Introduction:

Motors are electro-mechanical devices which convert electrical energy to mechanical energy. They are inevitable parts of numerous industrial systems. With the evolution of engineering technology and its ever-spreading branches, the applications of motors are being diversified even more. A recent study shows that in USA alone there are 2 billion induction motors in use.

The last two decades saw a tremendous development in the field of power electronics and control theory. Various new technology have been invented and developed by electrical engineers for smooth control of speed and performance of motors. The development of power electronics further resulted into enrichment of robotics and related fields.

Among all kinds of motors, dc motor is of significant importance. They are used where precise speed control is necessary. Pulse Width Modulation (PWM) is the engineers' choice today for speed-control of dc motors. PWM ensures high efficiency and constant torque- both desired characteristics of a top-class motor. In low current applications, Permanent-Magnet Direct Current Motor (PMDC) is generally used. PMDC motor ensures low cost and has better speed control characteristics then DC Shunt Motor.

In our project we have applied the PWM technique to implement bi-directional speed control of a PMDC motor. We have gone through several power electronics texts, related journals and papers in our study for the design. We also took suggestions from our honorable instructors and experts. Our project led us to the discovery of a new horizon of electrical engineering and ignited our passion for engineering.

Permanent magnet DC motors:

Permanent Magnet DC motors are useful in a range of applications, from battery powered devices like wheelchairs and power tools, to conveyors and door openers, welding equipment, X-ray and tomographic systems, and pumping equipment, to name a few. They are frequently the best solution to motion control and power transmission applications where compact size, wide operating speed range, ability to adapt to a range of power sources or the safety considerations of low voltage are important. Their ability to produce high torque at low speed makes them suitable substitutes for gear motors in many applications.

Because of their linear speed-torque curve, they particularly suit adjustable speed and servo control applications where the motor will operate at less than5000 rpm. Inside these motors, permanent magnets bonded to a flux-return ring replace the stator field windings found in shunt motors. A wound armature and mechanical brush commutation system complete the motor.

The permanent magnets supply the surrounding field flux, eliminating the need for external field current. This design yields a smaller, lighter, and energy efficient motor.

Armature interaction

Unlike a shunt wound dc motor, a PM motor is free of interaction between the permanent magnet field and the armature demagnetizing cross field. Shunt wound DC motors experience significant interaction between the armature and the stator. The stator's low reluctance (high permeability) iron core ultimately weakens the field as the load increases. The result is a dramatic drop in the speed-torque characteristics at some point.

The PM motor's field has a high reluctance (low permeability) that eliminates significant armature interaction. This high reluctance yields a constant field, permitting linear operation over the motor's entire speed-torque range. In operation with a constant armature voltage, as speed decreases, available torque increases, Figure 1. As the applied armature voltage increases, the linear speed-torque curves shift upwards. Thus, a series of parallel speed-torque curves, for different armature voltages, represents the speed-torque properties of a PM motor, Figure 2. Speed is proportional to voltage and torque is proportional to current.

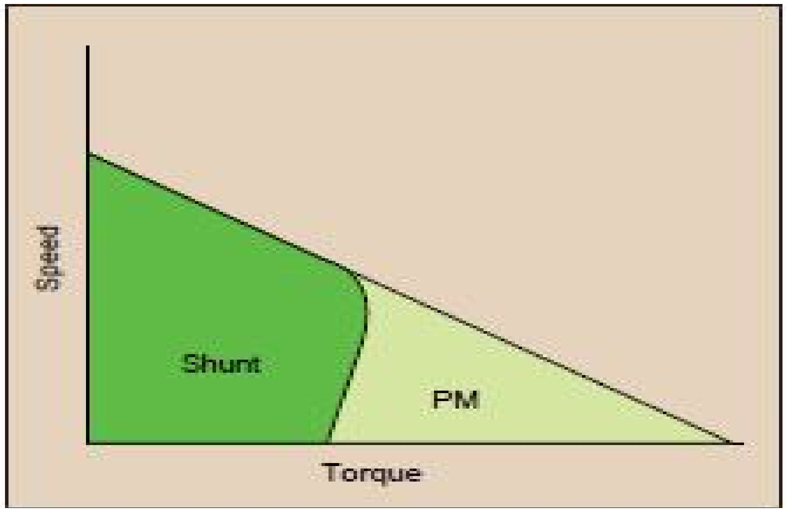


Figure 1: The high reluctance of PMDC motors prevents the torque drop off common with shunt-wound motors.

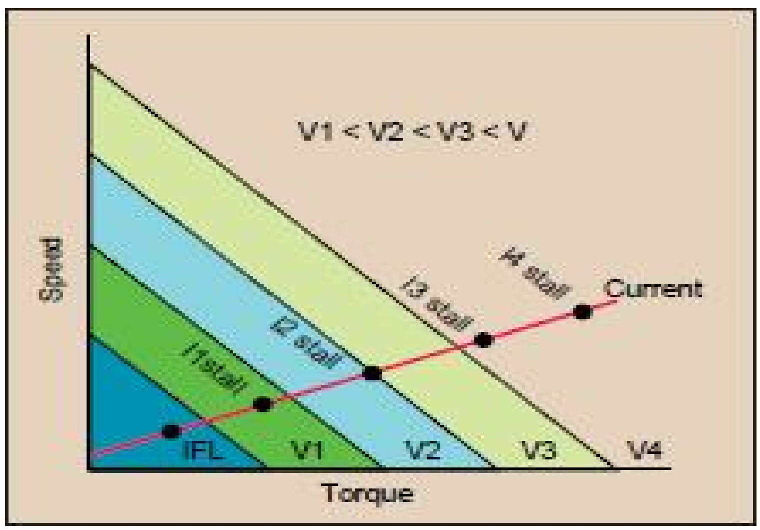


Figure 2: As applied armature voltage increases in a PMDC motor, the linear speed-torque curves shift upwards.

Speed control methods

Speed is controlled by varying the voltage applied to the armature. Feedback devices sense motor speed and send this information to the control to vary its output voltage up or down to keep speed at or near the set value. Feedback techniques include voltage tachometers, optical encoders, electromagnetic pulse generators, and back emf monitoring. Regulation is the ability of the motor and control system to hold speed constant over the torque range. It extends from 0.1% for highly divided (e.g., 1000 div/rev) optical encoders to 5% for a simple back emf system. Most manufacturers provide the servo constant data for predicting system response.

Form factor:

In practice, the voltage used to power a PM motor is not a pure DC. It is derived DC voltage formed by rectifying an AC voltage. Thus, the DC drive voltage has a wave or ripple component that is related to the frequency of the AC input. Form factor, which is the ratio of I_{rms} to I_{dc}, indicates how close the driving voltage is to pure DC. By definition, form factor for a pure DC source, such as a battery, is 1.0. For a power source, the higher the form factor is above 1.0, the more it deviates from pure dc. Table A shows typical form factors for commonly used voltage sources.

Table A—Comparison of driving voltage to pure DC.

Form factor	Dc voltage source
1.0	Battery (pure dc)
1.05	Pulse width modulation (PWM)
1.4	Full wave rectification
1.9	Half wave rectification

Most manufacturers of PMDC motors recommend that form factor not exceed 1.4 for continuous operation. Half wave rectification is also *not* recommended because it increases the form factor.

Driving a motor with a higher form factor control than intended can cause premature brush failure and excessive internal heating. If you use a control with a high form factor, you may need special brushes and commutators, a high temperature insulation system, or a larger motor. It may cost more, but a control that reduces form factor can reduce heating effects in the motor.

Because PM motors lack armature interaction, they can generate high momentary starting and acceleration torques, typically 10 to 12 times full rated torque. Thus, they suit applications requiring high starting torques or momentary bursts of power. However, they are not intended for continuous operation at the high levels of torque they can produce.

This can cause overheating, which can result in non-reversible demagnetization of the field magnets.

A torque (current) limiting function in drive controls limits stall conditions, plug reversing, and current draw, particularly during high torque demand periods, and protects against detrimental overload. (Plug reversing is not recommended because it subjects the armature to higher-than- rated-for voltages). Besides preventing the motor from overheating, a current limiter can help protect driven machinery from excessive motor torques.

Permanent magnets:

A number of magnetic materials are available for permanent magnets. These include ceramic oriented ferrites, rare earth permanent magnets, and Alnico, although Alnico's use is waning. Table B compares these commonly used materials.

Table B —
A comparison of permanent magnet motor materials.

Type	Cost	Resistance to demag	Energy product
Ceramic oriented ferrites	Low	Medium	Low
Samarium cobalt	High	High	High
Neodymium iron boron	High	High	High

Ceramic oriented ferrites, typically made with barium or strontium, develop into products with lower energy than Alnico. Therefore, they have become the material of choice in most PM motors, replacing Alnico, because of their greater resistance to demagnetization, ease of forming, and low cost.

Rare earth magnets may let engineers choose a downsized PM motor, or boost its power rating. They include samarium-cobalt and the more recently developed neodymium-iron-boron. Their characteristics, compared to the previously mentioned materials, include high energy and low susceptibility to demagnetization.
The cost of these materials, however, remains high The choice of material depends on the application requirements. The motor manufacturer can provide selection assistance.

Brushes:

PMDC motors use a mechanical commutation scheme to switch current to the armature winding. Commutator bars connect to the armature windings. A pair of spring loaded brushes makes mechanical contact with the commutator bars, carrying the current to the armature. Thus, the brushes link the power source to the armature field windings. The armature commutator and the brushes act as a rotary switch for energizing the windings. Design and selection of brushes tend to be something of a black art. The ideal brush offers low voltage loss, negligible dust formation, no arcing, little commutator wear, and generates little noise. In many cases, these requirements are contradictory, forcing a compromise in brush selection.

At low applied voltage, the voltage drop across the brushes is the prime consideration in brush selection. At higher voltages, the voltage drop in the brush is less important. Other parameters, such as operating speed, abrasiveness, lubricity and cost, become dominant. Commonly used brush materials include carbon and carbon graphite, graphite, electro-graphitic, and metal-graphite. Table C compares these brush materials.

Table C — A comparison of motor brush materials.

Type	Voltage drop	Current capacity	Usage limitations
Carbon, carbon-graphite	High	Low	High Voltage Low speed Fractional hp only
Graphite (natural)	Medium	Medium	Medium speed/high voltage
Electro-graphitic	Medium	High	Medium to high speed/Medium to high voltage
Copper graphite	Low	Low	Low voltage/Low speeds
Silver graphite	Very low	Very low	Very low voltage/lLow speeds

Metal graphite brushes consist of a mixture of copper or silver with graphite. They have low voltage loss and high wear rate, limiting their usage to low speed, low-voltage motors.

Carbon and carbon-graphite brushes have low current capacity, a relatively high voltage drop across the brush, and tend to be abrasive. These properties limit their use to low speed, high voltage, and fractional horsepower motor applications

Electro-graphitic brushes use a form of graphite developed from carbon subjected to intense heat. They have high current capacity, a relatively moderate voltage drop, and low abrasive properties. They handle high-speed, high-voltage and high-power motor applications.

Natural graphite brushes have a slightly lower current capacity than electro- graphitic brushes. They tend to have greater polishing action than electro-graphitics, low friction characteristics, and an inherent softness. They fit applications where high-speed operation and quietness are critical. However, their softness, which accounts for their quiet operation, also gives them a limited brush life.

Other factors also affect brush life and performance, including temperature, humidity, altitude, spring pressure, control form factor, size and duty cycle.

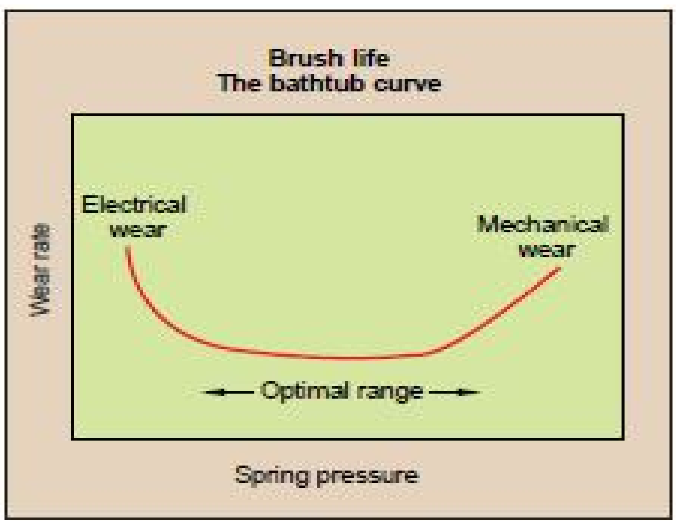
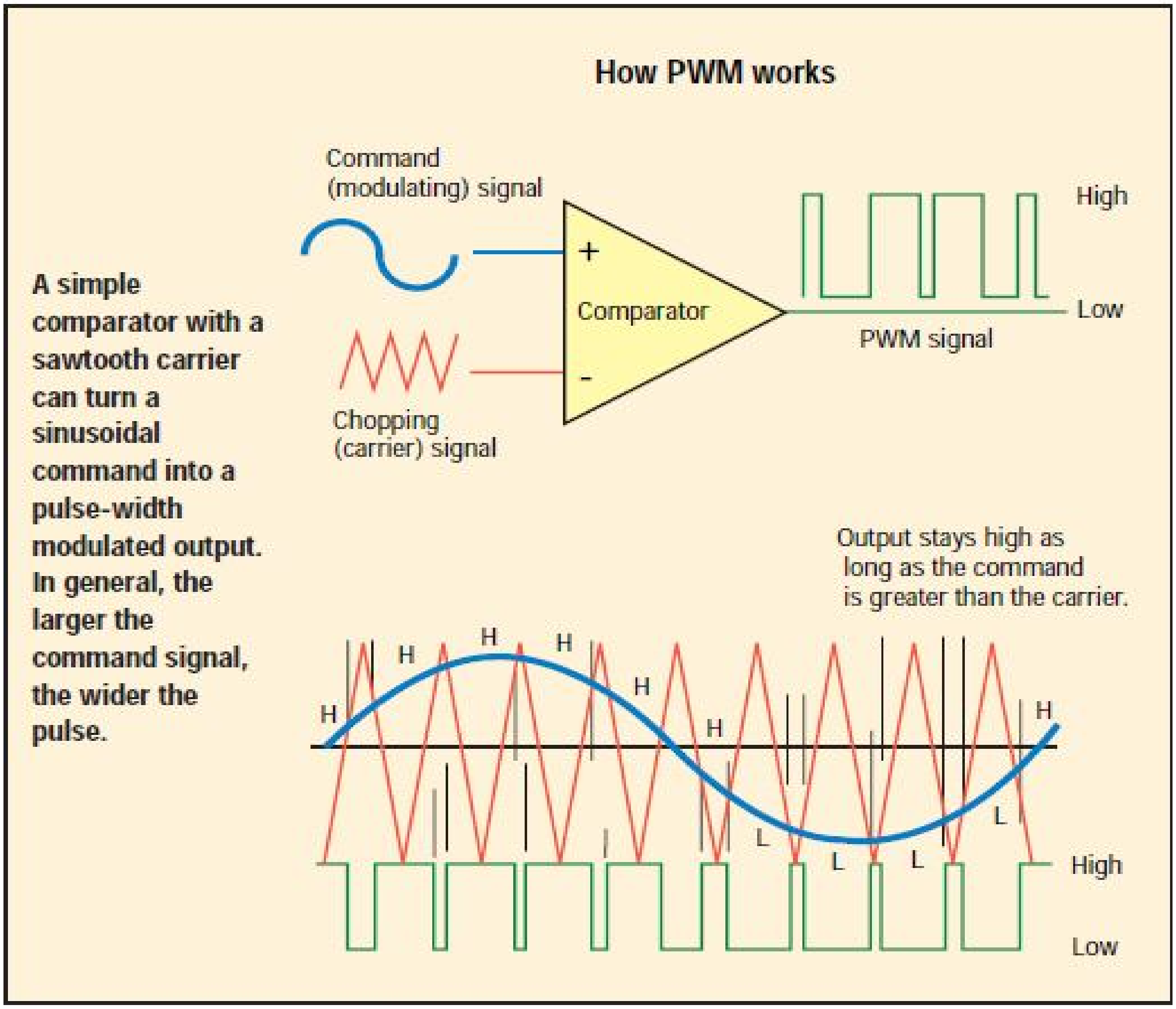


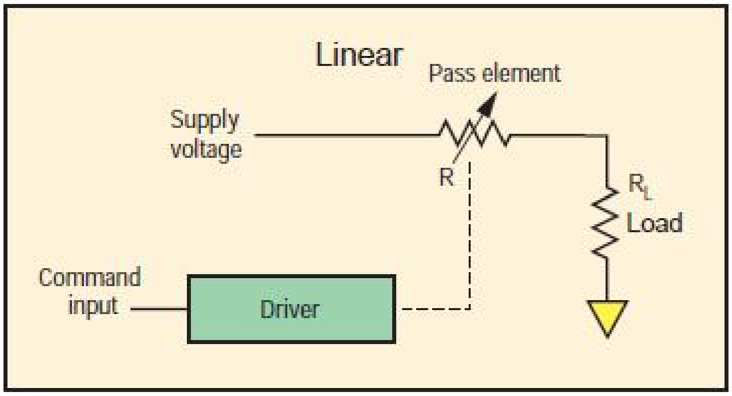
Figure: Too little spring pressure on brushes can result in excessive electrical wear. Too much pressure can result in excessive mechanical wear. Optimal spring pressure is between these regions.

Pulse width Modulation:

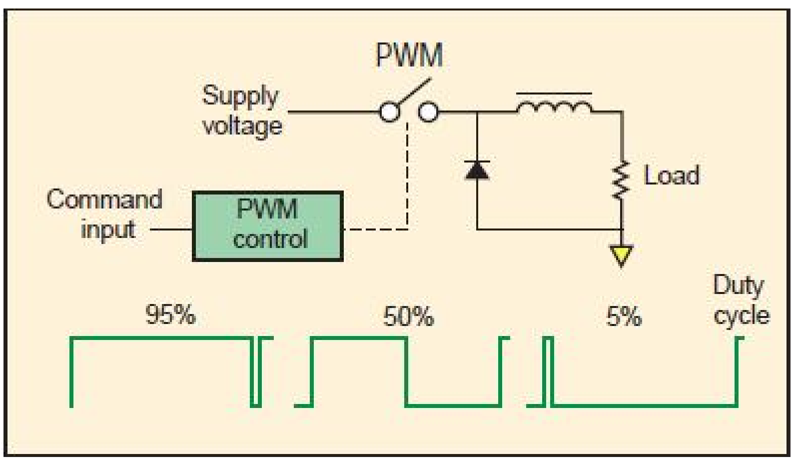
Pulse-width modulation (PWM), as it applies to motor control, is a way of delivering energy through a succession of pulses rather than a continuously varying (analog) signal. By increasing or decreasing pulse width, the controller regulates energy flow to the motor shaft. The motor's own inductance acts like a filter, storing energy during the "on" cycle while releasing it at a rate corresponding to the input or reference signal. In other words, energy flows into the load not so much the switching frequency, but at the reference frequency.

PWM is somewhat like pushing a playground-style merry-go-round. The energy of each push is stored in the inertia of the heavy platform, which accelerates gradually with harder, more frequent, or longer-lasting pushes. The riders receive the kinetic energy in a very different manner than how it's applied.





Linear amplifiers vary the resistance of a pass element to regulate power. Efficiency is fine at the extremes — losses are minimal when R = 0 or ° — but suffers elsewhere, bottoming out at midrange (R = RL) where the amount of energy wasted as heat in the amplifier equals that delivered to the load.

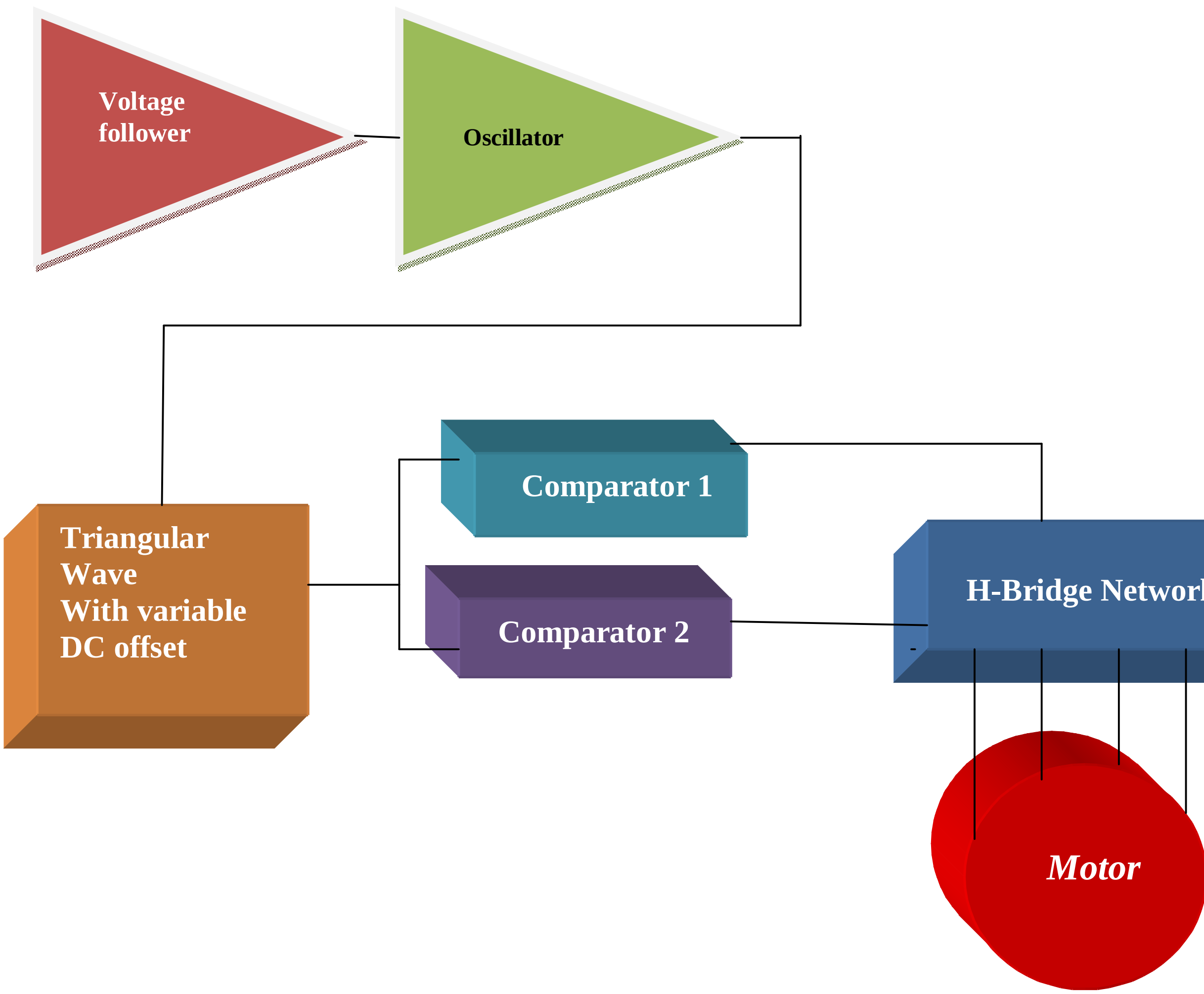


The output of a PWM amplifier is either zero or tied to the supply voltage, holding losses to a minimum. As the duty cycle changes to deliver more or less power, efficiency remains essentially constant.

Design ConsiDer a tions:

To design bi-directional dc motor speed controller we did not use any special purpose ICs. Although motor speed-controller ICs are commercially available, we decided to use components which are of general purpose. Our objective was to implement our circuit firstly from theoretical point of view. Hence, our circuit needed more components then commercially available packages.

Bl ock Diag r am:



CirCuit design:

Parts List:

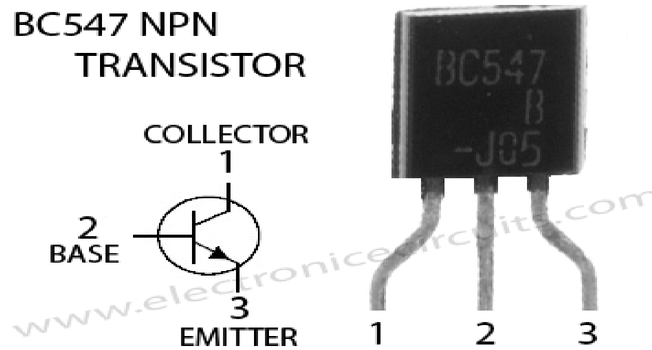
Resistors (0.25W carbon film unless specified)

100R............................... R15.................................... 1
4K7................................. R9,14 2
10K................................. R2,7,10,11,12,13 6
12K................................. R8...................................... 1
33K................................. R6...................................... 1
47K................................. R3...................................... 1
100K............................... R1...................................... 1
220K............................... R4...................................... 1
470K............................... R5...................................... 1
100K potentiometer.......... P1 1

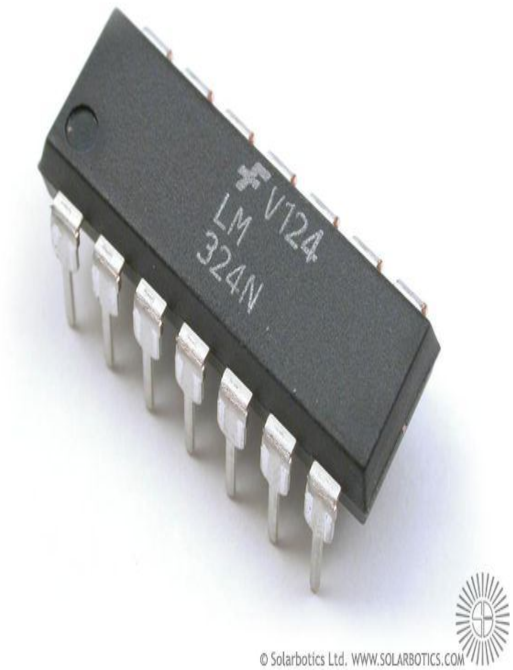
Capacitors

10nF 63V box poly C1 1
100nF mono, 0.1” .... C3...................................... 1
100uF 63V electrolytic..... C2 1
Semiconductors

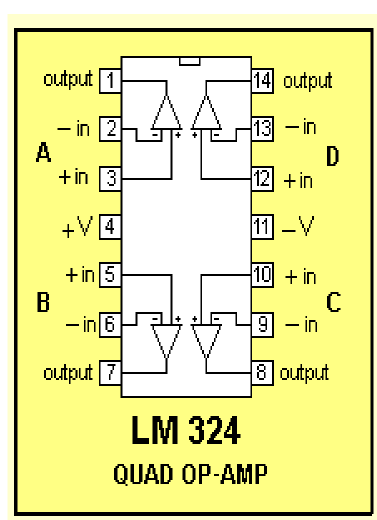
1N4004............................ D3...................................... 1
1N4148............................ D1,2................................... 2
BC547 transistor .... Q1,2................................... 4
IRF4905 .... Q3,5................................... 2
N-channel Power MOSFET
LM324............................. IC1..................................... 1

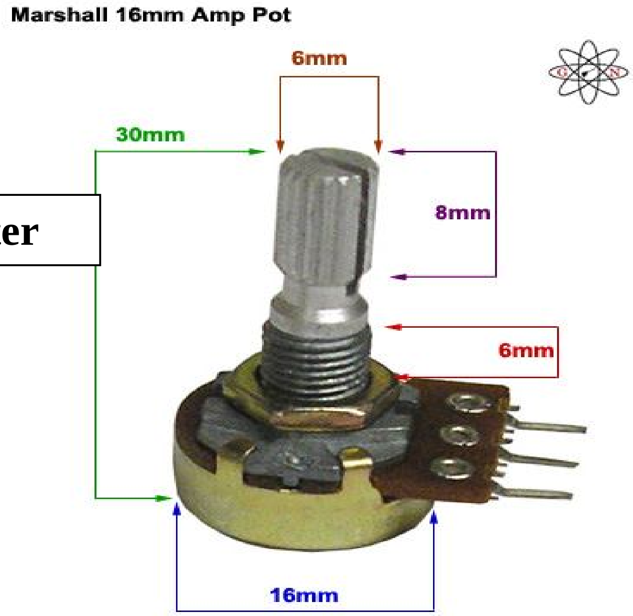


BJT BC547



Quad Op-Amp
LM324

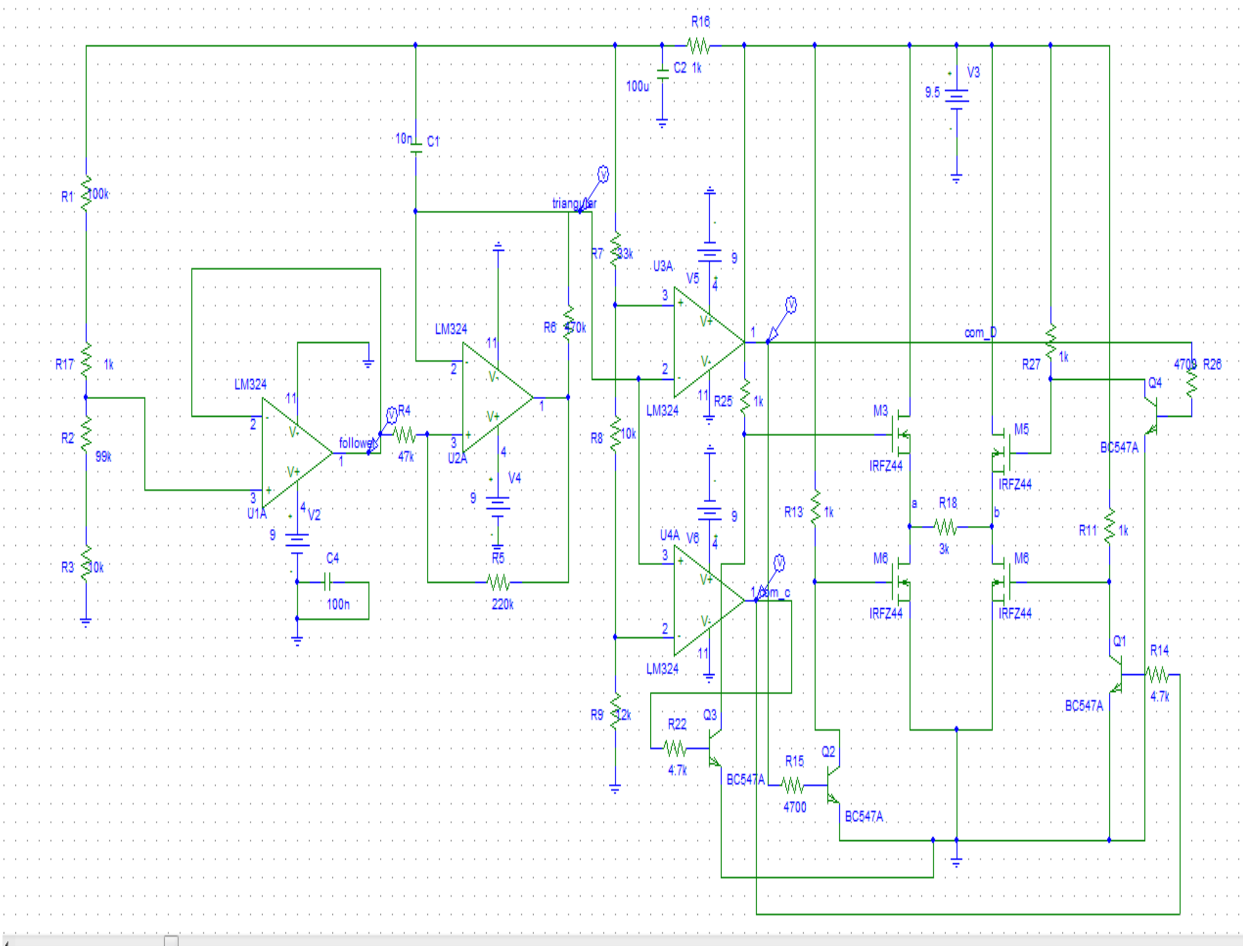




Potentiometer

MOSFET IRFZ44

CirCuit Diagram:



CirCuit OperatiOn:

The operation of this circuit is quite simple and interesting. Let's start from the motor drive section. As we are controlling DC motor, its direction of rotation depends on the direction of current flow. And the current flow is determined by 4 MOSFET's. Only two of these MOSFETs are on at any one time. When M3 and M6 are ON then current flows through the motor and it spins in one direction. When M4 and M5 are ON the current flow is reversed and the motor spins in the opposite direction. But who controls the fact that which motor will be ON and OFF. This is determined by the two comparator **circuit** C and D. Op-amps IC1: C and IC1: D are configured as voltage Comparators. The reference voltage that each triggers at is derived from the resistor voltage divider of R6, R7 and R8. Note that the reference voltage for IC1: D is connected to the '+' input but for IC1:C it is connected to the '-' input. Therefore IC1: D is triggered by a voltage greater than its reference whereas IC1: C is triggered by a voltage less than its reference.

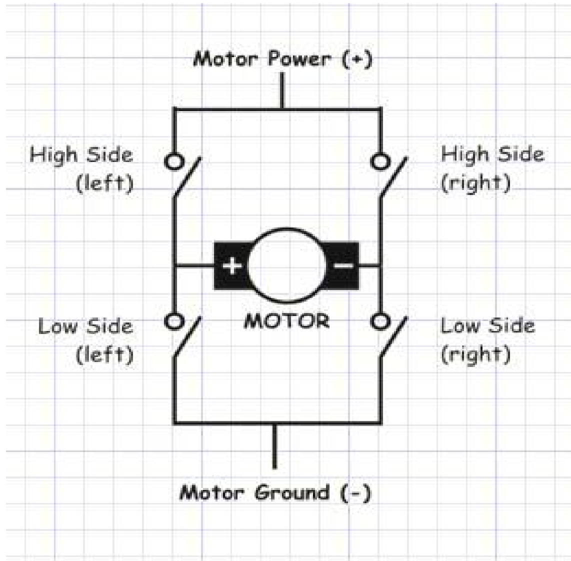
The peak-to-peak output level of the triangle wave is less than the difference between the two voltage references. Therefore it is impossible for both comparators to be triggered simultaneously. Otherwise all four MOSFETs would conduct, causing a short circuit that would destroy them.

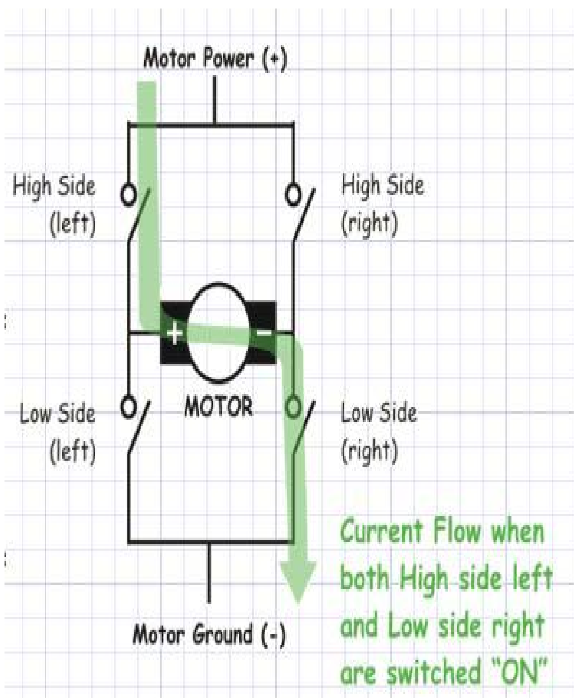
Now the question comes to mind that who provides the trigger signal and how? Op-Amp IC1: B does this. Op-amp IC1: B is set up as a triangle wave generator and provides the trigger signal for the voltage comparators.

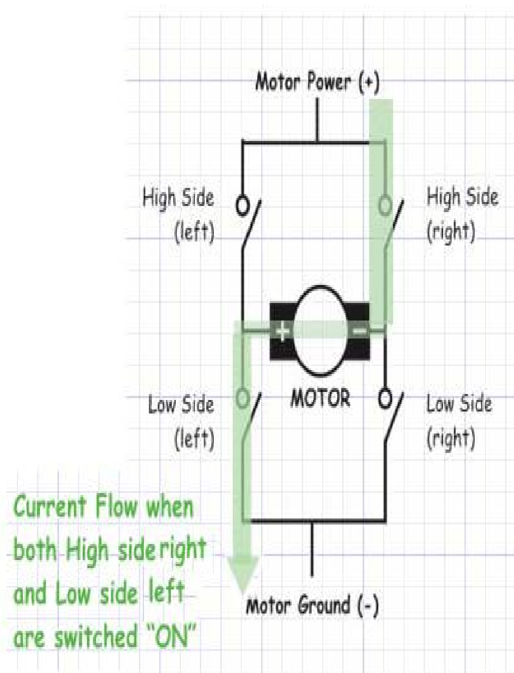
The triangle waveform is centered on a DC offset voltage. Raising or lowering the offset voltage changes the DC position of the triangle wave accordingly. Shifting the triangle wave up causes comparator IC1:D to trigger; lowering it causes comparator IC1:C to trigger. When the voltage level of the triangle wave is between the two voltage references then neither comparator is triggered. The DC offset voltage is controlled by the potentiometer P1 via IC1: A, which is configured as a voltage follower. This provides a low output impedance voltage source, making the DC offset voltage less susceptible to the loading effect of IC1:B. As the 'pot' is turned the DC offset voltage changes, either up or down depending on the direction the pot is turned.

The Role of BJT in our Design:

When one comparator triggers a pulse, the other comparator gives a DC value of 9 volts (supply). This output voltages are passed into 4 NPN BJT's, two connected with each comparator. As we know if we give High (1) to base of BJT, we get Low (0) at collector. The collectors are further connected to MOSFET H-bridge circuit. The interesting thing about our circuit is we used only n-channel MOSFETs. When comparator generates 9 volts, BJTs connected to it gets high at base, so their collector voltage gets low. Hence, the MOSFETs connected to their collectors remains off as their gate voltage is 0. The other two MOSFETs generate pulse as obvious from the circuit.


Motor Power (+)
High Side
(left)
High Side
(right)
+
−
MOTOR
Low Side
(left)
Low Side
(right)
Motor Ground (-)


Motor Power (+)
High Side
(left)
High Side
(right)
+
−
MOTOR
Low Side
(left)
Low Side
(right)
Motor Ground (-)
Current Flow when
both High side left
and Low side right
are switched "ON"


Motor Power (+)
High Side
(left)
High Side
(right)
+
−
MOTOR
Low Side
(left)
Low Side
(right)
Current Flow when
both High side right
and Low side left
are switched "ON"
Motor Ground (-)

Final assembly:

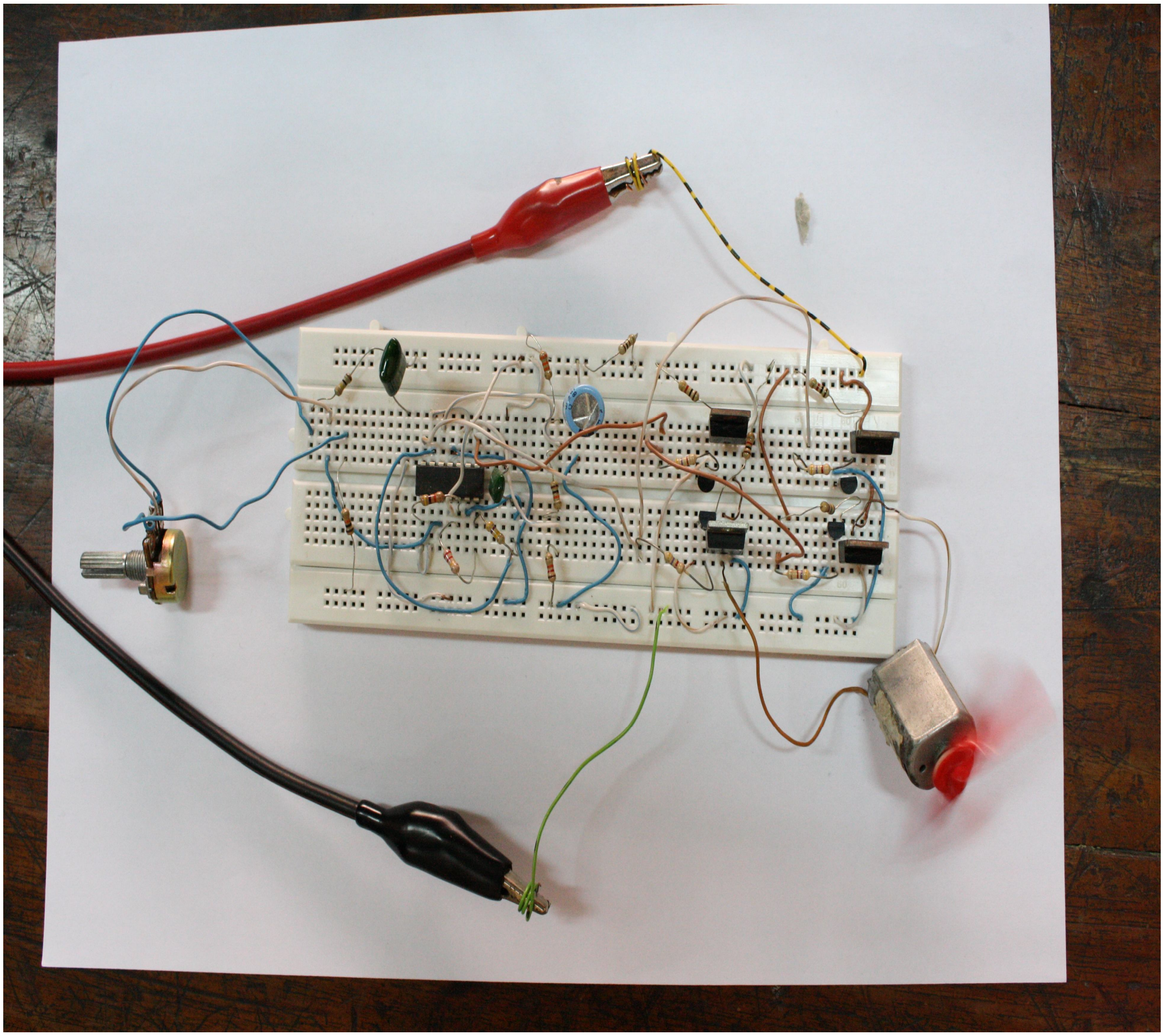


Figure: Final assembly of the circuit

Cost AnAlysis:

Here, Costs of some Bidirectional DC Motor Speed Controllers from renowned companies are given —

→ **PAiA Corporation USA** offers **$ 25.65**(equivalent to **1745 Tk.**) for their ***K166 Bidirectional DC Motor Speed Controller***
(Reference: http://www.paia.com/proddetail.asp?prod=K166)

→ **Hobby Engineering** offers **$ 25.00**(equivalent to **1700 Tk.**) for their ***Bidirectional DC Motor Speed Controller Electronic Kit***
(Stock No *H01742-01Z*)
(Reference: http://www.hobbyengineering.com/H1742.html)

Now, let's see how much cost we have needed to prepare our **Bidirectional Motor Controller**.

Cost Chart:

NO	EQUIPMENT(S)	MODEL NO	COST (Tk.)
1.	Quad Op-Amp (1)	LM324	**15.00**
2.	MOSFET (4)	IRFZ44	30 × 4 = **120.00**
3.	Bipolar Junction Transistor (4)	BC547	3.75 × 4 = **15.00**
4.	Potentiometer (1)	—	**20.00**
5.	Resistors + Capacitors + Connecting Wire	—	**50.00**
6.	Breadboard or PCB Board (1)	—	**60.00 – 150.00**
7.	Packaging	—	**30.00**
8.	Others	—	**100.00**
TOTAL COST			**410.00 – 500.00 Tk.**

So, from the above chart, we can conclude that we can supply you a Quality Bidirectional DC Motor Controller in almost **ONE-THIRD COST!!!**

APPLICATION:

Industry:

Small DC motors are designed for use in industrial and commercial of applications such as the following typical industries:

1. Business Machines
2. Systems & Gear Drives
3. Material Handling — Conveyors
4. Elevator Door Operators
5. Pumps & Blowers
6. Adjustable Speed Drives
7. Machine Tools
8. Agitators & Mixers

Efficient DC Motor Controller is a must in these sectors.
In this circumstance, our DC Motor Controller Design can be a splendid choice. Also, it is a Bidirectional speed controller adding more reasons to be chosen.

Experimental Purpose:

Now, come to the second point — In *Experimental* & *Laboratory Purposes*. Our DC Motor Controller can be a great helping hand in project & experiments.
One can easily use this controller CKT as a suitable means instead of those found in markets, as it is simple, easily understandable & above all, cheaper in cost.
Also, it'll be time & labor preserving in any laboratory purpose to get a fully prepared controlling CKT rather than to build one.

Robotics:

Robotics brings together very different engineering areas and skills like —
→ *Metalworking* for the body
→ *Mechanics* for mounting the wheels on the axles, connecting them to the motors keeping the body in balance.
→ *Electronics* to power the motors & connect the sensors to the controllers.
→ *Programming* to drive the ROBOT

In robotics, the use of DC Motors is very much common & widespread.
The reason behind that is — DC Motors are very easy to use, although like most other motors their usefulness for robotics is very dependent on the gearing available.
Also, here in Robotics, the Bidirectional Control of DC Motors is essential.
In this extent, an efficient Bidirectional Motor Controller CKT like Ours can become an elegant choice, as it has all the necessities fulfilled.
Our CKT is capable of controlling a small DC Motor of *Voltage Rating* of **5-–32 V** & Maximum Current Rating of **5 Amp**, ultimately Rated for a — *Maximum* **160 W** motor.
Now, the most common DC motors used in making a Robot is a **12–24 V** DC motor which makes our CKT a perfect match in this case.

ConClusion:

In our project we have successfully implemented the PWM technique for the bi-directional speed control of PMDC motors. The complications we faced were-

- Unavailability of Desired motor
- Low quality equipments in local market
- Lack of technical experience

Even though all this difficulties, we rose to the occasion and improvised our preliminary design to implement our goal. With our design we can control the speed of PMDC motors with ratings 5-32 Volts with maximum current of 5 amperes resulting into maximum power rating of 160 watts. Our project is of high practical value in the field of robotics and electric vehicle industry.

Our future plan includes the improvement of motor performance control techniques using power electronics. We wish to apply our ideas and projects into the commercial arena.

ReFeRences:

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