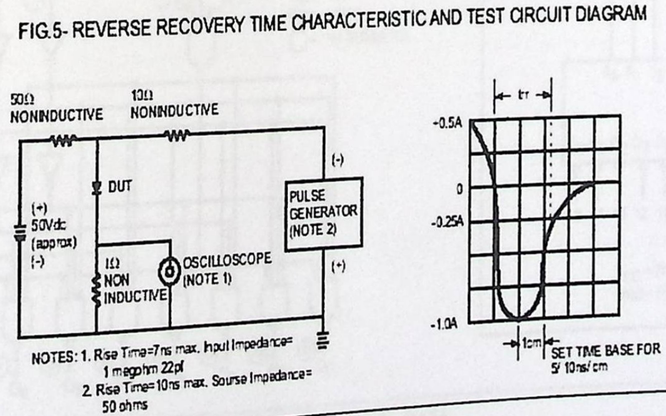


FIG.5- REVERSE RECOVERY TIME CHARACTERISTIC AND TEST CIRCUIT DIAGRAM



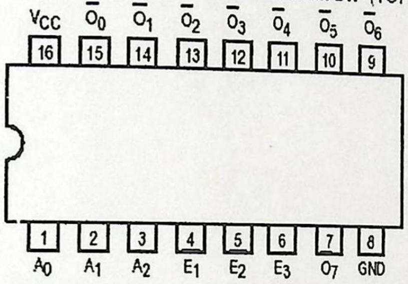
MOTOROLA

1-OF-8 DECODER/ DEMULTIPLEXER

The LSTTL/MSI SN54/74LS138 is a high speed 1-of-8 Decoder/Demultiplexer. This device is ideally suited for high speed bipolar memory chip select address decoding. The multiple input enables allow parallel expansion to a 1-of-24 decoder using just three LS138 devices or to a 1-of-32 decoder using four LS138s and one inverter. The LS138 is fabricated with the Schottky barrier diode process for high speed and is completely compatible with all Motorola TTL families.

- Demultiplexing Capability
- Multiple Input Enable for Easy Expansion
- Typical Power Dissipation of 32 mW
- Active Low Mutually Exclusive Outputs
- Input Clamp Diodes Limit High Speed Termination Effects

CONNECTION DIAGRAM DIP (TOP VIEW)



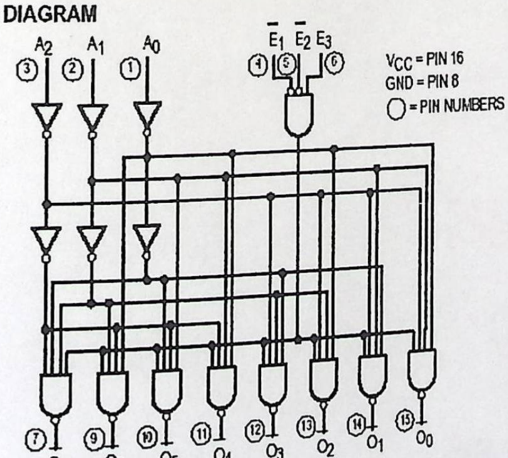
NOTE:
The Flatpak version has the same pinouts (Connection Diagram) as the Dual In-Line Package.

PIN NAMES

		LOADING (Note a)	
		HIGH	LOW
A_0–A_2	Address Inputs	0.5 U.L.	0.25 U.L.
$\overline{E}_1$, $\overline{E}_2$	Enable (Active LOW) Inputs	0.5 U.L.	0.25 U.L.
E_3	Enable (Active HIGH) Input	0.5 U.L.	0.25 U.L.
$\overline{O}_0$–$\overline{O}_7$	Active LOW Outputs (Note b)	10 U.L.	5 (2.5) U.L.

NOTES:
a) 1 TTL Unit Load (U.L.) = 40 µA HIGH/1.6 mA LOW.
b) The Output LOW drive factor is 2.5 U.L. for Military (54) and 5 U.L. for Commercial (74) Temperature Ranges.

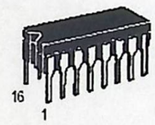
LOGIC DIAGRAM



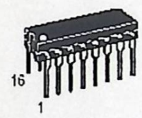
SN54/74LS138

1-OF-8 DECODER/ DEMULTIPLEXER

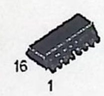
LOW POWER SCHOTTKY



J SUFFIX
CERAMIC
CASE 620-09



N SUFFIX
PLASTIC
CASE 648-08

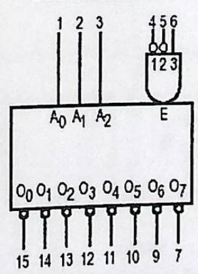


D SUFFIX
SOIC
CASE 751B-03

ORDERING INFORMATION

SN54LSXXXJ Ceramic
SN74LSXXXN Plastic
SN74LSXXXD SOIC

LOGIC SYMBOL



V_{CC} = PIN 16
GND = PIN 8

FUNCTIONAL DESCRIPTION

The LS138 is a high speed 1-of-8 Decoder/Demultiplexer fabricated with the low power Schottky barrier diode process. The decoder accepts three binary weighted inputs (A_0, A_1, A_2) and when enabled provides eight mutually exclusive active LOW Outputs ($\overline{O}_0 - \overline{O}_7$). The LS138 features three Enable inputs, two active LOW ($\overline{E}_1, \overline{E}_2$) and one active HIGH ($E_3$). All outputs will be HIGH unless $\overline{E}_1$ and $\overline{E}_2$ are LOW and E_3 is HIGH. This multiple enable function allows easy parallel expansion of the device to a 1-of-32 (5 lines to 32 lines) decoder with just four LS138s and one inverter. (See Figure a.)

The LS138 can be used as an 8-output demultiplexer by using one of the active LOW Enable inputs as the data input and the other Enable inputs as strobes. The Enable inputs which are not used must be permanently tied to their appropriate active HIGH or active LOW state.

TRUTH TABLE

INPUTS						OUTPUTS							
$\overline{E}_1$	$\overline{E}_2$	E_3	A_0	A_1	A_2	$\overline{O}_0$	$\overline{O}_1$	$\overline{O}_2$	$\overline{O}_3$	$\overline{O}_4$	$\overline{O}_5$	$\overline{O}_6$	$\overline{O}_7$
H	X	X	X	X	X	H	H	H	H	H	H	H	H
X	H	X	X	X	X	H	H	H	H	H	H	H	H
X	X	L	X	X	X	H	H	H	H	H	H	H	H
L	L	H	L	L	L	L	H	H	H	H	H	H	H
L	L	H	H	L	L	H	L	H	H	H	H	H	H
L	L	H	L	H	L	H	H	L	H	H	H	H	H
L	L	H	H	H	L	H	H	H	L	H	H	H	H
L	L	H	L	L	H	H	H	H	H	L	H	H	H
L	L	H	H	L	H	H	H	H	H	H	L	H	H
L	L	H	L	H	H	H	H	H	H	H	H	L	H
L	L	H	H	H	H	H	H	H	H	H	H	H	L

H = HIGH Voltage Level
L = LOW Voltage Level
X = Don't Care

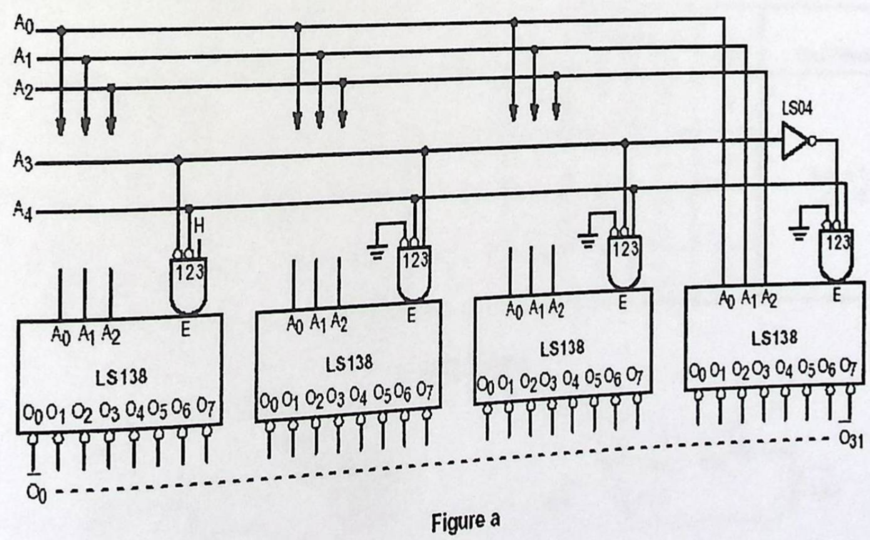


Figure a

SN54/74LS138

GUARANTEED OPERATING RANGES

Symbol	Parameter		Min	Typ	Max	Unit
V_{CC}	Supply Voltage	54 74	4.5 4.75	5.0 5.0	5.5 5.25	V
T_A	Operating Ambient Temperature Range	54 74	−55 0	25 25	125 70	C
I_{OH}	Output Current — High	54, 74			−0.4	mA
I_{OL}	Output Current — Low	54 74			4.0 8.0	mA

DC CHARACTERISTICS OVER OPERATING TEMPERATURE RANGE (unless otherwise specified)

Symbol	Parameter		Limits Min	Limits Typ	Limits Max	Unit	Test Conditions	
V_{IH}	Input HIGH Voltage		2.0			V	Guaranteed Input HIGH Voltage for All Inputs	
V_{IL}	Input LOW Voltage	54			0.7	V	Guaranteed Input LOW Voltage for All Inputs	
		74			0.8			
V_{IK}	Input Clamp Diode Voltage			−0.65	−1.5	V	V_{CC} = MIN, I_{IN} = −18 mA	
V_{OH}	Output HIGH Voltage	54	2.5	3.5		V	V_{CC} = MIN, I_{OH} = MAX, V_{IN} = V_{IH} or V_{IL} per Truth Table	
		74	2.7	3.5		V		
V_{OL}	Output LOW Voltage	54, 74		0.25	0.4	V	I_{OL} = 4.0 mA	V_{CC} = V_{CC} MIN, V_{IN} = V_{IL} or V_{IH} per Truth Table
		74		0.35	0.5	V	I_{OL} = 8.0 mA	
I_{IH}	Input HIGH Current				20	µA	V_{CC} = MAX, V_{IN} = 2.7 V	
					0.1	mA	V_{CC} = MAX, V_{IN} = 7.0 V	
I_{IL}	Input LOW Current				−0.4	mA	V_{CC} = MAX, V_{IN} = 0.4 V	
I_{OS}	Short Circuit Current (Note 1)		−20		−100	mA	V_{CC} = MAX	
I_{CC}	Power Supply Current				10	mA	V_{CC} = MAX	

Note 1: Not more than one output should be shorted at a time, nor for more than 1 second.

AC CHARACTERISTICS (T_A = 25 C)

Symbol	Parameter	Levels of Delay	Limits Min	Limits Typ	Limits Max	Unit	Test Conditions
t_{PLH} t_{PHL}	Propagation Delay Address to Output	2 2		13 27	20 41	ns	V_{CC} = 5.0 V C_L = 15 pF
t_{PLH} t_{PHL}	Propagation Delay Address to Output	3 3		18 26	27 39	ns	
t_{PLH} t_{PHL}	Propagation Delay E_1 or E_2 Enable to Output	2 2		12 21	18 32	ns	
t_{PLH} t_{PHL}	Propagation Delay E_3 Enable to Output	3 3		17 25	26 38	ns	

AC WAVEFORMS

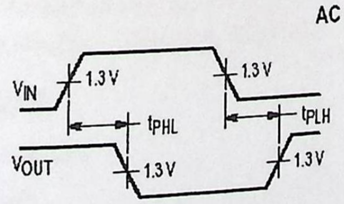


Figure 1

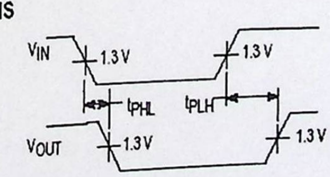


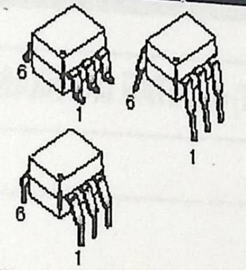
Figure 2

FAIRCHILD
SEMICONDUCTOR®

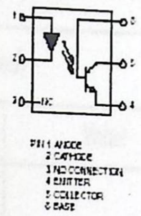
GENERAL PURPOSE 6-PIN PHOTOTRANSISTOR OPTOCOUPLERS

4N25 4N37	4N26 H11A1	4N27 H11A2	4N28 H11A3	4N35 H11A4	4N36 H11A5

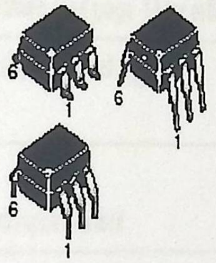
WHITE PACKAGE (-M SUFFIX)



SCHEMATIC



BLACK PACKAGE (NO -M SUFFIX)



DESCRIPTION

The general purpose optocouplers consist of a gallium arsenide infrared emitting diode driving a silicon phototransistor in a 6-pin dual in-line package.

FEATURES

- Also available in white package by specifying -M suffix. eg. 4N25-M
- UL recognized (File # E90700)
- VDE recognized (File # 94766)
  - Add option V for white package (e.g., 4N25V-M)
  - Add option 300 for black package (e.g., 4N25.300)

APPLICATIONS

- Power supply regulators
- Digital logic inputs
- Microprocessor inputs

FAIRCHILD SEMICONDUCTOR®

GENERAL PURPOSE 6-PIN PHOTOTRANSISTOR OPTOCOUPLERS

4N25 4N37	4N26 H11A1	4N27 H11A2	4N28 H11A3	4N35 H11A4	4N36 H11A5

ABSOLUTE MAXIMUM RATINGS (T_A = 25°C unless otherwise specified)

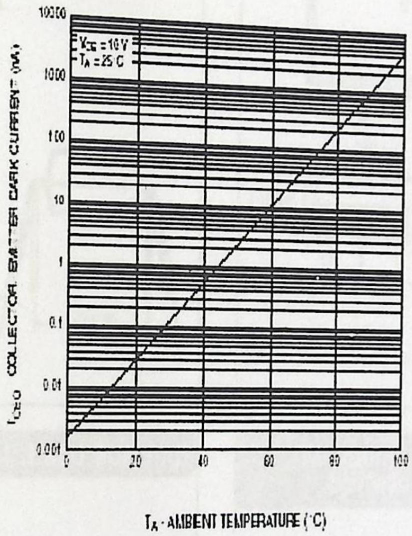
Parameter	Symbol	Value	Units
TOTAL DEVICE			
Storage Temperature	T_{STG}	-55 to +150	°C
Operating Temperature	T_{OPR}	-55 to +100	°C
Wave solder temperature (see page 14 for reflow solder profiles)	T_{SOL}	260 for 10 sec	°C
Total Device Power Dissipation @ T_A = 25°C	P_D	250	mW
Derate above 25°C		3.3 (non-M), 2.94 (-M)	
EMITTER			
DC/Average Forward Input Current	I_F	100 (non-M), 60 (-M)	mA
Reverse Input Voltage	V_R	6	V
Forward Current - Peak (300µs, 2% Duty Cycle)	I_F(pk)	3	A
LED Power Dissipation @ T_A = 25°C	P_D	150 (non-M), 120 (-M)	mW
Derate above 25°C		2.0 (non-M), 1.41 (-M)	mW/°C
DETECTOR			
Collector-Emitter Voltage	V_{CEO}	30	V
Collector-Base Voltage	V_{CBO}	70	V
Emitter-Collector Voltage	V_{ECO}	7	V
Detector Power Dissipation @ T_A = 25°C	P_D	150	mW
Derate above 25°C		2.0 (non-M), 1.76 (-M)	mW/°C

FAIRCHILD SEMICONDUCTOR®

GENERAL PURPOSE 6-PI PHOTOTRANSISTOR OPTOCOUPLER

4N25	4N26	4N27	4N28	4N35	4N36
4N37	H11A1	H11A2	H11A3	H11A4	H11A5

Fig. 19 Dark Current vs. Ambient Temperature



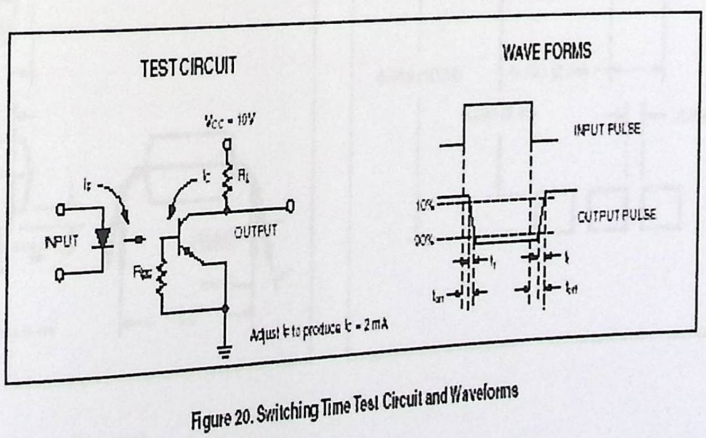


Figure 20. Switching Time Test Circuit and Waveforms

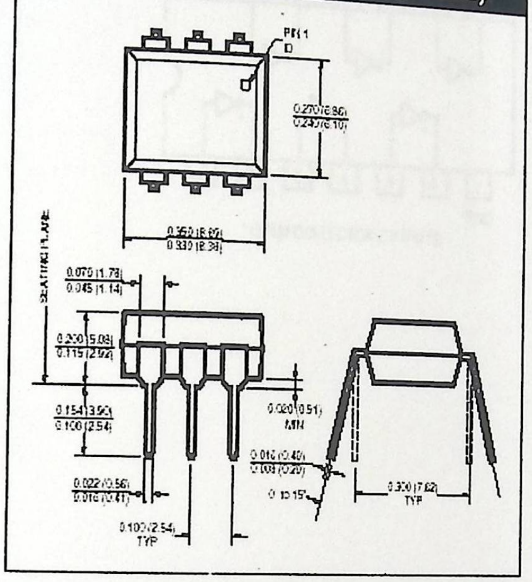
FAIRCHILD SEMICONDUCTOR®

GENERAL PURPOSE 6-PIN PHOTOTRANSISTOR OPTOCOUPLERS

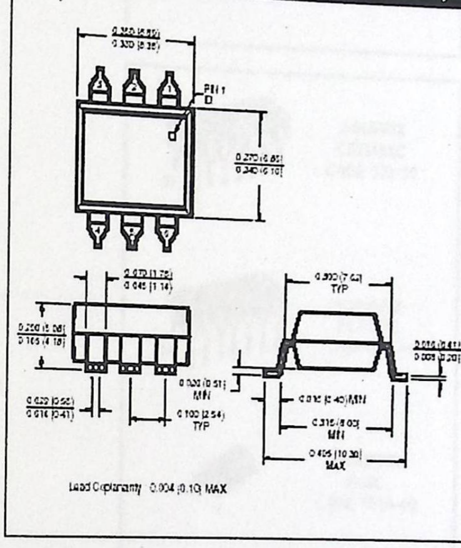
4N25	4N26	4N27	4N28	4N35	4N36
4N37	H11A1	H11A2	H11A3	H11A4	H11A5

Black Package (No -M Suffix)

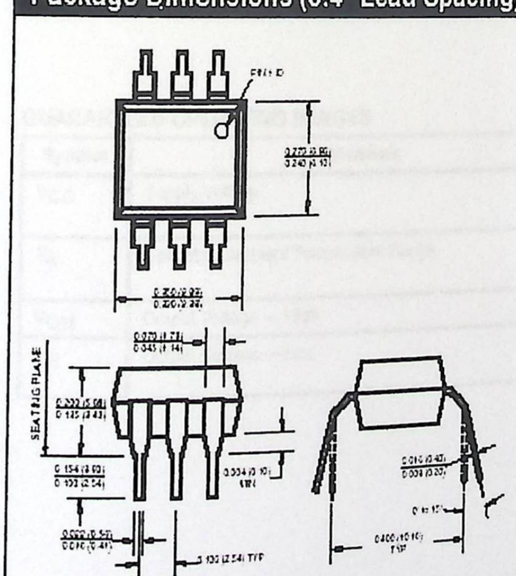
Package Dimensions (Through Hole)



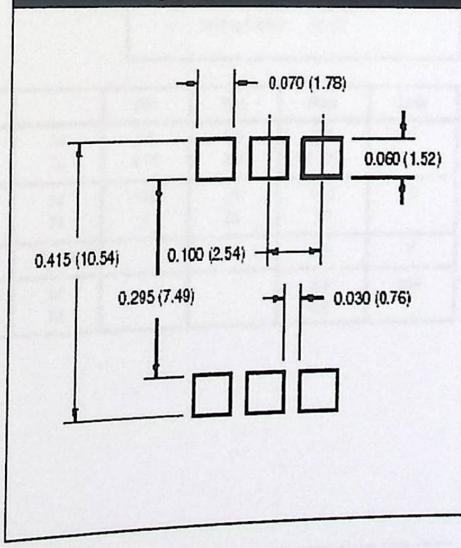
Package Dimensions (Surface Mount)



Package Dimensions (0.4" Lead Spacing)



Recommended Pad Layout for Surface Mount Leadform

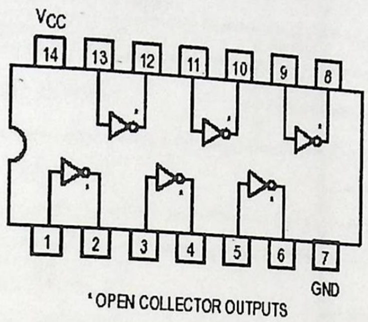


NOTE
All dimensions are in inches (millimeters)

MOTOROLA

HEX INVERTER

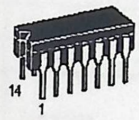
SN54/74LS05



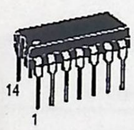
* OPEN COLLECTOR OUTPUTS

HEX INVERTER

LOW POWER SCHOTTKY



J SUFFIX
CERAMIC
CASE 632-08



N SUFFIX
PLASTIC
CASE 646-06

D SUFFIX
SOIC
CASE 751A-02

ORDERING INFORMATION

SN54LSXXJ Ceramic
SN74LSXXN Plastic
SN74LSXXD SOIC

GUARANTEED OPERATING RANGES

Symbol	Parameter		Min	Typ	Max	Unit
V_{CC}	Supply Voltage	54 74	4.5 4.75	5.0 5.0	5.5 5.25	V
T_A	Operating Ambient Temperature Range	54 74	−55 0	25 25	125 70	C
V_{OH}	Output Voltage — High	54, 74			5.5	V
I_{OL}	Output Current — Low	54 74			4.0 8.0	mA

SN54/74LS05

DC CHARACTERISTICS OVER OPERATING TEMPERATURE RANGE (unless otherwise specified)

Symbol	Parameter		Limits Min	Limits Typ	Limits Max	Unit	Test Conditions	
V_{IH}	Input HIGH Voltage		2.0			V	Guaranteed Input HIGH Voltage for All Inputs	
V_{IL}	Input LOW Voltage	54			0.7	V	Guaranteed Input LOW Voltage for All Inputs	
		74			0.8			
V_{IK}	Input Clamp Diode Voltage			−0.65	−1.5	V	V_{CC} = MIN, I_{IN} = −18 mA	
I_{OH}	Output HIGH Current	54, 74			100	µA	V_{CC} = MIN, V_{OH} = MAX	
V_{OL}	Output LOW Voltage	54, 74		0.25	0.4	V	I_{OL} = 4.0 mA	V_{CC} = V_{CC} MIN, V_{IN} = V_{IL} or V_{IH} per Truth Table
		74		0.35	0.5	V	I_{OL} = 8.0 mA	
I_{IH}	Input HIGH Current				20	µA	V_{CC} = MAX, V_{IN} = 2.7 V	
					0.1	mA	V_{CC} = MAX, V_{IN} = 7.0 V	
I_{IL}	Input LOW Current				−0.4	mA	V_{CC} = MAX, V_{IN} = 0.4 V	
I_{CC}	Power Supply Current Total, Output HIGH				2.4	mA	V_{CC} = MAX	
	Total, Output LOW				6.6			

AC CHARACTERISTICS (T_A = 25°C)

Symbol	Parameter	Limits Min	Limits Typ	Limits Max	Unit	Test Conditions
t_{PLH}	Turn-Off Delay, Input to Output		17	32	ns	V_{CC} = 5.0 V C_L = 15 pF, R_L = 2.0 kΩ
t_{PHL}	Turn-On Delay, Input to Output		15	28	ns	