DESIGN OF DRIVER FOR BRUSHLESS DIRECT CURRENT MOTOR (BLDC)

HAZRIMI BIN OMAR

This Report Is Submitted In Partial Fulfillment Of Requirement For The Degree Of Bachelor In Electrical Engineering (Industry Power)

Fakulti Kejuruteraan Elektrik
Kolej Universiti Teknikal Kebangsaan Malaysia

March, 2005

ABSTRAK

Objektif bagi projek ini adalah untuk membina litar pemacu (kawalan) ringkas untuk Brushless DC Motor (BLDC). Pembinaan litar pemacu ini bermula dengan pembinaan suis pada litar dimana ia menjadi nadi untuk menjana isyarat output. PIC controller akan digunakan untuk meningkatkan atau menurunkan tenaga pada suis dimana gelombang keluaran bpleh didapati semasa prosesnya. Proteus (ISIS) secara amnya digunakan menganalisasi litar pemacu (kawalan) dengan melibatkan parameter litar seperti spesifikasi komponen dalam bentuk voltan dan arus yang boleh dianggarkan. Secara tidak langsung pemilihan komponen boleh dilakukan. Apabila litar kawalan telah siap dibina litar pemacu(kawalan) boleh diuji untuk menjana BLDC motor.

ABSTRACT

The purpose of this project is to develop a simple drive circuit for the Three-phase Brushless DC Motor (BLDC). The construction of this drive circuit will be began with the development of switching circuit, which is the heart of generating output signal. PIC controller will be used to energize and de-energize switches so that the required output waveform can be obtained at the load. Proteus (ISIS) is primarily used to analyze the drive circuit virtually so that the circuit parameters such as component specifications in terms of voltage and current can be predicted so that component selection can be done. Once the control circuit is already built, the drive circuit can be tested to drive the BLDC motor.

CHAPTER 1

INTRODUCTION

Brushless Direct Current (BLDC) motors are one of the motor type rapidly gaining popularity. BLDC motor are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC have are advantages over brushed DC motor and induction motors. Are few of they are:

- Better speed versus torque characteristics.
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

In addition, the ratio of torque delivered to the size of the motor is higher, making is useful in applications where space and weight are critical factors. Each commutation sequence has one of the windings energized to positive power (current enters into the winding), the second winding is negative (current exits the winding) and the third is in a non-energized condition. Torque is produced because of the interaction between the magnetic field generated by the stator coils and the permanent magnets. Ideally, the peak torque occurs when these two fields are at 90° to each other and falls off as the fields move together. In order to keep the motor running, the magnetic field produced by the windings should shift position, as the rotor moves to catch up with the stator field. What is known as "Six-Step Commutation" defines the sequence of energizing the windings. See the (page 53) **"Commutation Sequence"** section for detailed information and an example on six-step commutation.

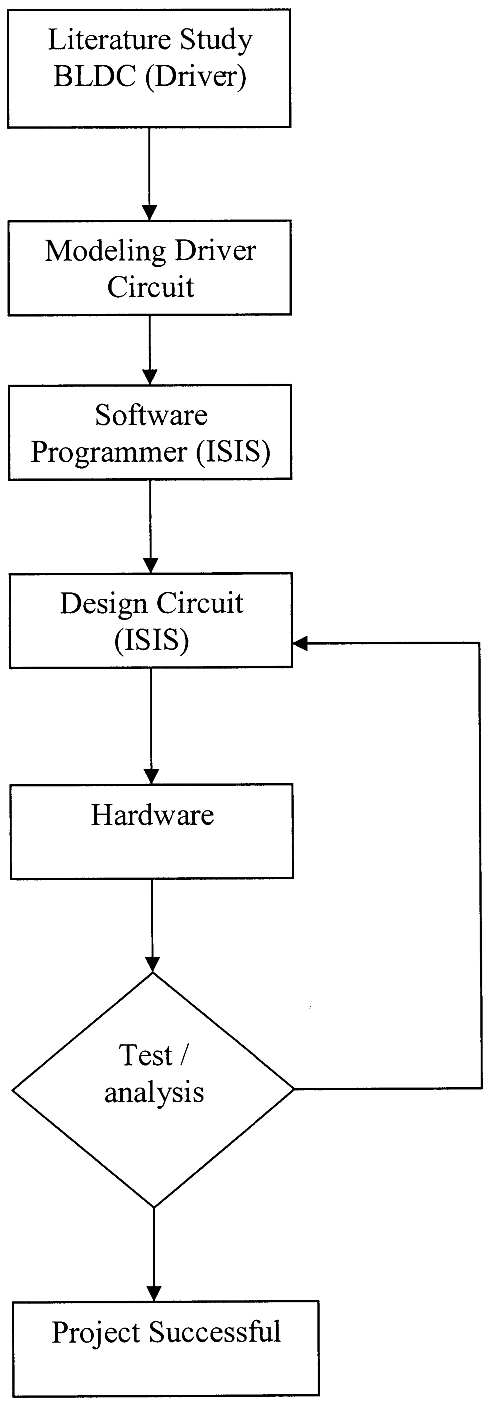

Figure 1.1: Flow Chart of Project

CHAPTER 2

THEORY ABOUT BRUSHLESS DIRECT CURRENT CIRCUIT

2.1 Typical BLDC Motor Application.

BLDC motors find applications in every segment of the market. Automotive, appliance, industrial controls, automation, aviation and so on, have applications for BLDC motors. Out of these, we can categorize the type of BLDC motor control into three major types:

- Constant load
- Varying loads
- Positioning applications

2.2 Applications With Constant Loads

These are the types of applications where a variable speed is more important than keeping the accuracy of the speed at a set speed. In addition, the acceleration and deceleration rates are not dynamically changing. In these types of applications, the load is directly coupled to the motor shaft. For example, fans, pumps and blowers come under these types of applications. These applications demand low-cost controllers, mostly operating in open-loop.

2.3 Applications With Varying Loads

These are the types of applications where the load on the motor varies over a speed range. These applications may demand a high-speed control accuracy and good dynamic responses. In home appliances, washers, dryers and compressors are good examples. In automotive, fuel pump control, electronic steering control, engine control and electric vehicle control are good examples of these. In aerospace, there are a number of applications, like centrifuges, pumps, robotic arm controls, gyroscope controls and so on. These applications may use speed feedback devices and may run in semi-closed loop or in total closed loop. These applications use advanced control algorithms, thus complicating the controller. Also, this increases the price of the complete system.

2.4 Positioning Applications

Most of the industrial and automation types of application come under this category. The applications in this category have some kind of power transmission, which could be mechanical gears or timer belts, or a simple belt driven system. In these applications, the dynamic response of speed and torque are important. Also, these applications may have frequent reversal of rotation direction. A typical cycle will have an accelerating phase, a constant speed phase and a deceleration and positioning phase. The load on the motor may vary during all of these phases, causing the controller to be complex. These systems mostly operate in closed loop. There could be three control loops functioning simultaneously: Torque Control Loop, Speed Control Loop and Position Control Loop. Optical encoder or synchronous resolves are used for measuring the actual speed of the motor. In some cases, the same sensors are used to get relative position information. Otherwise, separate position sensors may be used to get absolute positions. Computer Numeric Controlled (CNC) machines are a good example of this. Process controls, machinery controls and conveyer controls have plenty of applications in this category.

4.5 Contraction and Operating Principle:

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

BLDC motor come in single-phase, 2-phase and 3-phase configuration. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motor are the most popular and widely used. This application Project Sarjana Muda focus on 3-phase motor (BLDC).

2.7 Stator

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slot that are axially cut along the inner periphery. Traditionally, the stator resembles that of an induction motor; however, the winding are distributed in a different manner. Most BLDC motors have three stator winding connected in star fashion. Each of these winding are constructed with numerous coil interconnected to form a winding. One or more coil are placed in the slots and they are interconnected to make a winding. Each of these windings are distributed over the stator periphery to form an even numbers of poles.

There are two type of stator winding variants: trapezoidal and sinusoidal motors. This differentiation of coil in the stator winding to give the different type of back Electromotive Force (EMF). As their names indicated, the trapezoidal motor gives a back in trapezoidal fashion and the sinusoidal motor's back EMF is sinusoidal, as shown in figure 2.0 and figure 2.1

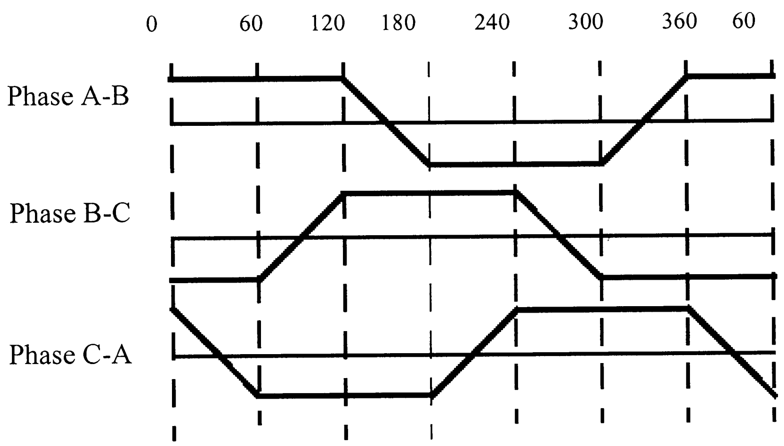

Figure 2.0 :Trapezoidal Back Emf.

60 120 180 240 320 360 60

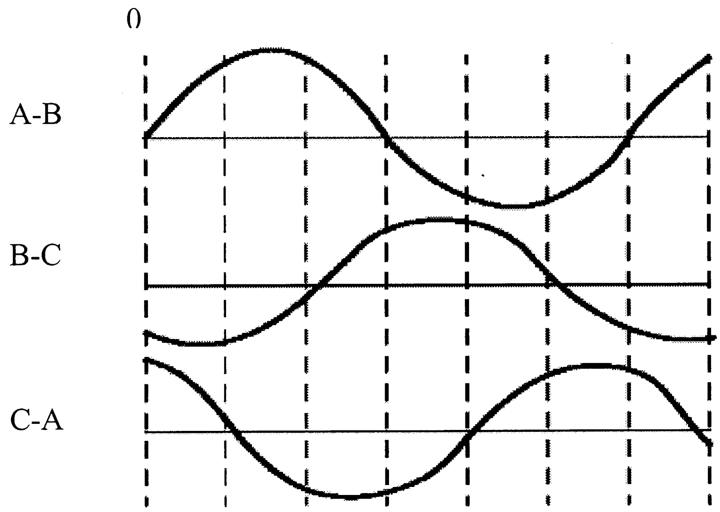

Figure 2.1: Sinusoidal Back Emf.

In addition to the back EMF, the phase current also has trapezoidal and sinusoidal variations in the respective types of motor. This makes the torque output by sinusoidal motor smoother than that of a trapezoidal motor. However, this come with an extra cost, as the sinusoidal motors take extra winding interconnection because of the coils distribution on the stator periphery, thereby increasing the copper intake by the stator windings.

Depending upon the control power supply capability, the motor with the correct voltage rating of the stator can be chosen. Forty-eight volt, or less voltage rated motor are used in automotive, robotics, small arm movements and so on. Motors with 100 volt, or higher rating, are used in appliances, automation and in industrial applications.

2.7 Rotor

The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles.

Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets. As the technology advances, rare earth alloy magnets are gaining popularity. The ferrite magnets are less expensive but they have the disadvantage of low flux density for give volume. In contrast, the alloy material high magnet density per volume and enables the rotor to compress further for the same torque. Also, there alloy magnets improve the size-to-weigh ratio and give higher torque for the same size motor using ferrite magnets.

Neodymium (Nd), Samarium cobalt (SmCo) and the alloy of Neodymium, ferrate and Boron (NdFeB) are some examples of rare earth alloy magnets. Continuous research is going on to improve the flux density to compress the rotor further.

2.8 Hall sensors

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. Is it important to know the rotor position in order to understand which winding will be energizing sequence. Rotor position is sensed using Hall effect sensors embedded into the stator. Most BLDC motors have three hall sensors embedded into the stator on the non-driving end of the motor.

Whenever the rotor magnetic poles pass near the hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Figure 3 shows a transverse section of a BLDC motor with a rotor that has alternate N and S permanent magnets. Hall sensors are embedded into the stationary part of the motor. Embedding the Hall sensors into the stator is a complex process because any misalignment in these Hall sensors, with respect to the rotor magnets, will generate an error in determination of the rotor position. To simplify the process of mounting the Hall sensors onto the stator, some motors may have the Hall sensor magnets on the rotor, in addition to the main rotor magnets. These are a scaled down replica version of the rotor. Therefore, whenever the rotor rotates, the Hall sensor magnets give the same effect as the main magnets. The Hall sensors are normally mounted on a PC board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors, to align with the rotor magnets, in order to achieve the best performance.

Based on the physical position of the Hall sensors, there are two versions of output. The Hall sensors may be at 60° or 120° phase shift to each other. Based on this, the motor manufacturer defines the commutation sequence, which should be followed when controlling the motor.

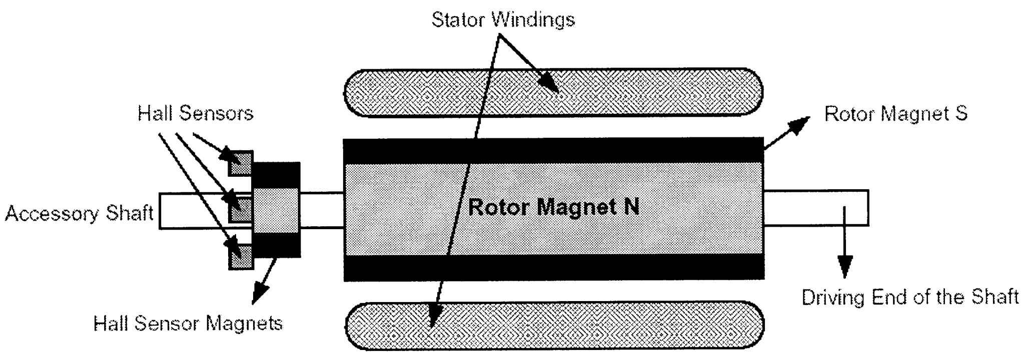

Figure 2.2: BLDC Motor Transverse Section

2.9 Comparing BLDC Motors to other Motor Type.

Compared to brushed DC motors and induction motors, BLDC motors have many advantages and few disadvantages. Brushless motors require less maintenance, so they have a longer life compared with brushed DC motors. BLDC motors produce more output power per frame size than brushed DC motors and induction motors. Because the rotor is made of permanent magnets, the rotor inertia is less, compared with other types of motors. This improves acceleration and deceleration characteristics, shortening operating cycles. Their linear speed/torque characteristics produce predictable speed regulation. With brushless motors, brush inspection is eliminated, making them ideal for limited access areas and applications where servicing is difficult. BLDC motors operate much more quietly than brushed D motors, reducing Electromagnetic Interference (EMI). Low-voltage models are ideal for battery operation, portable equipment or medical applications.

Table 2.0: Summarizes the comparison between a BLDC motor and a brushed DC motor.

Feature	**BLDC Motor**	**Brushed DC Motor**
Commutation	Electronic commutation based on Hall position	Brushed commutation.
Maintenance	Less required due to absence of brushes.	Periodic maintenance is required.
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.
Output Power/	High - Reduced size due to	Moderate/Low - The heat

Frame Size	superior thermal characteristics. Because BLDC has the windings on the stator, which is connected to the case, the heat dissipation is better	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.
Rotor Inertia	Low, because it has permanent magnets on the rotor. This improves the dynamic response.	Higher rotor inertia which limits the dynamic characteristics
Speed Range	Higher - No mechanical limitation imposed by brushes/ commutator.	Lower— Mechanical limitations by the brushes.
Electric Noise Generation	Low.	Arcs in the brushes will generate noise causing EMI in the equipment nearby.
Cost of Building	Higher - Since it has permanent magnets, building costs are higher.	Low.
Control	Complex and expensive.	Simple and inexpensive.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is required only if variable speed is desired.

CHAPTER 3

Literature Review

3.1 Speed Control Systems

The basic block diagrams and outline of the control methods are shown below. Both brushless DC and AC speed control systems employ a closed-loop control system.

3.2 Brushless DC Motor and Driver System Control Method

1. The speed setting voltage is supplied via a potentiometer.
2. The motor speed is sensed and the speed signal voltage is supplied.
3. The difference between the speed setting voltage and speed signal voltage is output.
4. Current determined by the output from the comparator is supplied to the motor so that it will reach the set speed.

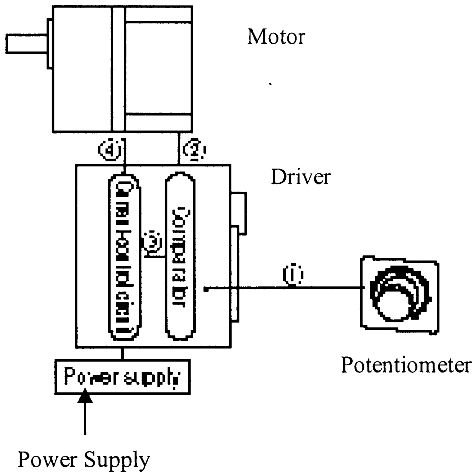

Figure 3.0: Brushless DC Motor and Driver System Control

3.3 AC Speed Control Motor System Control Method

1. The speed setting voltage is supplied via a potentiometer.
2. The motors speed is sensed and the speed signal voltage is supplied.
3. The difference between the speed setting voltage and speed signal voltage is output.
4. A voltage determined by the output from the comparator is supplied to the motor so that it will reach the set speed.

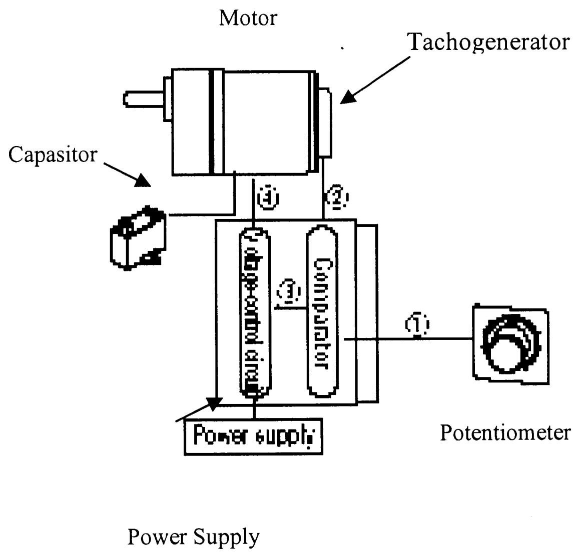

Figure 3.1: AC Speed Control Motor System Control

3.4 Brushless DC Motor Construction and Principle of Operation

3.4.1 Motor

The construction of a brushless DC motor is similar to that of a standard AC motor, except that the brushless DC motor has a built-in magnetic element or optical encoder for the detection of rotor position. The position sensors send signals to the drive circuit. The brushless DC motor uses three phase windings in a “star” connection. A permanent magnet is used in the rotor.

3.4.2 Construction of Brushless DC Motor

U : Phase-U winding
V : Phase-V winding
W : Phase-W winding
Rotor : Magnet

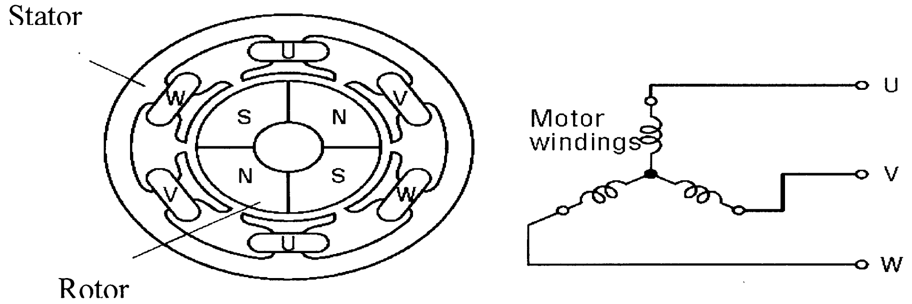

Figure 3.2: Construction of Brushless DC Motor

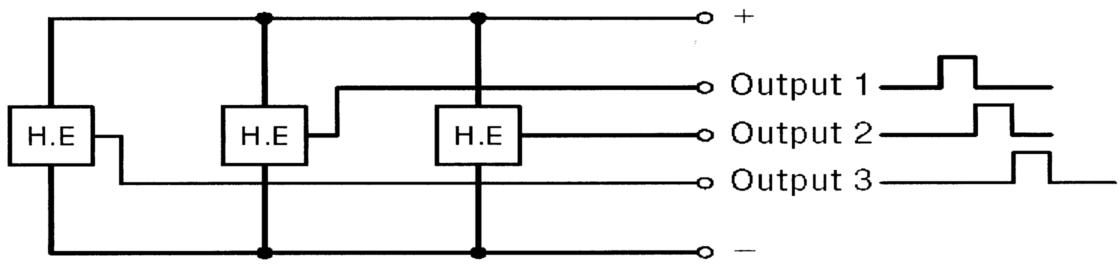

Figure 3.3: Hall effect IC

3.4.3 Brushless DC Motor Drive Circuit

The drive circuit of the brushless DC motor is connected in the configuration shown in the figure below, and is comprised of five main blocks.

- Power circuit
- Setting comparison circuit
- Current control circuit
- Power-supply circuit
- Logic circuit

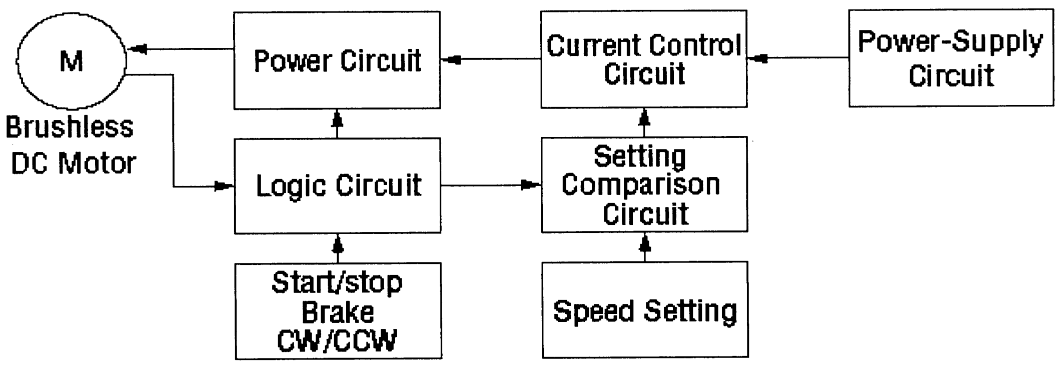

Figure 3.4: Main Block BLDC Driver Circuit

3.4.4 Power Circuit

This circuit uses six transistors to control the current flow in the motor windings. The transistors provided at the top and bottom turn on and off repeatedly according to a predetermined sequence, thereby controlling the flow of current to the motor windings.

3.4.5 Current Control Circuit

The flow of current to the motor varies according to the size of the load. The current flow to the motor is constantly monitored and controlled so that the speed will not deviate from the specified range.

3.4.6 Logic Circuit

The logic circuit detects the rotor position by receiving feedback signals from the motor's Hall effect IC and determines the excitation sequence of motor windings. The circuit signal is connected to each transistor base in the power circuit, driving the transistors according to a predetermined sequence. It also detects the motor's speed. The logic circuit is also used to control commands to the motor, including start/stop, brake/run and CW/CCW.

3.4.7 Setting Comparison Circuit

This circuit compares the motor speed signal against the set speed signal in order to determine whether the motor speed is higher or lower than the set speed. The input to the motor is lowered if the motor speed is higher than the set speed, but the input is raised if it is lower than the set speed. In this manner, the speed that has varied is returned to the set speed.

3.4.8 Power Supply Circuit

This circuit converts a commercial power supply into the voltage necessary to drive the motor and control circuits.

3.5 Principle of Brushless DC Motor Rotation

The motor windings are connected to switching transistors, six of which make up the inverter. The top and bottom transistors turn on and off, according to a predetermined sequence, to change the direction of current flow in the windings. The mechanism of brushless DC motor rotation can be described as follows:

In step 1 of the transistor's switching sequence, as shown in the following figure, transistors Tr1 and Tr6 are in the "ON" state. At this time the winding current flows from phase U to phase W, and phases U and W are excited so that they become N and S poles, respectively, thus causing the rotor to turn 30°. Repeating such a motion 12 times thereby facilitates rotation of the motor.

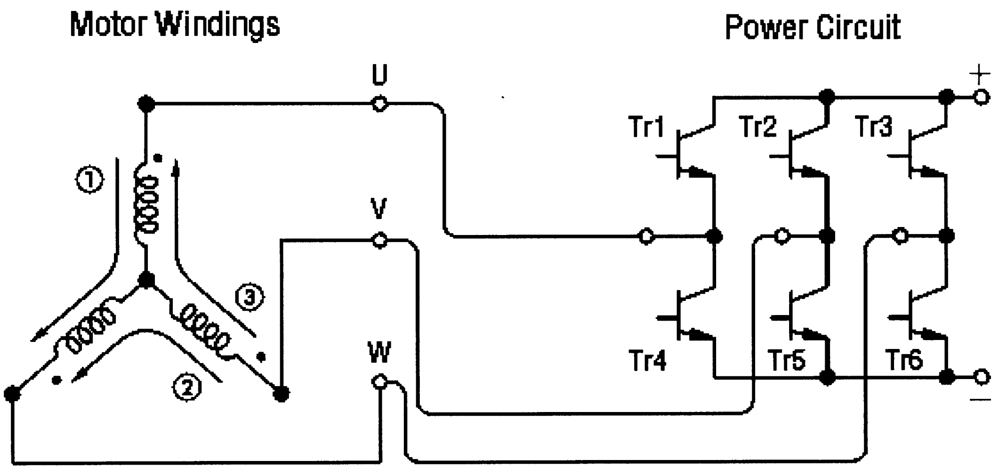

Figure 3.5: The motor windings are connected to switching transistors

Table 3.0: Switching Sequences of Individual Transistors

Step / Transistor	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬
Tr1	ON					ON	ON					ON	ON
Tr2		ON	ON					ON	ON				
Tr3				ON	ON					ON	ON		
Tr4			ON	ON					ON	ON			
Tr5					ON	ON					ON	ON	
Tr6	ON	ON					ON	ON					ON
Phase U	N	—	S	S	—	N	N	—	S	S	—	N	N
Phase V	—	N	N	—	S	S	—	N	N	—	S	S	—
Phase W	S	S	—	N	N	—	S	S	—	N	N	—	S

CHAPTER 4

MAIN COMPONENT HARDWARE AND MODELLING DRIVER CIRCUIT

4.1 Three Main Component Hardware:

1. TC4469
2. PMOSFET and NMOSFET
3. PIC16F877

4.1.1 Integrated .Circuit (TC4469)

The TC4469 family of four-output CMOS buffer/drivers are an expansion from our earlier single- and dual-output drivers. Each driver has been equipped with a two-input logic gate for added flexibility. The TC4469 drivers can source up to 250 mA into loads referenced to ground. Heavily loaded clock lines, coaxial cables, and piezoelectric transducers can all be easily driven with the 4469 series drivers. The only limitation on loading is that total power dissipation in the IC must be kept within the power dissipation limits of the package. The TC4469 series will not latch under any conditions within their power and voltage ratings. They are not subject to damage when up to 5V of noise spiking (either polarity) occurs on the ground line. They can accept up to half an amp of inductive kickback current (either polarity) into their outputs without damage or logic upset. In addition, all terminals are protected against ESD to at least 2000V.

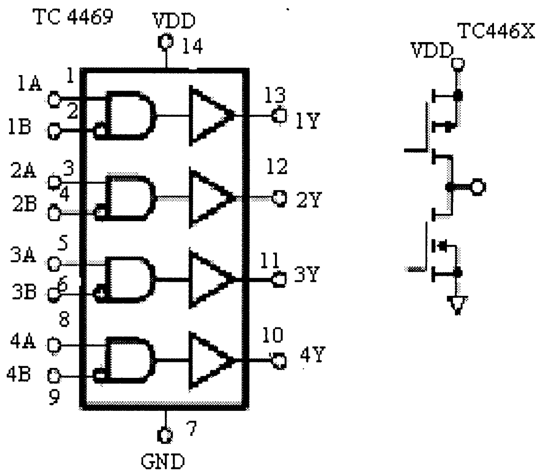

Figure 4.0: Logic Diagram TC4469

4.1.2 Supply Bypassing

Large currents are required to charge and discharge large capacitive loads quickly. For example, charging a 1000pF load to 18V in 25nsec requires 0.72A from the device's power supply. To guarantee low supply impedance over a wide frequency range, a 1µF film capacitor in parallel with one or two low-inductance 0.1µF ceramic disk capacitors with short lead lengths (<0.5 in.) normally provide adequate bypassing.

4.1.3 Grounding

The TC4467 and TC4469 contain inverting drivers. Potential drops developed in common ground impedances from input to output will appear as negative feedback and degrade switching speed characteristics. Instead, individual ground returns for input and output circuits, or a ground plane, should be used.

4.1.4 Input Stage

The input voltage level changes the no-load or quiescent supply current. The N-channel MOSFET input stage transistor drives a 2.5mA current source load. With logic "0" outputs, maximum quiescent supply current is 4mA. Logic "1" output level signals reduce quiescent current to 1.4mA maximum. Unused driver inputs must be connected to VDD or VSS. Minimum power dissipation occurs for logic "1" outputs. The drivers are designed with 50mV of hysteresis. This provides clean transitions and minimizes output are approximately 1.5V, making any voltage greater than 1.5V up to VDD a logic 1 input stage current spiking when changing states. Input voltage thresholds. Input current is less than 1µA over this range.

4.2 PMosfet and NMosfet

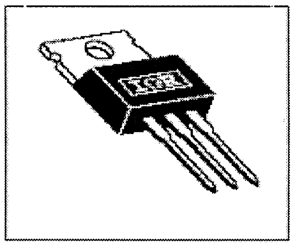

Figure 4.1: Mosfet Picture

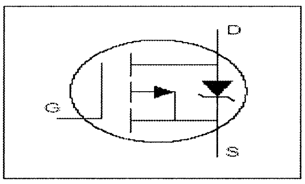

Figure 4.2: PMosfet

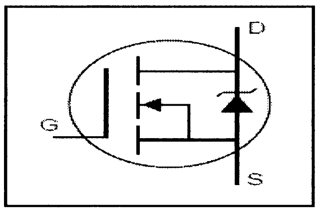

Figure 4.3: NMosfet

There are several ways to modulate the motor drivers. We could switch the high and low side drivers together, or just the high or low driver while leaving the other driver on. Some high side MOSFET drivers use a capacitor charge pump to boost the gate drive above the drain voltage. The charge pump charges when the driver is off and discharges into the MOSFET gate when the driver is on. It makes sense then to switch the high side driver to keep the charge pump refreshed. Even though this application does not use the charge pump type drivers, we will modulate the high side driver while leaving the low side driver on. There are three high side drivers, any one of which could be active depending on the position of the rotor. The motor drive word is 6-bits wide, so if we logically AND the drive word with zeros in the high driver bit positions, and 1's in the low driver bit positions, we will turn off the active high driver regardless which one of the three it is.

4.2.1 Pmosfet Description

VDSS = -55V
RDS(on) = 0.06W
ID = -31A

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 rugged zed 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-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry.