TTE Training Ltd.

Phase 2

Electrical Course Notes

E2-CN-012

DC Motors Basics

&

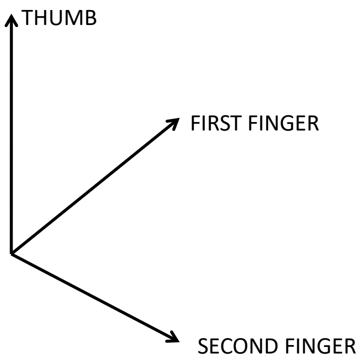
Speed Control

DC Motors Theory Basics

1. Understanding Flemings' Right Rule and Left-Hand Rule

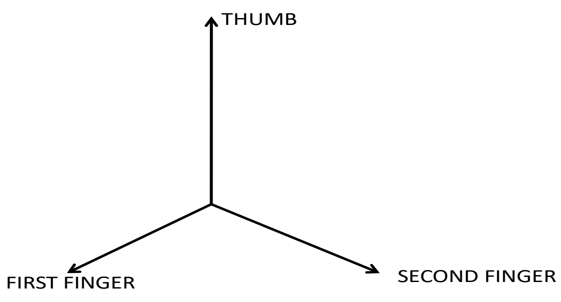
2. Remember that the 'g' in Right stands for Generator so the Left-Hand Rule is for Motors

Left Hand Rule – MOTOR *(electrical energy to mechanical energy)*

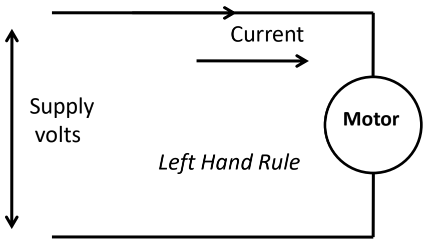


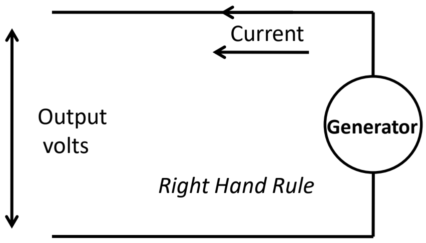
THUMB = MOTION *i.e. direction motor is turning*
FIRST FINGER = F Field i.e. direction of magnetic field
North Pole → *South Pole*
South Pole ← *North Pole*
SECOND FINGER = C + Current i.e. direction current is flowing

Right Hand Rule – GENERATOR *(mechanical energy to electrical energy)*

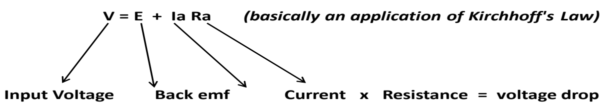


Comparison of the Right-Hand Rule and Left Rule shows that the only difference is the direction of current. The direction of the Magnetic Field the direction of Motion is both the same. Current however flows IN to the Motor and OUT of the Generator.





In the case of a DC Motor when we connect it to a DC supply voltage (V), current (I_a) will flow into it. The current flows into the motor coils and creates a back e.m.f (E_b). The back e.m.f (E_b) will always be a bit less than the supply voltage; this is because some voltage is lost due to the resistance of the coils (R_a) the 'a' in R_a and I_a is an abbreviation of 'Armature' – what we called the Rotor in AC motors.



In the case of a DC Generator, current flows out of the generator. When the generator is run up a Back e.m.f. is created but some of this voltage is lost due to the resistance of the generator coils, so the output voltage is less than the back e.m.f. So, the only difference between these two equations is the polarity of the current I_a.

$V = E - I_a R_a$ *(basically an application of Kirchhoff's Law)*

Output Voltage **Back emf** **Current x Resistance = voltage drop**

DC Motor Overview

The DC motor has two basic parts: the rotating part that is called the Armature and the stationary part that includes coils of wire called the 'Field'– what we called the Stator in AC motors. Figure 1 shows a picture of a typical DC motor, Fig 2 shows a picture of a DC Armature, and Fig 3 shows a picture of a typical stator. From the picture in Fig 2 you can see the Armature is made of coils of wire wrapped around the core, and the core has an extended shaft that rotates on bearings. You should also notice that the ends of each coil of wire on the Armature are terminated at one end of the Armature. The termination points are called the Commutator, and this is where the brushes make electrical contact to bring electrical current from the stationary part to the rotating part of the machine.

The picture in Fig 3 shows the location of the coils that are mounted inside the stator. These coils will be referred to as Field coils in future discussions and they may be connected in series or parallel with each other to create changes to torque in the motor. You will find the size of wire in these coils and the number of turns of wire in the coil will depend on the effect that is trying to be achieved.

FIGURE 1: A typical DC motor

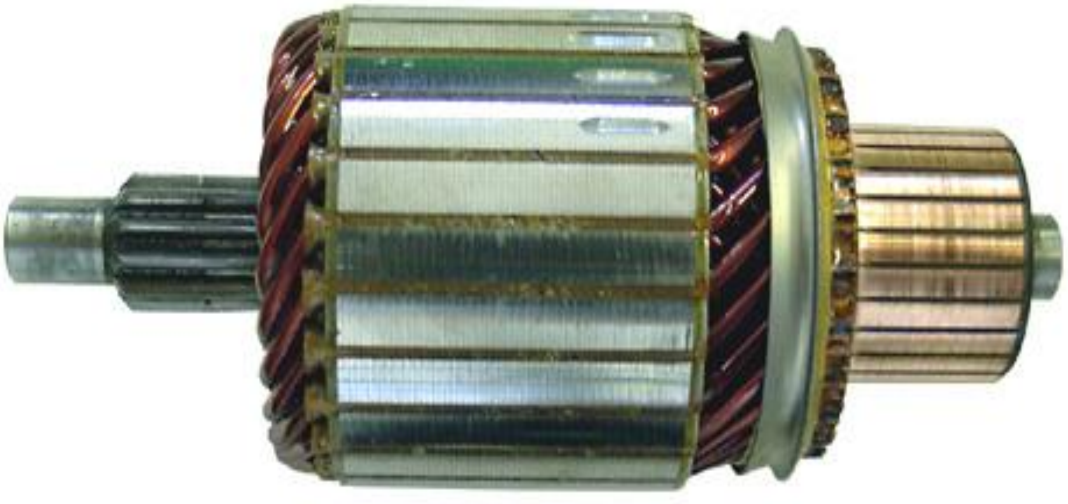


FIGURE 2: Typical Armature

The Armature (rotor) of a DC motor has coils of wire wrapped around its core. The ends of each coil are terminated at Commutator segments located on the end of the shaft. The brushes make contact on the Commutator to provide current for the Armature.

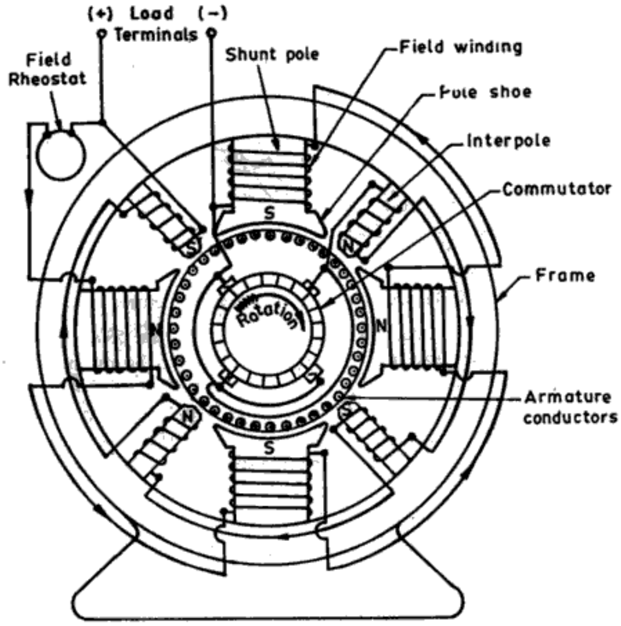


FIGURE 3: the stationary part of a DC motor has the Field coils mounted in it

Magnetic Diagram of a DC Motor

It will be easier to understand the operation of the DC motor from a basic diagram that shows the magnetic interaction between the rotating Armature and the stationary Field's coils. Figure 4 shows three diagrams that explain the DC Motor's operation in terms of the magnetic interaction. In Fig 4 you can see that a bar magnet has been mounted on a shaft so that it can spin. The Field winding is one long coil of wire that has been separated into two sections. The top section is connected to the positive pole of the battery and the bottom section is connected to the negative pole of the battery. It is important to understand that the battery represents a source of voltage for this winding. In the actual industrial type of motor this voltage will come from the DC voltage source for the motor. The current flow in this direction makes the top coil the north pole of the magnet and the bottom coil the south pole of the magnet.

The bar magnet represents the Armature, and the coil of wire represents the Field. The arrow shows the direction of the Armature's rotation. Notice that the arrow shows the Armature starting to rotate in the clockwise direction. The north pole of the Field coil is repelling the north pole of the Armature, and the south pole of the Field coil is repelling the south pole of the Armature.

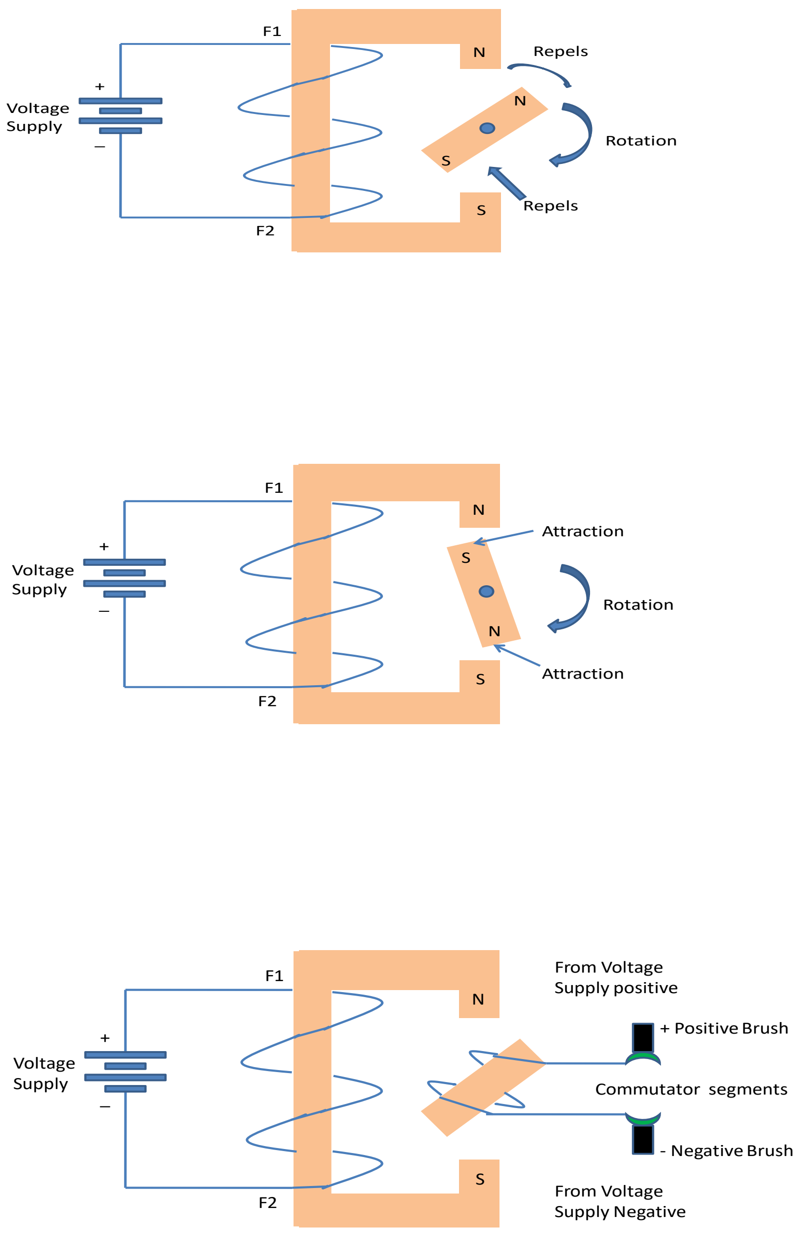


FIGURE 4: Magnetic diagram that explains the operation of a DC motor.

Initially in diagram 1 the rotating magnet moves clockwise because like poles repel, in the next diagram the rotating magnet is attracted because the poles are opposite. In the third diagram the rotating magnet is now shown as the Armature coil, and its polarity is determined by the brushes and Commutator segments.

As the Armature begins to move, the North Pole of the Armature comes closer to the south pole of the Field and the south pole of the Armature is coming closer to the north pole of the Field. As the two unlike poles near each other, they begin to attract. This attraction becomes stronger until the Armature's North Pole moves directly in line with the Fields South Pole, and its South Pole moves directly in line with the Fields North Pole.

When the opposite poles are at their strongest attraction, the Armature will be ‘locked up’ and will resist further attempts to continue spinning. For the Armature to continue its rotation, the Armatures polarity must be switched. Since the Armature in this diagram is a permanent magnet, you can see that it would lock up during your first rotation and not work. If the Armature is an electromagnet, its polarity can be changed by changing the direction of current flow through it. For this reason, the Armature must be changed to a coil (electromagnet) and a set of Commutator segments must be added to provide a means of making contact between the rotating member and the stationary member. One Commutator segment is provided for each terminal of the magnetic coil. Since this Armature has only one coil, it will have only two terminals, so the Commutator has two segments.

Since the Armature is now a coil of wire it will need DC current flowing through it to become magnetized. This presents another problem; since the Armature will be rotating, the DC voltage wires cannot be contacted directly to the Armature coil. A stationary set of carbon brushes is used to make contact to the rotating Armature. The brushes ride on the Commutator segments to make contact so that current will flow through the Armature coil.

In the last diagram you can see the voltage is applied to the Field and the brushes. Since negative DC voltage is connected to one of the brushes, the Commutator segment the negative brush rides on will also be negative. The Armatures magnetic Field causes the Armature to begin to rotate. This time when the Armature gets to the point where it becomes locked up with the magnetic Field, the negative brush begins to touch the end of the Armature coil that was previously positive, and the positive brush begins to touch the end of the Armature coil that was negative. This action switches the direction of current flow through the Armature, which also switches the polarity of the Armature coils magnetic Field at just the right time so that the repelling and attracting continues. The Armature continues to switch its magnetic polarity twice during each rotation, which causes it to continually be attracted and repelled with the Field poles.

Series Motor

The Series motor provides high starting torque and is able to move very large shaft loads when it is first energized. Figure 5 shows the circuit diagram of a Series motor. From the diagram you can see that the Field winding in this motor is wired in series with the Armature winding. This is the attribute that gives the series motor its name.

Since the series Field winding is connected in series with the Armature, it will carry the same amount of current that passes through the Armature. For this reason, the Field is made from heavy-gauge wire that is large enough to carry the load. Since the wire gauge is so large, the winding will have only a few turns of wire. In some larger DC motors, the Field winding is made from copper bar stock rather than the conventional round wire used for power distribution.

The square or rectangular shape of the copper bar stock makes it fit more easily around the Field pole pieces. It can also radiate more easily the heat that has built up in the winding due to the large amount of current being carried.

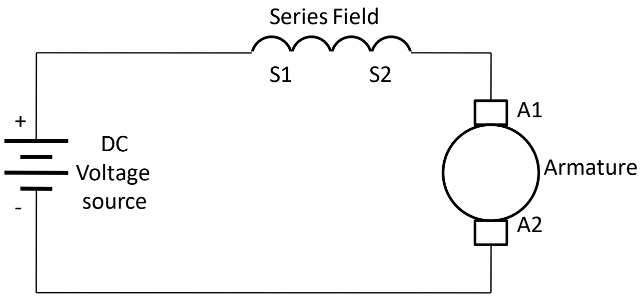


FIGURE 5: Electrical diagram of a Series motor

Notice that the series Field is now identified as S1 and S2.

The amount of current that passes through the winding determines the amount of torque the motor shaft can produce. Since the series Field is made of large conductors, it can carry large amounts of current and produce large torques. For example, the starter motor that is used to start an automobile's engine is a series motor and it may draw up to 500 A when it is turning the engines crankshaft on a cold morning. Series motors can be used to power for example hoists or cranes and railway traction motors and may draw currents of thousands of amperes during operation.

Series Motor Operation

Referring to Fig. 5 the Field winding is connected in series with Armature winding. This means that power will be applied to one end of the series Field winding and to one end of Armature winding (connected at a brush).

When voltage is applied, current begins to flow from positive power supply terminals through the series winding and Armature winding and return back to the supply. The Armature is not rotating when voltage is first applied, and the only resistance in this circuit will be provided by the large conductors used in the Armature and Field windings. Since these conductors are so large, they will only have a small amount of resistance. This causes the motor to draw a large amount of current from the power supply. When the large current begins to flow through the Field and Armature windings, it causes a strong magnetic field to be built. Since the current is so large, it will cause the coils to reach saturation, which will produce the strongest magnetic field possible.

Producing Back EMF

The strength of these magnetic fields provides the Armature shafts with the greatest amount of torque possible. The large torque causes the Armature to begin to spin with the maximum amount of power. When the Armature begins to rotate, it begins to produce voltage i.e., the back e.m.f.

When the Armature begins to rotate, it will produce a voltage that is of opposite polarity to that of the power supply. The faster the Armature coil passes the stationary magnetic flux lines from the series Field winding then the larger the back e.m.f. will be. This voltage is called the back EMF (electro-motive force).

Going back to the basic motor formulae $V = E_b + I_a R_a$

As the back e.m.f, (E_b), increases then current I_a will decrease as V is the fixed supply voltage and R_a the Armature resistance. This means that the series motor will see less current as its speed is increased, which will happen when there is only a small mechanical load on the motor, this reduced current will mean that the motor will continue to lose torque as the motor speed increases.

Figure 6 shows the relationship between Series motor speed and Armature current. From this curve you can see that when current is low (at the top left), the motor speed is maximum, and when current increases, the motor speed slows down (bottom right). You can also see from this curve that a DC motor will run away if the load current is reduced to zero.

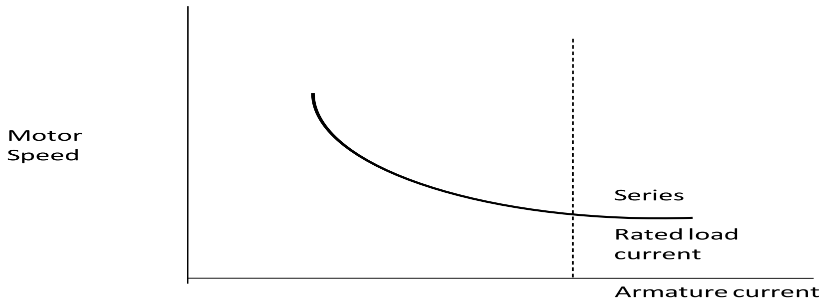


Fig 6: Speed / Armature current characteristic for Series Motor

Shunt Motor

The shunt motor is different from the series motor in that the Field winding is connected in parallel with the Armature instead of in series. (Shunt is an old-fashioned term meaning parallel). Since the Field winding is placed in parallel with the Armature, it is called a shunt winding and the motor is called a Shunt motor. Figure 7 shows a diagram of a shunt motor. When compared to the series Field winding, the shunt Field is made up of a lot more turns of thinner wire.

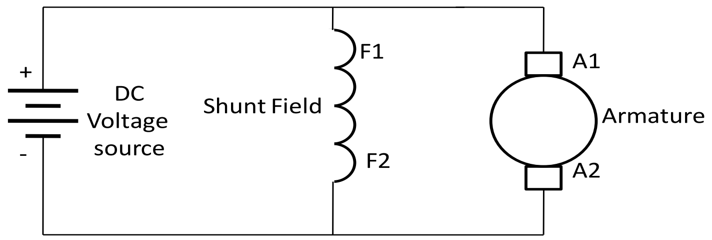


FIG 7: Diagram of a DC shunt motor

The shunt winding is made of small-gauge wire with many turns on the coil. Since the wire diameter is small, the coil can have many turns and still fit in the slots. The small-gauge wire cannot handle as much current as the heavy-gauge wire in the series Field, but since this coil has many more turns of wire, it can still produce a very strong magnetic Field.

Shunt Motor Operation

A Shunt motor has slightly different operating characteristics than a Series motor. Since the Shunt Field coil is made of fine wire, it cannot produce the large current for starting like the series Field. This means that the shunt motor has very low starting torque, which requires that the shaft load be rather small.

When voltage is applied to the motor, the high resistance of the shunt coil keeps the overall current flow low. The Armature for the shunt motor is similar to the series motor and it will draw current to produce a magnetic Field strong enough to cause the Armature shaft and load to start turning. Like the series motor, when the Armature begins to turn, it will produce back EMF.

The back EMF will cause the current in the Armature to begin to diminish to a very small level, following the basic motor formula $V = E_b + I_a R_a$.
The amount of current the Armature will draw is directly related to the size of the load when the motor reaches full speed. Since the load is generally small the Armature current will be small, so when the motor reaches full rpm, its speed will remain fairly constant.

Controlling the Speed

When the shunt motor reaches full rpm, its speed will remain fairly constant. The speed of a series motor could not be controlled since it was totally dependent on the size of the load in comparison to the size of the motor. If the load was very large for the motor size, the speed of the Armature would be very slow. If the load was light compared to the motor, the Armature shaft speed would be much faster, and if no load was present on the shaft, the motor could run away.

The Shunt motor's speed can be controlled and the motor's ability to maintain a set rpm at high speed when the load changes, is due to the characteristic of the shunt Field and Armature.

Since the Armature begins to produce back EMF as soon as it starts to rotate, it will use the back EMF to maintain its rpm at high speed. If the load increases slightly and causes the Armature shaft to slow down, less back EMF will be produced. This will allow the difference (i.e., potential difference – Pd) between the back EMF and applied voltage to become larger, which will cause more current (I_a) to flow.

Again, following the basic motor formula $V = E + Ia\ Ra$. The extra current (I_a) provides the motor with the extra torque required to regain its rpm from the load having increased. This increase in speed causes the back e.m.f. (E) to return to its original level and hence reduce I_a.

The Shunt motor's speed can be varied in two different ways. These include varying the amount of current supplied to the shunt Field and controlling the amount of voltage supplied to the Armature. Controlling the current to the shunt Field allows the rpm to be changed 10-20% when the motor is at full rpm.

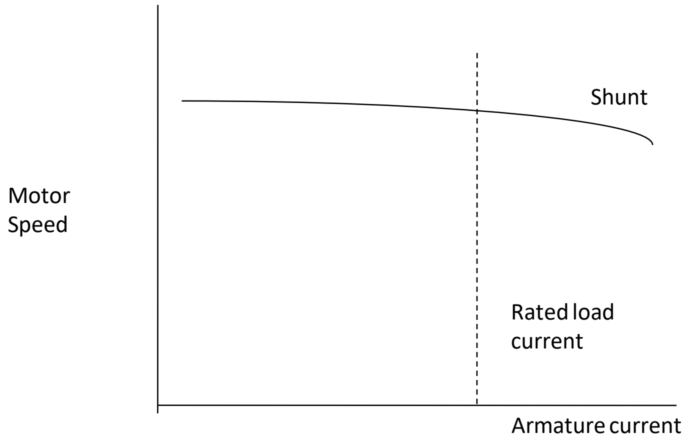


FIGURE 8: graph that shows the Armature current versus the Armature speed for a shunt motor.

Notice that the speed of a shunt motor is nearly constant**.**

The Armature continues to have full voltage applied to it while the current to the shunt Field is regulated. When the shunt Field's current is increased, the motor's rpm will increase slightly. When the shunt Field's current is reduced, the Armature can rotate at a slower rpm and maintain the amount of back EMF to produce the Armature current to drive the load. The Field current can be adjusted with a Field rheostat – (on older control systems) or by use of SCR current control in series with the Field coil on modern systems.

The Shunt motor's rpm can also be controlled by regulating the voltage that is applied to the motor Armature. This means that as the motor is operated on less voltage than is shown on its data plate rating, it will run less than full rpm. However, the shunt motor's efficiency will drop off drastically when it is operated below full voltage, so motor ventilation must be provided to reduce any excess heat generated. The motor's torque is reduced when it is operated below the full voltage level. Although rheostats can again be used to control the Armature current, SCR control will be used on more modern control systems.

Compound Motors

Overview

The DC Compound motor is a combination of the series motor and the shunt motor. It has a series Field winding that is connected in series with the Armature and a shunt Field that is in parallel with the Armature. The combination of series and shunt winding allows the motor to have the torque characteristics of the series motor and the regulated speed characteristics of the shunt motor. Figure 9 shows a diagram of the compound motor. Several versions of the compound motor are also shown in this diagram.

Cumulative Compound Motors

Figure 9a shows a diagram of the Cumulative Compound motor. It is so called because the shunt Field is connected so that its coils are aiding the magnetic Fields of the series Field and Armature. The shunt winding can be wired as a long shunt or as a short shunt. Figure 9a and figure 9b show the motor connected as a short shunt where the shunt Field is connected in parallel with only the Armature. Figure 9c shows the motor connected as a long shunt where the shunt Field is connected in parallel with the series Field the Interpole’s and the Armature.

Figure 9a also shows the short shunt motor as a Cumulative Compound motor, which means the polarity of the shunt Field matches the polarity of the Armature. You can see in this figure that the top of the shunt Field is positive polarity and that it is connected to the positive terminal of the Armature. In figure 9b you can see that the shunt Field has been reversed so that the negative terminal of the shunt Field is now connected to the positive terminal of the Armature. This type of motor is called a Differential Compound because the polarities of the shunt Field and the Armature are opposite.

The Cumulative Compound motor is one of the most common DC motors because it provides high starting torque and good speed regulation at high speeds. Since the shunt Field is wired with similar polarity in parallel with the magnetic Field aiding the series Field and Armature Field it is called cumulative. When the motor is connected in this way, it can start even with a large load and then operate smoothly when the load varies slightly.

Compound Motors

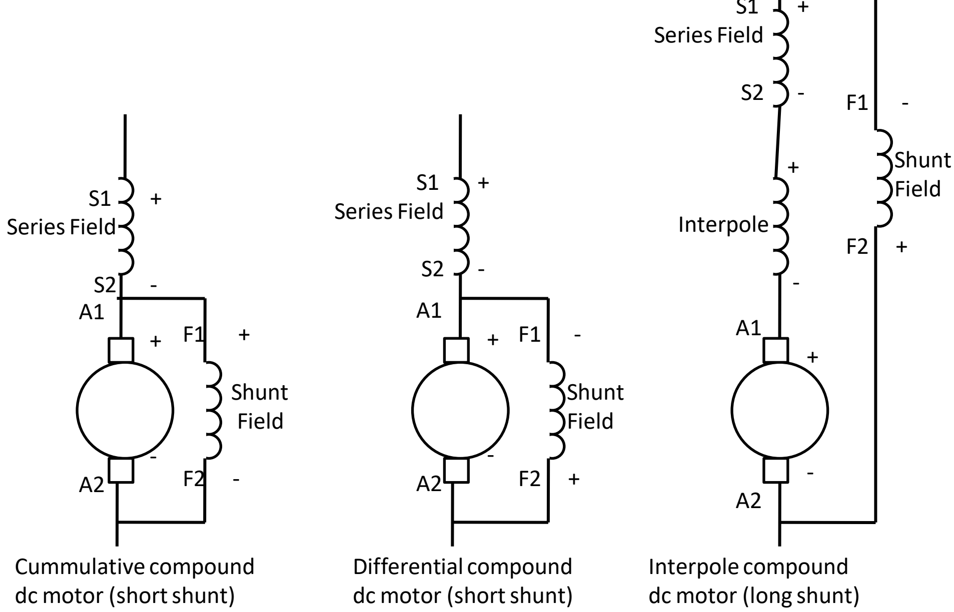


Figure 9: Diagrams of a Cumulative Compound motor, a Differential Compound motor and an Interpole Compound motor.

Differential Compound Motors

Differential Compound motors use the same motor and windings as the Cumulative Compound motor, but they are connected in a slightly different manner to provide slightly different operating speeds and torque characteristics. Figure 9b shows the diagram for a Differential Compound motor with the shunt shield connected so its polarity is reversed to the polarity of the Armature. Since the shunt Field is still connected in parallel with only the Armature, it is considered a short shunt.

In this diagram you should notice that F1 and F2 are connected in reverse polarity to the Armature. In the Differential Compound motor, the shunt Field is connected so that its magnetic Field opposes the magnetic Fields in the Armature and series Field. When the shunt Field's polarity is reversed like this, its Field will oppose the other Fields and the characteristics of the shunt motor are not as pronounced in this motor. This means that the motor will tend to over speed when the load is reduced just like a series motor. Its speed will also drop more than the cumulative compound motor when the load increases at full rpm. These two characteristics make the Differential Compound motor less desirable than the Cumulative Compound motor for most applications.

Compound Interpole Motors

The Compound Interpole motor is built slightly differently from the Cumulative Compound and the Differential Compound motor. This motor has interpoles connected in series with the Armature (Fig 9c). The interpoles are connected in series between the Armature and series winding. These are physically located beside the series coils in the stator. They are made of wire that is the same gauge as the series winding and are connected so that their polarity is the same as the series winding pole it is mounted beside. Remember that these motors may have any number of poles to make the Field stronger.

The interpoles prevent the Armature and brushes from arcing due to the build up of magnetic forces. These forces are created from another form of EMF called Armature Reaction. They are so effective that normally all DC compound motors that are larger than ½ hp will utilise them. The brushes now produce practically no arcing and they will therefore last longer and the Armature will not need to be cut down (skimmed) as often. The interpoles also allow the Armature to draw heavier currents and carry larger shaft loads.

When the interpoles are connected, they must be tested carefully to determine their polarity so that it can be matched with the main pole. If the polarity of the interpoles does not match the main pole it is mounted beside; it will cause the motor to overheat and may damage the series winding.

Reversing the Rotation

Each of the Compound motors shown in Fig 9 can be reversed by changing the polarity of the Armature winding. If the motor has interpoles, the polarity of the Interpole must be changed when the Armature’s polarity is changed. Since the Interpole is connected in series with the Armature, it should be reversed when the Armature is reversed. The interpoles are not shown in the diagram to keep it simplified. The Armature winding is always marked as A1 and A2 and these terminals should be connected to the contacts of the reversing motor starter.

Controlling the Speed

The speed of a compound motor can be changed very easily by adjusting the amount of voltage applied to it. In fact, it can be generalized that prior to the late 1970s, any industrial application that required a motor to have a constant speed would be handled by an AC motor, any application that required the load to be driven at variable speeds would automatically be handled by a DC motor, because the speed of a DC motor was easier to change than an AC motor. Since the advent of solid-state components and microprocessor controls, this condition is no longer true. In fact, today a solid-state AC variable-frequency motor drive can vary the speed an AC motor as easily as that of DC motors.

Figure 10 shows the characteristic curves of the speed versus Armature current for the compound motors. From the diagram you can see that the Differential Compound motor increases slightly when the motor Armature is drawing the highest current. The increase in speed occurs because the extra current in the differential winding causes the magnetic field in the motor to weaken slightly because the magnetic field in the differential winding opposes the magnetic in series field. As you learned earlier in the speed control of shunt motors, speed of the motor will increase if the magnetic field is weakened.

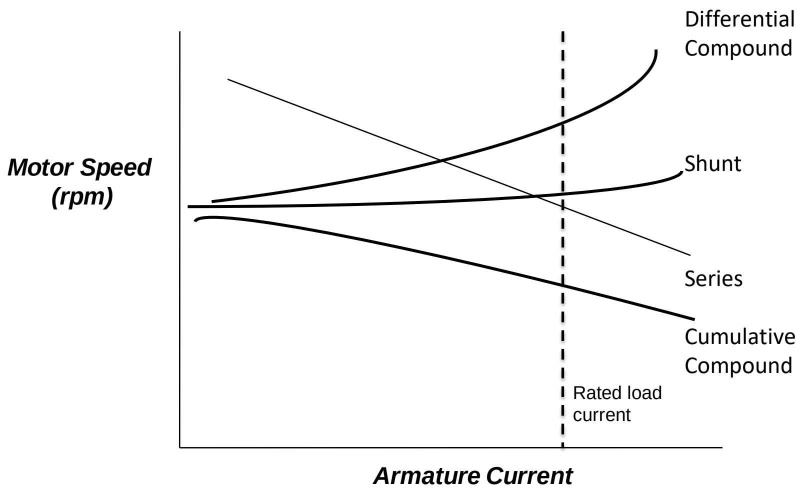


FIGURE 10: Composite of the characteristic curves for all of the DC motors.

Figure 10 also shows the characteristic curve for the Cumulative Compound motor. This curve shows that the speed of the Cumulative Compound motor decreases slightly because the field is increased, which slows the motor because the magnetic field in the shunt winding aids the magnetic field of the series field.

Torque and Speed in a DC Motor

Control of both torque and speed on a DC motor is derived from several formulae. For the purpose of Phase 2 Power & Control Record of Achievement there is no intention to explain how these formulae are derived.

Torque is proportional to the Magnetic Flux and Armature Current

$T \propto \phi$

Speed is proportional to: -

Supply Voltage – (Armature Current x Armature Resistance) / Magnetic Flux

$$N \propto \frac{V - (I_a - R_a)}{\phi}$$

From the above equations if Flux is increased then the Torque will increase, and the speed will decrease.

To vary the Armature current, an additional variable resistance could be used but using modern technology SCR firing circuits are now used.

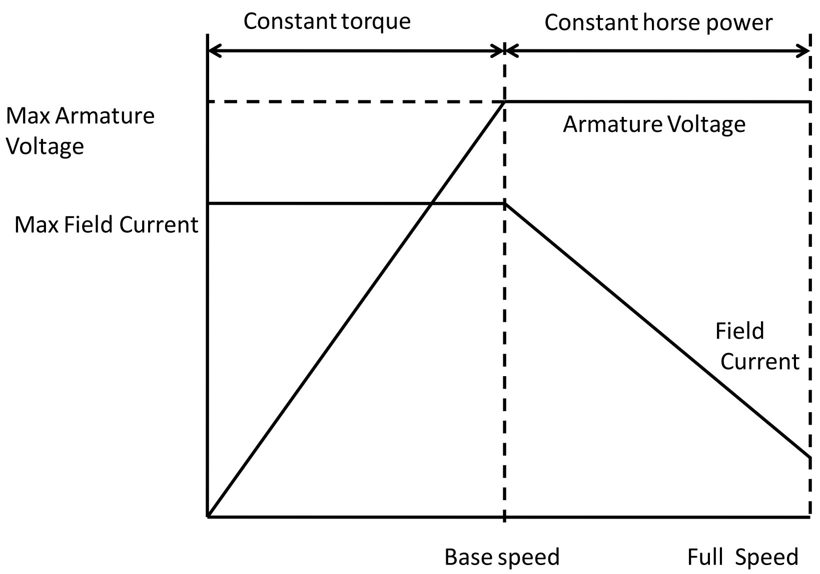
Similarly, to vary Magnetic Flux; as Magnetic Flux is proportional to current, again variable resistance would be required, today replaced by SCR firing circuits.

<u>Basic Speed Control of DC Motor Drive systems</u>

Speed of a DC motor can be altered by variation of either Field Current or Armature Voltage. Both variations of Field Current and Armature Voltage in industry are achieved by using existing AC supplies which is then rectified by use of Thyristors into a variable DC voltage.

Thyristors are used in place of rectifiers because (as previously studied using the Feedback electronic boards) a pulse can be applied to the Thyristor gate terminal to trigger the Thyristor on and thus control the amount of rectified DC flowing to the motor Armature and or Field coil.

Referring to the graph of speed control below, when the DC motor starts from rest i.e. zero speed, the current into the Field coil is kept at maximum value and the voltage supplied to the Armature is steadily raised from zero volts to the maximum Armature voltage.

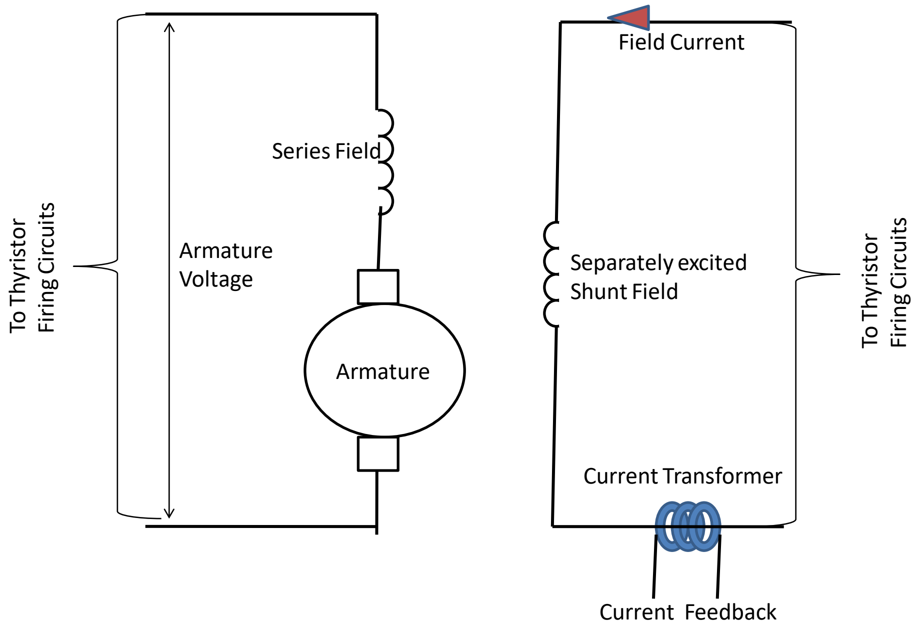


This takes the motor from stand still to the base speed (minimum required operation speed). The time taken to reach base speed depends upon operational requirements – and some very sophisticated electronics. However, at the heart of the very sophisticated electronics would be Operational Amplifier circuits which would operate on a time basis.

From your previous work on operational amplifiers what type of Op Amp circuit would be employed here? --

When base speed has been achieved, the Armature voltage is held at maximum value. Now the field current is reduced from its maximum value until full speed is achieved. Again using 'very sophisticated electronics', the field current is reduced over a set period of time using Operational Amplifiers – *suggest what type of Op Amp would be employed here* ………………………………………………………….

This speed control system uses a Closed Loop System utilising some or possibly all three of a Proportional Integral Derivative (PID) technology. As studied previously in previous carousels PID in practice relies heavily on Operational Amplifier circuits

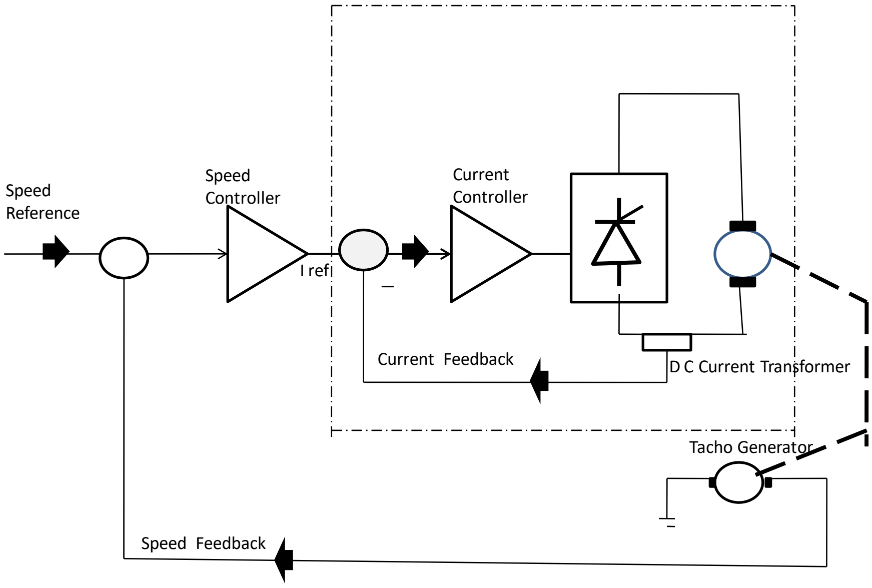


In a Closed Loop System – in this case a DC Compound motor with separately excited Shunt Field which possibly is used to coil or uncoil a large roll of steel weighing up to 40 tons – the speed is precisely controlled by feeding back information electronically regarding the actual speed of the motor. This information would need to include the rotational speed and any acceleration and deceleration. There would be a lot of inertia in a motor driving 40 tons of coiled steel hence the need for precise PID control.

What type of Operational amplifier circuit would be used here ………………………?

Information regarding the speed of the motor is obtained using a tacho-generator. This is a small generator attached to the motor. Information regarding Armature Current is obtained via a current transformer monitoring Armature current as shown above.

Referring back to the graph no need to feedback information regarding Armature voltage as it is now kept constant between base speed and full speed.



Current Control (The Inner Loop)

As per the diagram the Inner Loop is contained within the dotted lines. A current transformer provides an output relative to the current drawn by the motor field. This provides current feedback which is compared at the summing point – represented in diagram by a circle – with a current reference signal which originates from the speed amplifier.

What type of Operational amplifier circuit would be used here ……………………….?

When the current feedback and current reference signals are compared any difference becomes the Error signal which is then fed to the current controller, which is then used to control or modify the gate pulses on the Thyristor firing circuits to the thyristor gates which will regulate the motor field current.

Speed Control (The Outer Loop)

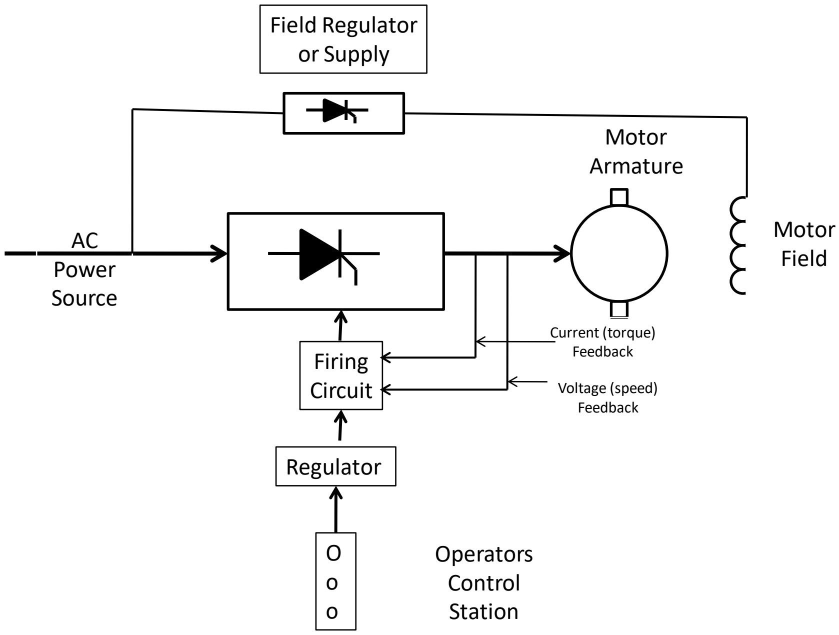
The speed of the motor is obtained from the tacho-generator and the speed feedback signal is compared with a speed reference signal' which is the required speed of the motor. Again, using operational amplifiers – *what type of Op amp would be used……………………………………..*

The difference between the two signals is the Speed Error signal. The signal will need to be boosted – so is fed into the Speed Controller which would be some sort of high gain Operational Amplifier. *What type would this be? ……………………….*

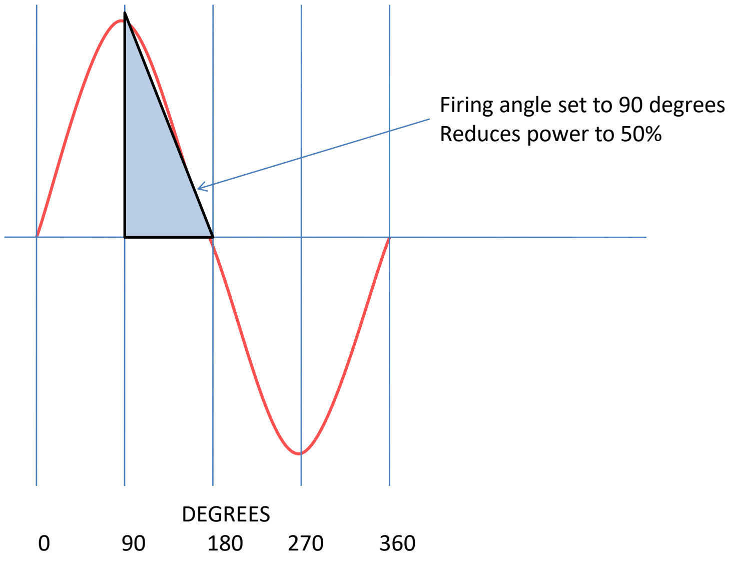
The output now forms the current reference signal which is fed into the Inner Loop.

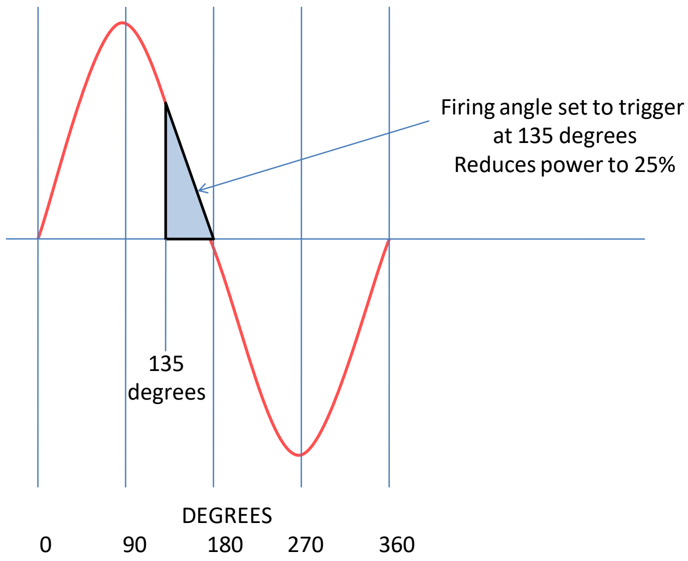
DC DRIVES – PRINCIPLES OF OPERATION

DC drives, because of their simplicity, ease of application, reliability and favourable cost have long been a backbone of industrial applications. A typical adjustable speed drive uses a Silicon Controlled Rectifier (SCR) power conversion' section, common for this type unit, is shown in below. The SCR, (also termed a Thyristor) converts the fixed voltage alternating current (AC) of the power source to an adjustable voltage, controlled direct current (DC) output which is applied to the Armature of a DC motor.



SCR's provide a controllable power output by "phase angle control", so called because the firing angle (a point in time where the SCR is triggered into conduction) is synchronised with the phase rotation of the AC power source. If the device is triggered early in half cycle, maximum power is delivered to the motor; late triggering in the half cycle provides minimum power, as illustrated on next page. The effect is similar to a very high-speed switch, capable of being turned on and "conducted" off at an infinite number of points within each half cycle. This occurs at a rate of 50 times a second on a 50 Hz line, to deliver a precise amount of power to the motor. The efficiency of this form of power control is extremely high since a very small amount of triggering energy can enable the SCR to control a great deal of output power.


Firing angle set to 90 degrees
Reduces power to 50%
DEGREES
0
90
180
270
360


Firing angle set to trigger
at 135 degrees
Reduces power to 25%
135
degrees
DEGREES
0
90
180
270
360

DC DRIVE TYPES

Non regeneration DC Drives – Non regeneration DC drives are the most conventional type in common usage. In their most basic form, they are able to control motor speed and torque in one direction only as shown by Quadrant I in Figure 11. The addition of an electromechanical (magnetic) Armature reversing contactor or manual switch (units rated 2 HP or less) permits reversing the controller output polarity and therefore the direction of rotation of the motor Armature as illustrated in Quadrant III. In both cases torque and rotational direction are the same.

Regeneration DC Drives – Regenerative adjustable speed drives, also known as four-quadrant drives, are capable of controlling not only the speed and direction of motor rotation, but also the direction of motor torque. This is illustrated on next page.

The term regenerative describes the ability of the drive under braking conditions to convert the mechanical energy of the motor and connected load into electrical energy which is returned (or regenerated) to the AC power source.

When the drive is operating in Quadrants 1 and 3, both motor rotation and torque are in the same direction and it functions as a conventional non regenerative unit. The unique characteristics of a regenerative drive are apparent only in Quadrants 2 and 4. In these quadrants, the motor torque opposes the direction of motor rotation which provides a controlled braking or retarding force. A high-performance regenerative drive is able to switch rapidly from motoring to braking modes while simultaneously controlling the direction of motor rotation.

A regenerative DC drive is essentially two coordinated DC drives integrated within a common package. One drive operates in quadrants I and IV, the other operates in quadrants II and III. Sophisticated electronic control circuits provide interlocking between the two opposing drive sections for reliable control of the direction of motor torque and/or direction of rotation.

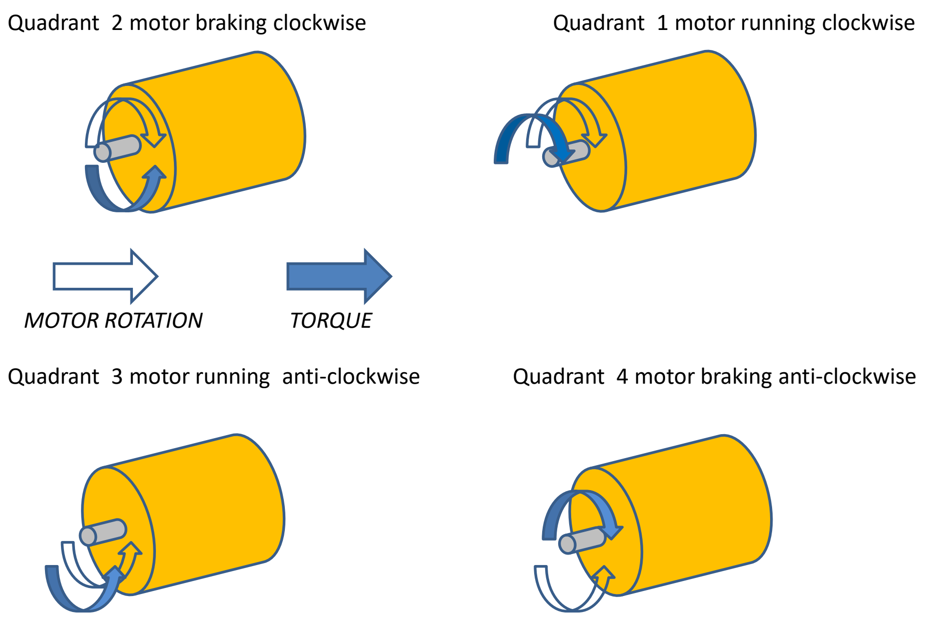


Figure 11

Thyristors (SCR)

Thyristors are available in many different sizes and configurations

A Thyristor or **SCR** (Silicon Controlled Rectifier) is so called because Silicon is used for its construction and its operation as a rectifier (very low resistance in the forward conduction and very high resistance in the reverse direction) can be controlled. Like the Diode, an SCR is a unidirectional device that blocks the current flow from Cathode to Anode.

Unlike the Diode, a Thyristor also blocks the current flow from Anode to Cathode until it is triggered into conduction by a proper gate signal between gate and Cathode terminals.

The Thyristor is a four layer three-junction, p-n-p-n semiconductor switching device. It has three terminals: Anode, Cathode and Gate. Fig. 12 (a) gives constructional details of a typical Thyristor. Basically, a Thyristor consists of four layers of alternate p-type and n-type silicon semiconductors forming three junctions J1, J2 and J3 as shown in Fig. 12 (a). The threaded portion is for the purpose of tightening the Thyristor to the frame or heat sink with the help of a nut. The gate terminal is usually kept near the Cathode terminal Fig. 12 (a). Schematic diagram and circuit symbol for a Thyristor are shown respectively in Figs. 12 (b) and (c). The terminal connected to outer p region is called Anode (A), the terminal connected to outer n region is called Cathode and that connected to inner p region is called the Gate (G). For large current applications, Thyristors need cooling; this is achieved to a great extent by mounting them onto heat sinks.

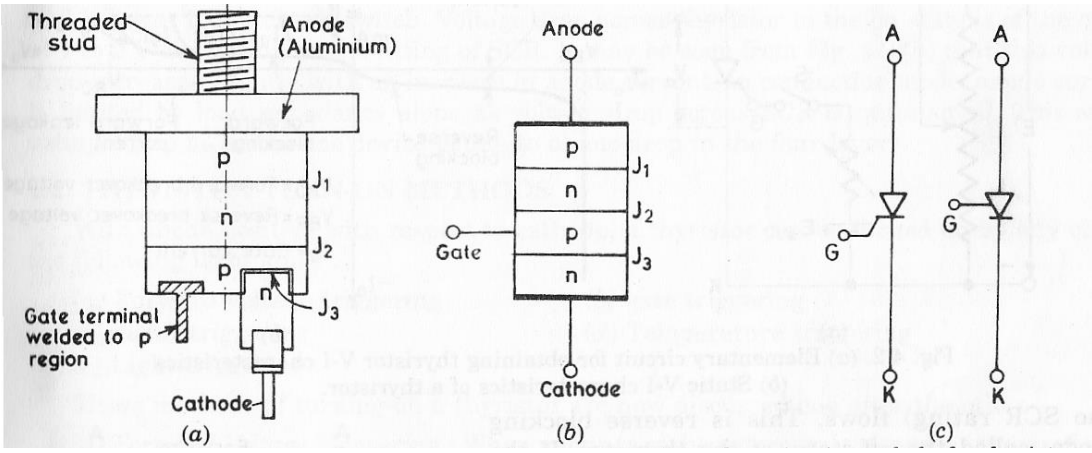


Figure 12

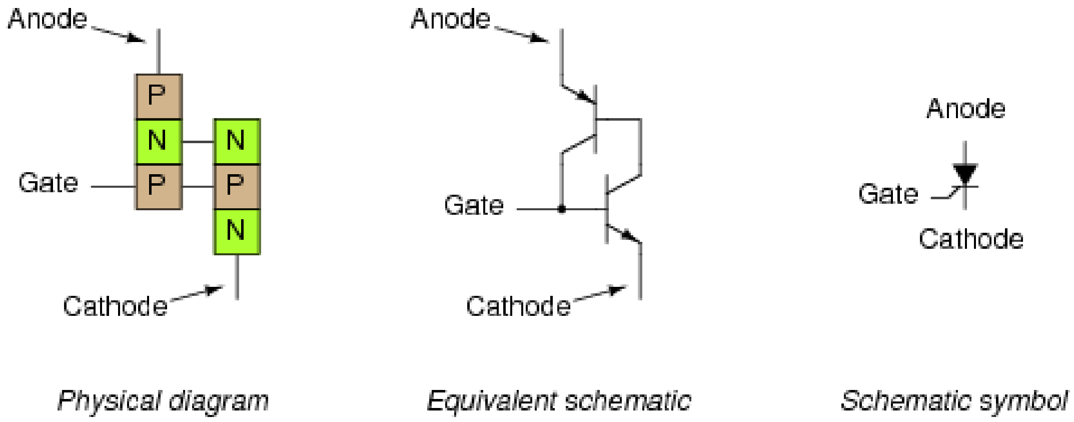
Thyristors have three states:

1. Reverse blocking mode — voltage is applied in the direction that would be blocked by a diode.

2. Forward blocking mode — voltage is applied in the direction that would cause a diode to conduct, but the thyristor has not yet been triggered into conduction.

3. Forward conducting mode — the thyristor has been triggered into conduction and will remain conducting until the forward current drops below a threshold value known as the "holding current".

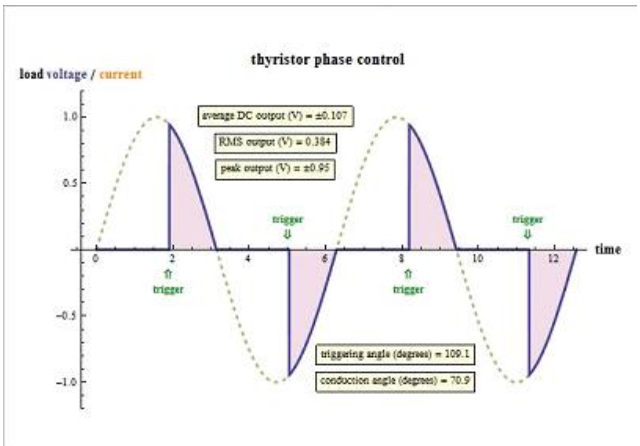
Function of the gate terminal



When the Anode is at a positive potential V_{AK} with respect to the cathode with no voltage applied at the gate, junctions J_1 and J_3 are forward biased, while junction J_2 is reverse biased. As J_2 is reverse biased, no conduction takes place (Off state). Now if V_{AK} is increased beyond the breakdown voltage V_{BO} of the Thyristor, avalanche breakdown of J_2 takes place and the Thyristor starts conducting (On state).
If a positive potential V_G is applied at the gate terminal with respect to the Cathode, the breakdown of the junction J_2 occurs at a lower value of V_{AK}. By selecting an appropriate value of V_G, the Thyristor can be switched into the on state suddenly.
Once avalanche breakdown has occurred, the Thyristor continues to conduct, irrespective of the gate voltage, until both: (a) the potential V_G is removed and (b) the current through the device (anode−cathode) is less than the holding current specified by the manufacturer. Hence V_G can be a voltage pulse. These gate pulses are characterised in terms of gate trigger voltage (V_{GT}) and gate trigger current (I_{GT}). Gate trigger current varies inversely with gate pulse width in such a way that it is evident that there is a minimum gate charge required to trigger the Thyristor.

Switching characteristics

In a conventional Thyristor, once it has been switched on by the gate terminal, the device remains latched in the on-state (*i.e.,* does not need a continuous supply of gate current to conduct), providing the Anode current has exceeded the latching current (I_L). As long as the Anode remains positively biased, it cannot be switched off until the anode current falls below the holding current (I_H).



Thyristors are mainly used where high AC currents and voltages are involved, where the change of polarity of the current causes the device to switch off automatically. A **Thyristor Drive** is a motor drive circuit where AC supply current is regulated by a Thyristor phase control to provide variable DC voltage to a DC motor.

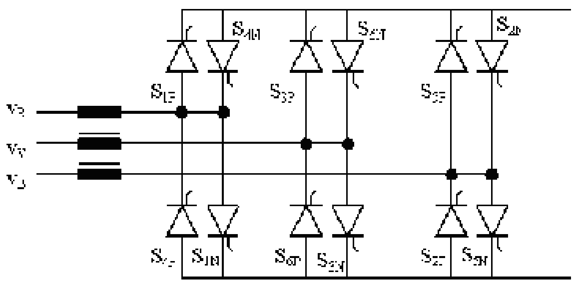
Some controllers can only supply (source) current to power the motor. These are 'single-quadrant' controllers.

Other controllers can also sink current, which is generated by the motor when it runs faster than the speed set by the controller. These are '2 quadrant' controllers.

A '4 quadrant' controller is like a two quadrant but can also reverse the motor to give the extra quadrants.

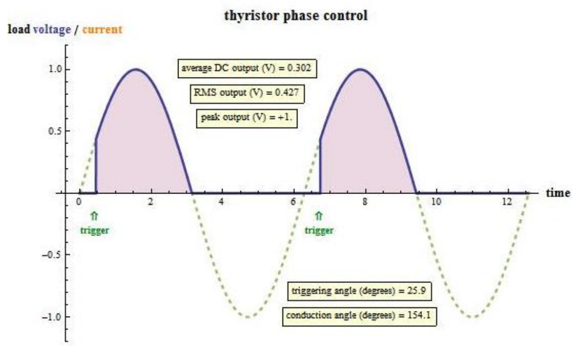
If the controller can sink, as well as source current, then it will give regenerative braking (or regen for short) - regenerative since the braking energy is fed back - re-generated - to the mains.

The process of regeneration is entirely automatic and occurs when the motor over-runs (or the demand speed is reduced) so that the motor's back EMF is greater than the output voltage from the controller. The diagram below shows the Thyristor configuration for 4-quadrant control that is to say control of both motoring and regenerative current also in the forward and reverse direction. This can be easily proven by using Flemings Left Rule for motors. Thumb stands for Motion and Second Finger stands for current. If you move your left hand so your second finger is pointing in the opposite direction, then your Thumb (Motion) has now also changed direction.



Firing Circuit

The function of the firing circuit is to sequentially turn on each Thyristor at the proper time. This is accomplished by detecting a reference point with the applied voltage cycle and initiating a firing pulse train after the proper delay time. It can be seen that the "on" time of the Thyristor is increased by decreasing the delay time and vice-versa. It follows that changing the delay time can vary the output power.



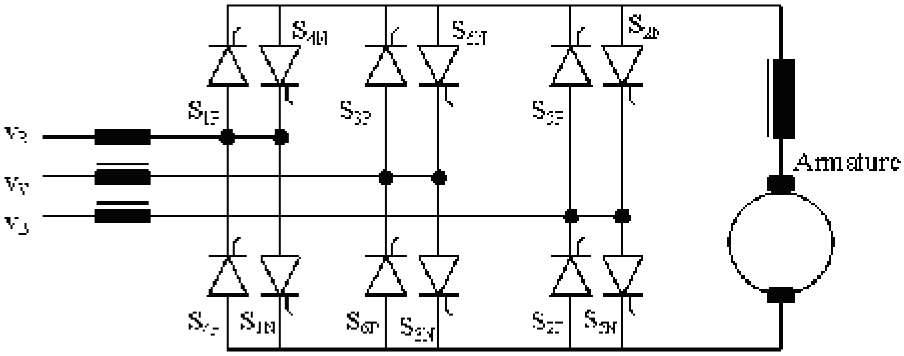
The rectifier section may use six Thyristors as a bridge similar to the Diode bridge rectifiers in AC drives. Or larger drives may connect two Thyristors in parallel for each of the six sections of the bridge to provide a 12 SCR full-wave rectifier circuit. When Thyristors are connected in parallel, the current rating of the rectifier is nearly doubled. The firing circuit for the Thyristors is synchronised with the three-phase incoming voltage. The firing circuit also receives an input signal called a reference signal or command signal from the speed amp and the current amp.

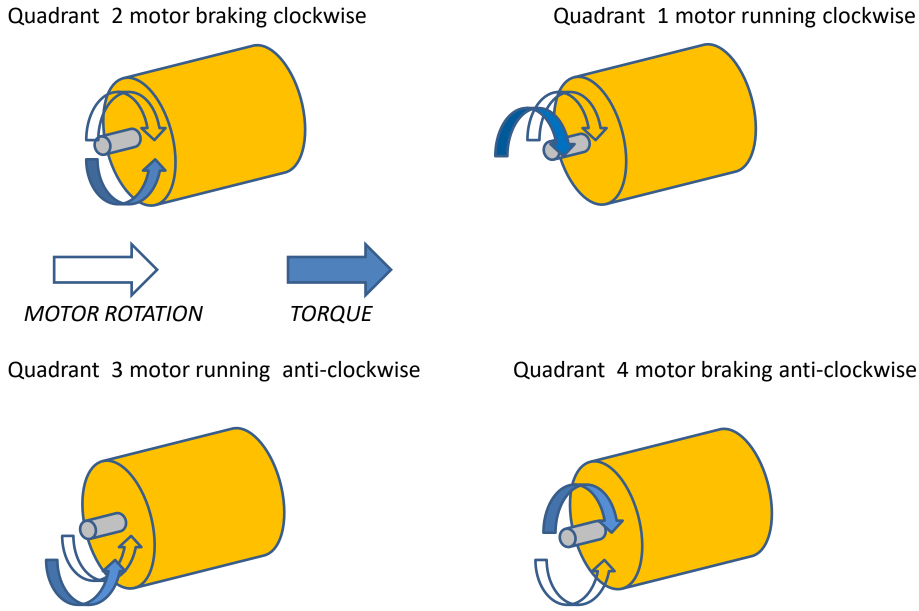
The speed amp receives a feedback signal from a tachometer, and the current amp receives a signal from a current transducer (shunt) that is connected in series with the Armature. As the current in the wire to the Armature increases or decreases, the voltage across the shunt will increase or decrease and provide a feedback signal to the current amplifier.

CIRCUIT OPERATION

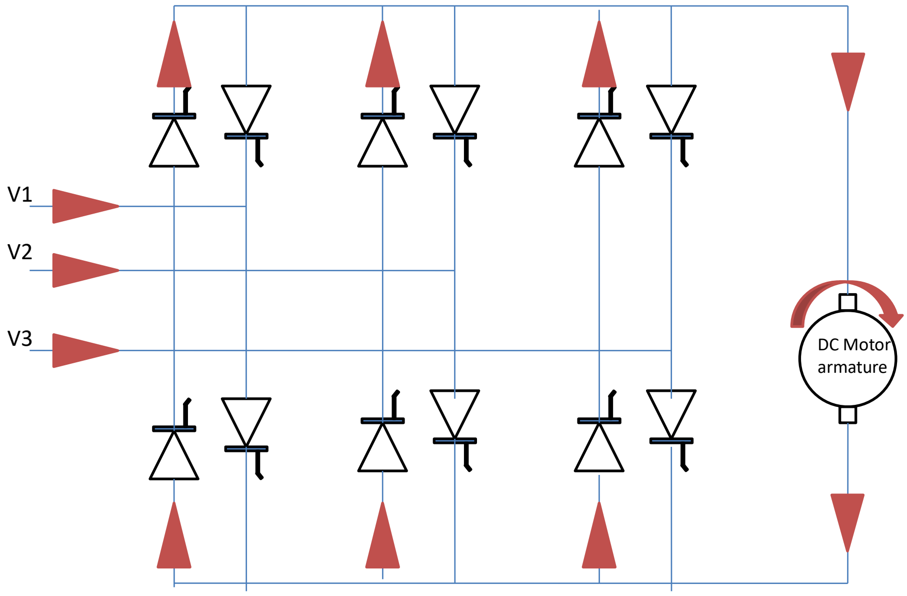
The operation of the circuit in the circulating-current free mode is not very much different from that described in the previous pages. In order to drive the motor in the forward direction, the positive converter is controlled. To control the motor in the reverse direction, the negative converter is controlled. When the speed of motor is to be changed fast from a high value to a low value in the forward direction, the conduction has to switch from the positive converter to the negative converter. Then the direction of current flow changes in the motor and it regenerates, feeding power back to the source. When the speed is to be reduced in the reverse direction, the conduction has to switch from the negative converter to the positive converter. It is seen that conduction has to switch from one converter to the other when the direction of motor rotation is to change, so that regeneration can occur. During regeneration, the direction torque developed by motor is opposite to that of the motoring torque. Thus, the regenerating torque acts as the breaking torque and the motor decelerates fast.

In a dual converter, the firing angles for the converter can be changed. But it needs to be emphasised that only one converter operates at any instant.


Armature

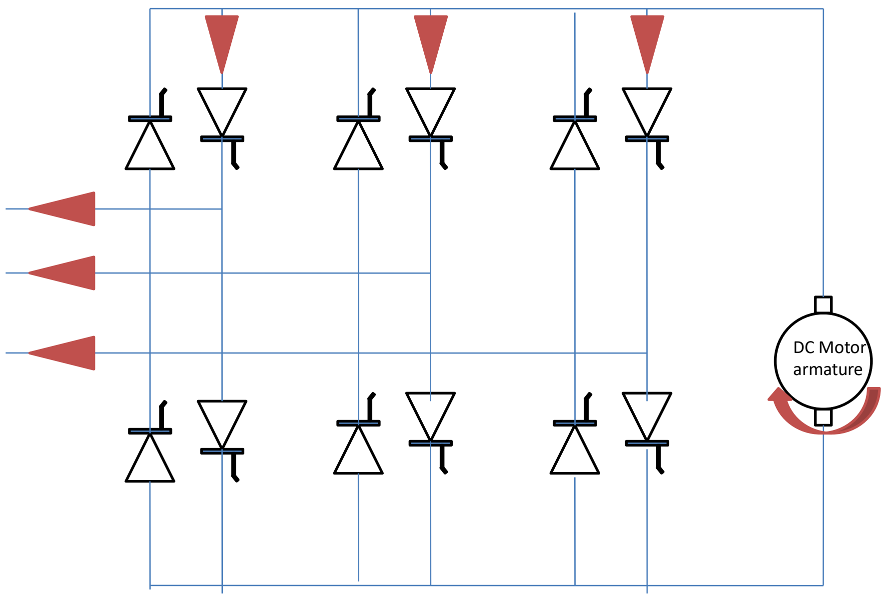

Quadrant 2 motor braking clockwise
Quadrant 1 motor running clockwise
MOTOR ROTATION
TORQUE
Quadrant 3 motor running anti-clockwise
Quadrant 4 motor braking anti-clockwise

Thyristor switching for Clockwise rotation



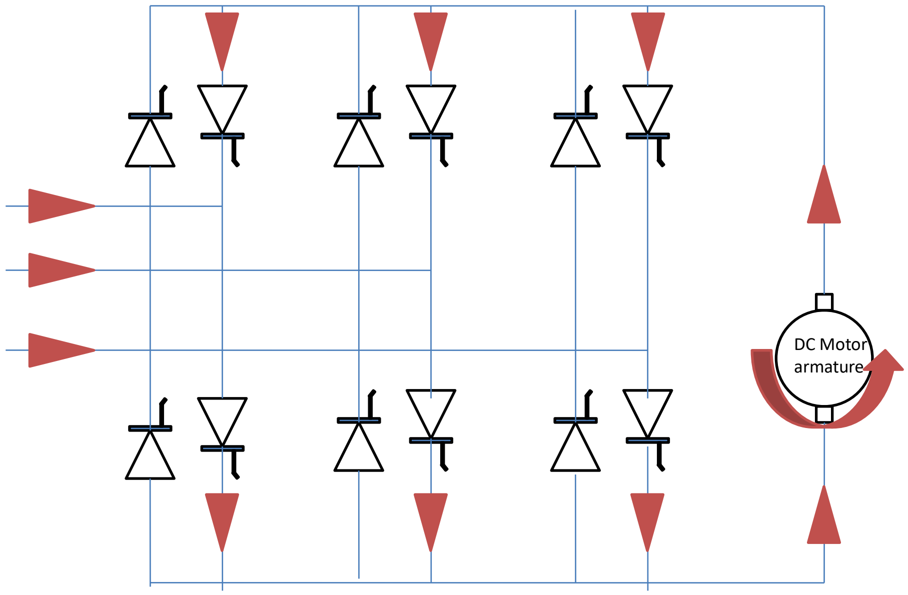
Quadrant 1: Motor running clockwise

Thyristor switching for Re-generative braking clockwise rotation



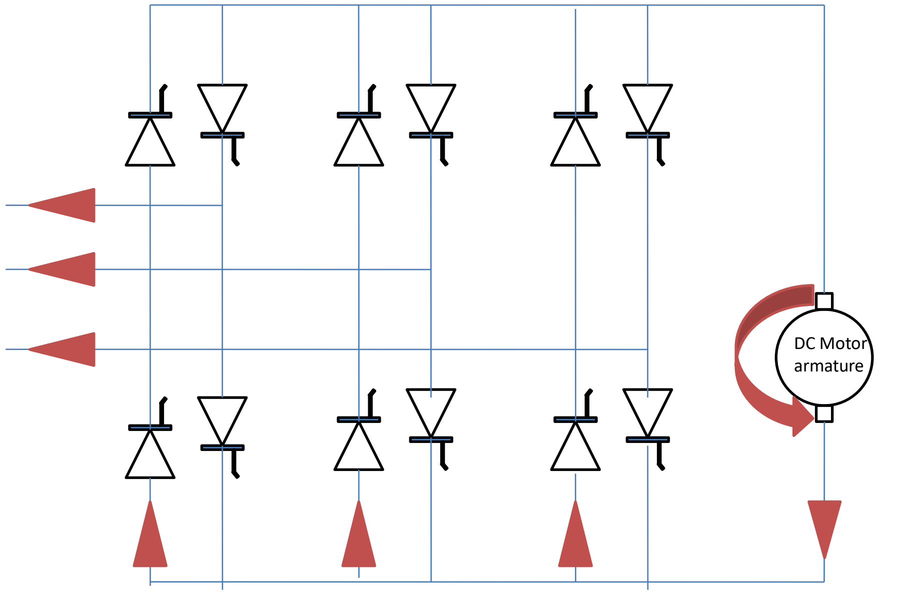
Quadrant 2; Motor Braking Clockwise

Thyristor switching for Anti- clockwise rotation



Quadrant 3: Motor running Anti – Clockwise

Thyristor switching for Re-generative braking anti-clockwise rotation



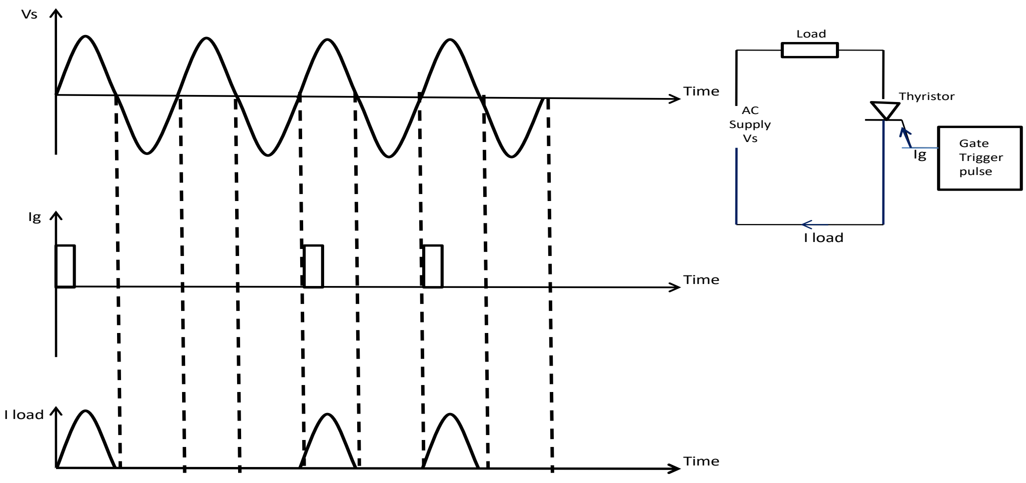
Quadrant 4: Motor braking Anti – Clockwise

Power control using the Thyristor.

The Thyristor is a power rectifier which is triggered into its forward conducting state by applying a small positive pulse or continuous D.C. voltage to the ‘gate’ connection. It is also called a Silicon-Controlled Rectifier (SCR) since the gate pulse controls the switching of the device which is made from silicon. Once switched into the forward conducting state by the gate pulse, the device cannot be switched off until the applied voltage falls to zero. Thyristors, therefore, lend themselves to the control of power in A.C. mains as it passes through zero twice on each cycle, which allows the device to be switched off. Two methods are generally employed to control a Thyristor in an A.C. circuit, burst trigger control or phase control.

Burst trigger control.

Burst triggering, synchronous triggering or zero voltage triggering are different names for the same method of Thyristor control which is directly comparable with traditional methods of control in which power is switched on and off for various intervals of time as shown in diagram below.



Burst trigger control for a thyristor / SCR

3023-21

In this case the Thyristor is triggered only on the first, third and fourth cycles, but more power could be delivered to load by triggering every cycle, or less power by triggering fewer cycles. Mechanical or thermal inertia is used to smooth out the effects of this bumpy waveform on the load. Switching the Thyristor on the mains waveform passes through zero has the advantage of reducing the effect of Mainsborne interference which occurs if the Thyristor is switched on part way through a cycle but a much smoother and more desirable method of controlling the mains waveform is provided by phase control.