5.7 Applications of DC Motors

The main applications of the three types of direct current motors are given below.

Series Motors

The series DC motors are used where high starting torque is required and variations in speed are possible. For example – the series motors are used in the traction system, cranes, air compressors, Vaccum Cleaner, Sewing machine, etc.

Shunt Motors

The shunt motors are used where constant speed is required and starting conditions are not severe. The various applications of DC shunt motor are in Lathe Machines, Centrifugal Pumps, Fans, Blowers, Conveyors, Lifts, Weaving Machine, Spinning machines, etc.

Compound Motors

The compound motors are used where higher starting torque and fairly constant speed is required. The examples of usage of compound motors are in Presses, Shears, Conveyors, Elevators, Rolling Mills, Heavy Planners, etc.

The small DC machines whose ratings are in fractional kilowatt are mainly used as control device such in techno generators for speed sensing and in servo motors for positioning and tracking.

5.4 REGENERATIVE BRAKING OF DC MOTOR

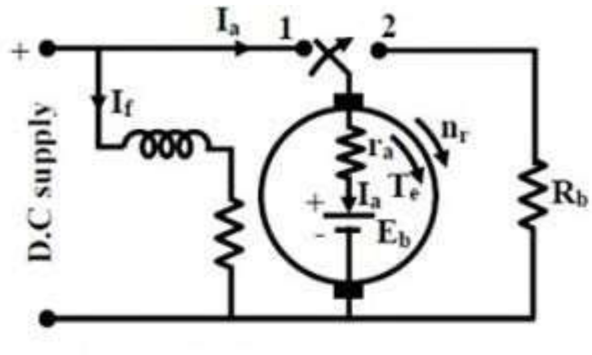


Figure 5.4.1 Machine act as Motor

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 389]*

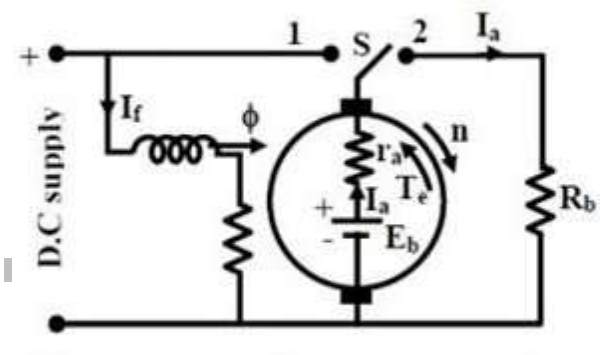


Figure 5.4.2 Machine act as Generator during Regenerative Braking

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 389]*

Regenerative braking takes place whenever the speed of the motor exceeds the synchronous speed. This baking method is called regenerative baking because here the motor works as generator and supply itself is given power from the load, i.e. motors. The main criteria for regenerative braking is that the rotor has to rotate at a speed higher than synchronous speed, only then the motor will act as a generator and the direction of current flow through the circuit and direction of the torque reverses and braking takes place. The only disadvantage of this type of braking is that the motor has to run at super synchronous speed which may damage the motor mechanically and electrically, but regenerative braking can be done at sub synchronous speed if the variable frequency source is available. Under this condition, the back emf E_b of the motor is greater than the supply voltage V, which reverses the direction of motor armature current. The machine now begins to operate as a generator and the energy generated is supplied to the source.

Regenerative braking can also be performed at very low speeds if the motor is connected as a separately excited generator. The excitation of the motor is increased as the speed is reduced so that the two equations shown below are satisfied.

$$E_b = \frac{nP\varphi Z}{A} \quad \text{and} \quad V = E_b - I_a R_a$$

The motor does not enter into saturation on increasing excitation.

Regenerative braking is possible with the shunt and separately excited motors. In compound motors, braking is possible only with weak series compounding.

Regenerative Braking in DC Shunt Motors

Under normal operating conditions the armature current is given by the equation shown below:

$$-I_a = \frac{V - E_b}{R_a}$$

When the load is lowered by a crane, hoist or lift causes the motor speed to be greater than the no-load speed, the back EMF becomes greater than the supply voltage. Consequently, armature current Ia becomes negative. The machines now begins to operate as a generator.

Regenerative Braking in DC Series Motors

In the case of DC Series Motor an increase in speed is followed by a decrease in the armature current and field flux. The back EMF Eb cannot be greater than the supply voltage. Regeneration is possible in DC Series Motor since the field current cannot be made greater than the armature current.

Regeneration is required where DC Series Motor is used extensively such as in traction, elevator hoists etc. For example – In an electro-locomotive moving down the gradient, a constant speed may be necessary. In hoist drives, the speed is to be limited whenever it becomes dangerously high.One commonly used method of regenerative braking of DC Series Motor is to connect it as a shunt motor. Since the resistance of the field winding is low, a series resistance is connected in the field circuit to limit the current within the safe value.

Applications of Regenerative Braking

- Regenerative braking is used especially where frequent braking and slowing of drives is required.
- It is most useful in holding a descending load of high potential energy at a constant speed.
- Regenerative braking is used to control the speed of motors driving loads such as in electric locomotives, elevators, cranes and hoists.
- Regenerative braking cannot be used for stopping the motor. It is used for controlling the speed above the no-load speed of the motor driving.

Plugging Type Braking or Counter Current Braking

In a dc motor a reversed torque is obtained by reversing the current either in the armature or in the field (not both), Polarity reversal of field winding is rarely used because it results in longer braking time due to relatively large inductance of the field winding in comparison to that can be obtained by polarity reversal of armature winding.

The connections for dc series and shunt motors during normal running and braking conditions are shown in Figs. In case of a dc series motor it should be ensured that the direction of flow of current in the field winding remains unchanged when the current flow in the armature winding is reversed.

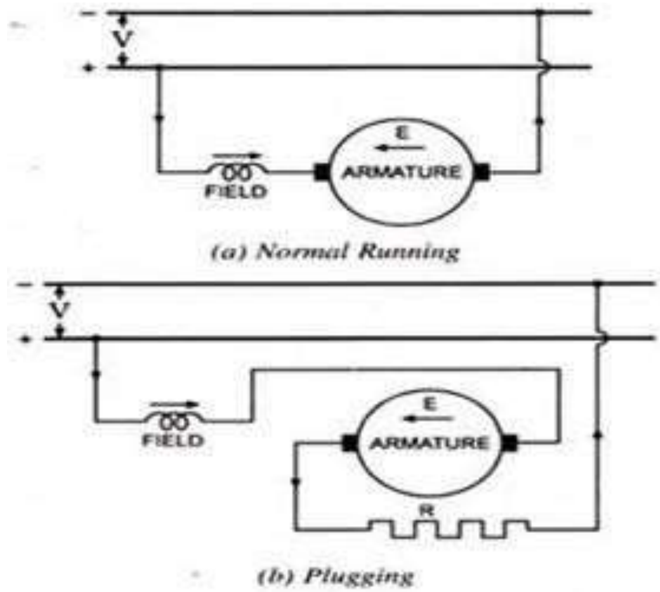


Figure 5.4.3 Normal Running and Plugging of DC Series Motor

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman*, Page: 393]*

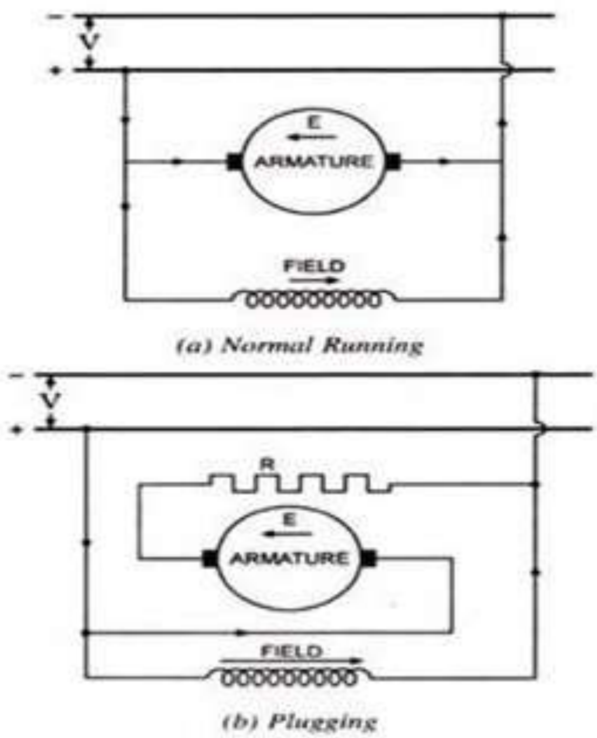


Figure 5.4.3 Normal Running and Plugging of DC Shunt Motor

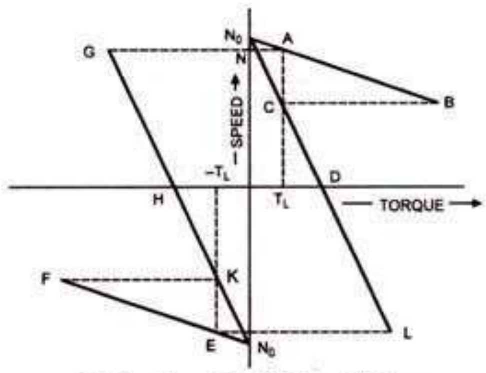
[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman*, Page: 393]*

In the normal running position the back emf is nearly equal to applied voltage and opposite in direction, so that a small voltage acts across the armature circuit to drive the normal current through a small resistance of the motor. In the plugging position, the induced emf acts in the direction of applied voltage, therefore, at the instant of switching the motor to the plugging position, twice of supply voltage acts across the machine circuit and heavy current would flow (about twice the current drawn by the stationary motor on normal rated voltage). Hence to avoid flow of heavy current and limit it to the safer value, it is necessary that switching performing the plugging operation may also re-insert starting resistance and some additional resistance in series with the armature circuit of the motor.

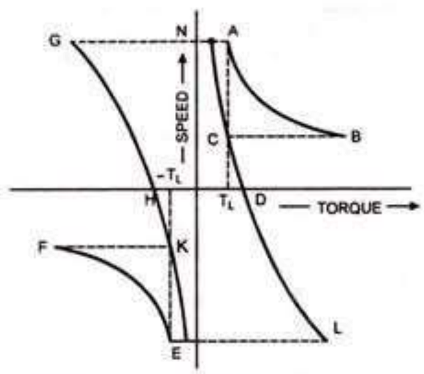
Figures explain the plugging operation of the dc shunt and series motors respectively on a quadrant diagram.

AB and EF represent the speed-torque characteristics of the motor in normal and reverse direction of rotation without any external resistance, while CL and KG represent the same with external resistances respectively. A is the initial operating point with load, speed N and load torque T_L and the external resistance zero.

When plugging is resorted, the motor continues to run in the normal direction but develops torque in reverse direction and point G is the operating point (on characteristic KHG, as resistance is inserted here). The speed falls till it reaches point H (zero) and at this stage supply should be switched off, failing which the motor attains speed in reverse direction under motoring action and operates at point E on switching out external resistance.



(a) Plugging of a DC Shunt Motor



(b) Plugging of a DC Series Motor

Figure 5.4.4 Quadrant Diagram

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 396]*

Dynamic Braking of DC Motor

If an electric motor is simply detached from the power supply, then it will stop but for large motors, it will take a longer time due to high rotating inertia because the energy which is stored has to dissolve throughout bearing & wind friction. The condition can be enhanced by pushing the motor to function as a generator through braking; a torque opposite to the path of rotation will be forced on the shaft, thus helping the device to come to discontinue rapidly. Throughout the braking action, the early KE which is stored within the rotor is either dissolute in an exterior resistance otherwise fed back to the power supply.

In this kind of braking, the dc shunt motor is detached from the power supply & a braking resistor (Rb) is connected across the armature. So this motor will function as a generator to generate the braking torque.

Throughout this braking, once this motor functions as a generator, then K.E (kinetic energy) will store within the rotary parts of the DC motor. The load which is connected can be changed into electrical energy. This energy will dissipate like a heat within the braking resistance (Rb) & the resistance of the armature circuit (Ra). This kind of Braking is an ineffective method of braking because the energy which is generated will dissipate like heat within the resistances.

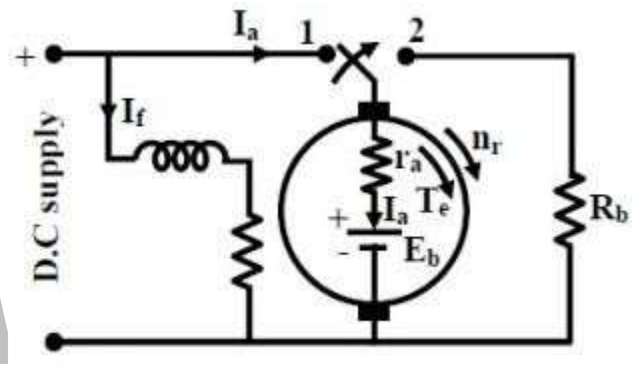


Figure 5.4.5(a) Dynamic Braking of DC motor

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 397]*

In a common motoring method, switch 'S' is connected to two positions like 1& 1′. The supply voltage including polarity and external resistance (Rb) is connected across 2 & 2′ terminals. But, in motor mode, this circuit part remains stationary. To start braking, the switch is thrown in the direction of positions 2 & 2′ at t = 0, thus detaching the armature as of the supply of left hand. The armature current at t = 0+ will be Ia = (Eb + V)/(ra + Rb) because 'Eb' & the voltage supply from the right hand have preservative polarities through the good features of the connection.

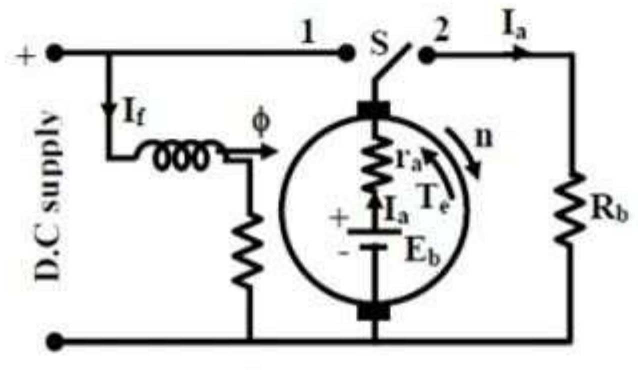


Figure 5.4.5(b) Dynamic Braking of DC motor

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman*, Page: 397]*

In a common motoring method, switch 'S' is connected to two positions like 1& 1′. The supply voltage including polarity and external resistance (Rb) is connected across 2 & 2′ terminals. But, in motor mode, this circuit part remains stationary. To start braking, the switch is thrown in the direction of positions 2 & 2′ at t = 0, thus detaching the armature as of the supply of left hand. The armature current at t = 0+ will be Ia = (Eb + V)/(ra + Rb) because 'Eb' & the voltage supply from the right hand have preservative polarities through the good features of the connection.

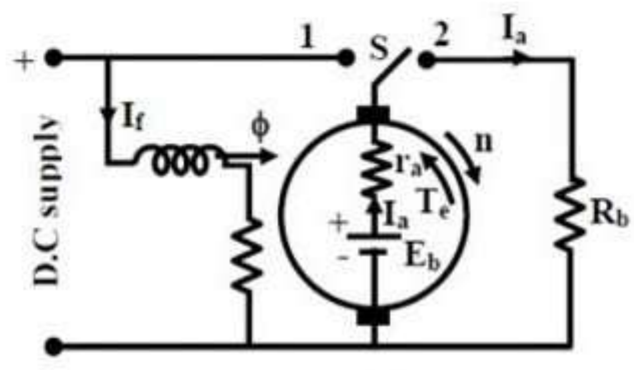


Figure 5.4.5(c) Dynamic Braking of DC motor

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman*, Page: 397]*

Here the direction of 'Ia' can be reversed by generating 'Te' within reverse direction toward 'n'. Once the 'Eb' decreases, 'Ia' decreases with time while speeding decreases. But, 'Ia' cannot turn into zero at any time because of the occurrence of the voltage supply. So dissimilar to rheostatic, an extensive magnitude of braking torque will exist. Therefore, stopping the motor is probably faster compare with rheostatic braking. However, if the switch ‘S’ constant within the positions of 1′ & 2′ & even after zero speed so the machine will begin picking up speed within the opposite direction to work as a motor. So maintenance must be taken for detaching the supply at the right hand, and then the armature speed moment will become zero.

Advantages & Disadvantages

The advantages and disadvantages are

- This is a much-used method where en electric motor is worked as a generator once it is detached from the power source
- In this braking, the energy which is stored will dissipate through the resistance of braking & other components used in the circuit.
- This will reduce braking components based on wear on friction & regeneration reduces the usage of net energy.

Applications of Dynamic Braking

- The dynamic braking technique is used to stop a DC motor & widely used in industrial applications.
- These systems are utilized in the applications of fans, centrifuges, pumps, rapid or continuous braking, and certain conveyor belts.
- These are used where rapid slow down & reversing are required.
- These are used on railcars through several units, trolleybuses, electric trams, light rail vehicles, hybrid electric & electric automobiles.

5.6 PMDC Motor

We know that a DC motor has an armature which rotates within a magnetic field, and the main working principle of this motor depends on a current carrying conductor which is arranged in a magnetic field, and the mechanical force will be experienced with the conductor. DC motors are classified into different types which work on the same principle. Thus, the DC motor construction can be done by establishing a magnetic field with any kind of magnet like electromagnet otherwise a permanent magnet. **A** PMDC (Permanent Magnet DC motor) is a kind of DC motor that includes a permanent magnet to form the magnetic field necessary for the DC motor operation. This article discusses an overview of PMDC or Permanent Magnet DC motor.

The permanent magnet dc motor can be defined as a motor which includes a permanent magnet pole is called Permanent Magnet DC Motor. In this motor, the magnet can be used to make the flux working within the air gap in its place of the field winding. The rotor structure is similar to the straight DC Motor. PMDC Motor's rotor includes armature core, commutator, & armature winding. Normally, in a conventional DC motor, there are two kinds of winding such as armature as well as Filed.

The main function of field winding is to produce the functioning magnetic flux within the air gap as well as wound on the stator of the motor while armature winding can be wound on the rotor. Inactive carbon brushes are pushed on the commutator like in conventional DC motor. The operating voltage of the PMDC motor is 6 volts, 12 volts otherwise 24 volts DC supply attained from the voltage sources.

The PMDC motor's permanent magnets are maintained with a cylindrical-steel stator and these supplies like a return lane for the magnetic flux. The rotor supplies like an armature, and it includes commutator segments, winding slots, & brushes like in conventional dc machines. The permanent magnets used in this motor are classified into three namely Alnico magnets, Ceramic (ferrite) magnets, and Rare-earth magnets.

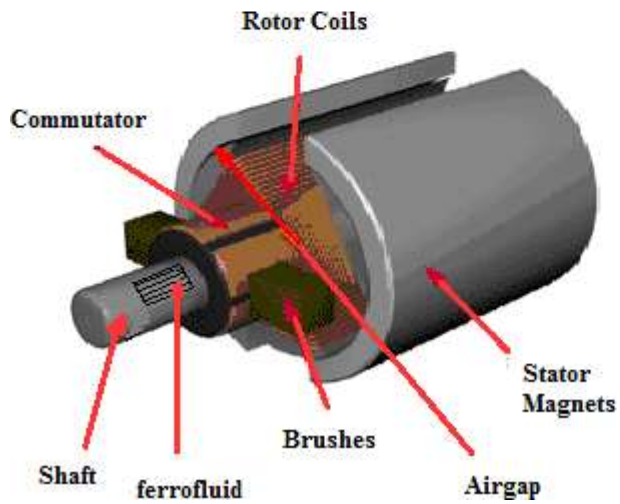


Figure 5.6.1 Permanent Magnet DC Motor

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman*, Page: 416]*

- lnico magnets are used within motors which have the ratings in the range of 1kW-150kW.
- Ferrite or Ceramic magnets are much cheap within fractional kw (kilowatt) motors.
- Rare-earth magnets are made with samarium cobalt as well as neodymium iron cobalt.

Operation :

- In this motor, a permanent magnetic field can be generated with the permanent magnets communicate by the perpendicular field stimulated by the flow of currents within the rotor windings; therefore a mechanical torque can be created.
- When the rotor rotates in response to the created torque, then the position among the stator as well as rotor fields can be reduced, and the torque would be reversed in a 90-degree rotation. To maintain the torque performing on the rotor, PMDC motors include a commutator, set to the rotor shaft.

The commutator activates the current supply toward the stator thus as to continue a steady angle = 90, among two fields. As the flow of current is frequently activated among windings like the rotor twists, then the current within every stator winding is truly exchanging at a frequency comparative to the no.of motor magnetic poles as well as the speed.

Characteristics of PMDC Motor

The characteristics of PMDC Motor include the following.

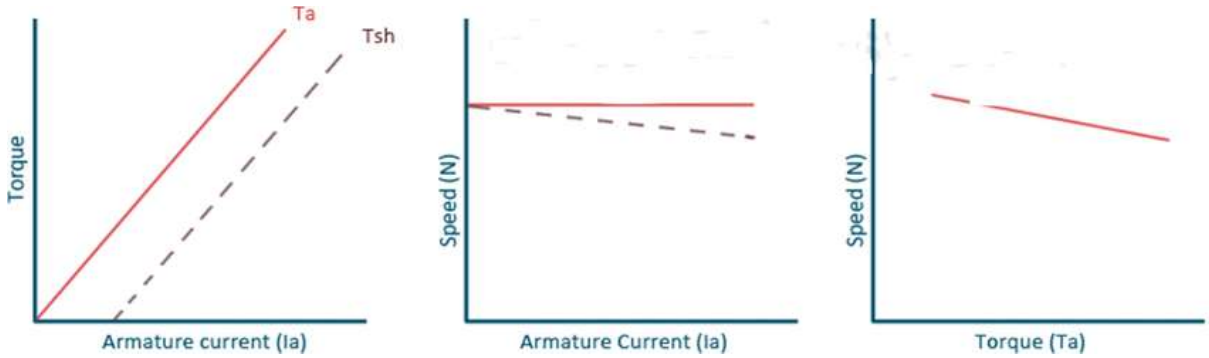


Figure 5.6.2 PMDC Motor Characteristics

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman*, Page: 417]*

The PMDC Motor characteristics are related to the dc shunt motor characteristic in terms of speed, torque, as well as armature current. But, the characteristics of speed-torque are more linear as well as conventional in these types of motors.

Advantages and Disadvantages of the PMDC Motor

The advantages and disadvantages of the PMDC motor include the following.

- The size of these motors is smaller
- These motors are cheaper
- These motors do not need field windings, and they don't have the copper losses in the field circuit.
- The major drawback of this motor is, the generating capacity of working flux within the air gap is limited. But, due to the expansion of some latest magnetic material such as Samarium Cobalt & Neodymium Iron Boron, this trouble has been determined to some level.

Applications of the PMDC Motor

- These motors are in several applications varying from fractions to numerous horsepower. These are designed with 200 kW to use in various industries.

- These are applicable in automobiles for operating windshield wipers as well as washers, to move up the lower windows, to drive blowers for air conditioners as well as heaters.
- These are used in computer drives, toy industries.
- These motors are applicable in food mixers, electric toothbrushes, and moveable vacuum cleaners,.
- These are used in a handy electric tool like hedge trimmers, drilling machines, etc.

5.1 D.C MOTOR PRINCIPLE

A machine that converts D.C power into mechanical power is known as a d.c motor. Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. The direction of this force is given by Fleming's left hand rule and magnitude, Basically, there is no constructional difference between a D.C motor and a D.C generator. The same D.C machine can be run as a generator or motor.

Working of D.C Motor

When the terminals of the motor are connected to an external source of d.c. supply:

(i) the field magnets are excited developing alternate N and S poles;

(ii) the armature conductors carry currents.

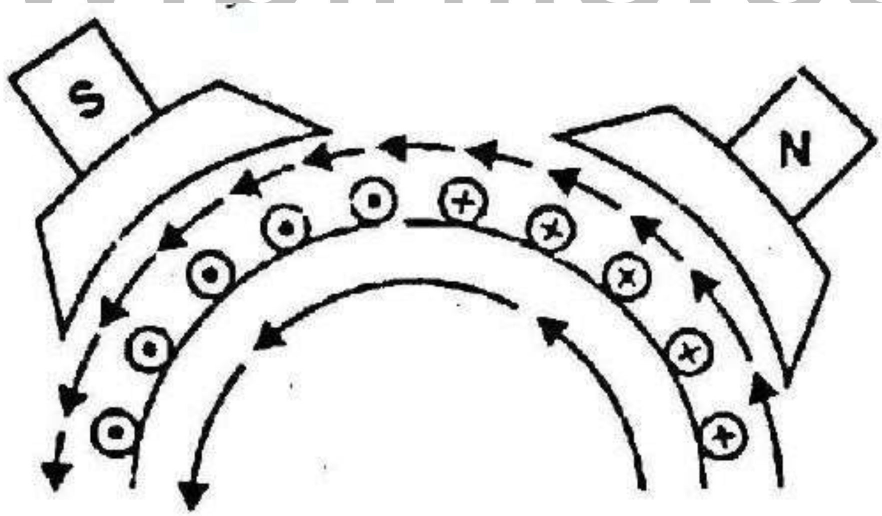


Figure 5.1.1 Armature conductors

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 373]*

All conductors under N-pole carry currents in one direction while all the conductors under S-pole carry currents in the opposite direction. Suppose the conductors under N-pole carry currents into the plane of the paper and those under S-pole carry currents out of the plane of the paper as shown in Fig. Since each armature conductor is carrying current and is placed in the magnetic field, mechanical force acts on it. Applying Fleming's left hand rule, it is clear that force on each conductor is tending to rotate the armature in anticlockwise direction. All these forces add together to produce a driving torque which sets the armature rotating. When the conductor moves from one side of a brush to the other, the current in that conductor is reversed and at the same time it comes under the influence of next pole which is of opposite polarity. Consequently, the direction of force on the conductor remains the same.

Types of D.C. Motors

Like generators, there are three types of d.c. motors characterized by the connections of field winding in relation to the armature viz.:

(i) Shunt-wound motor in which the field winding is connected in parallel with the armature. The current through the shunt field winding is not the same as the armature current. Shunt field windings are designed to produce the necessary m.m.f. by means of a relatively large number of turns of wire having high resistance. Therefore, shunt field current is relatively small compared with the armature current.

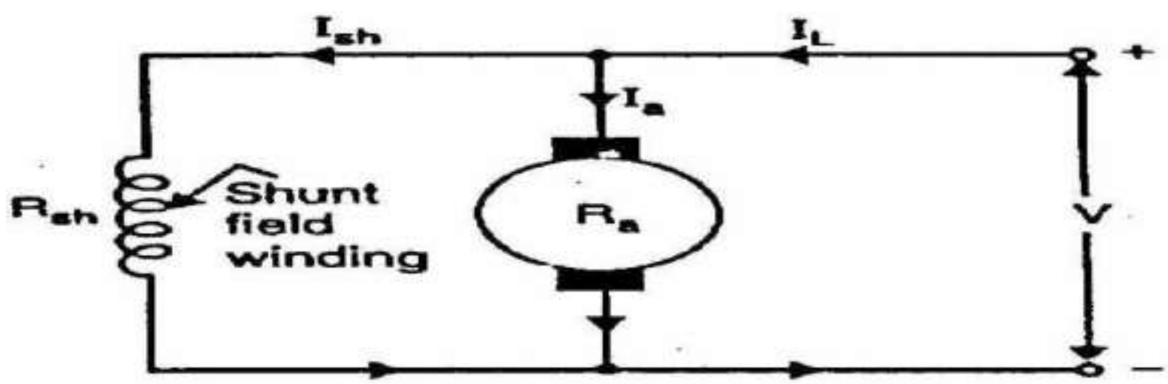


Figure 5.1.2 Shunt Field DC Motor

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 361]*

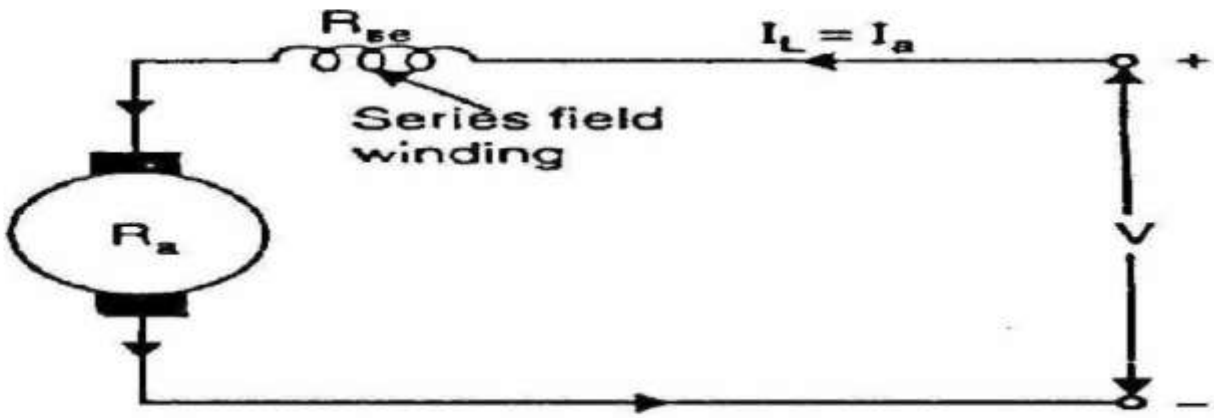


Figure 5.1.3 Series Field Motor

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 362]*

(ii) Series-wound motor in which the field winding is connected in series with the armature Therefore, series field winding carries the armature current. Since the current passing through a series field winding is the same as the armature current, series field windings must be designed with much fewer turns than shunt field windings for the same m.m.f. Therefore, a series field winding has a relatively small number of turns of thick wire and, therefore, will possess a low resistance.

(iii) Compound-wound motor which has two field windings; one connected in parallel with the armature and the other in series with it. There are two types of compound motor connections (like generators). When the shunt field winding is directly connected across the armature terminals it is called short-shunt connection. When the shunt winding is so connected that it shunts the series combination of armature and series field it is called long- shunt connection

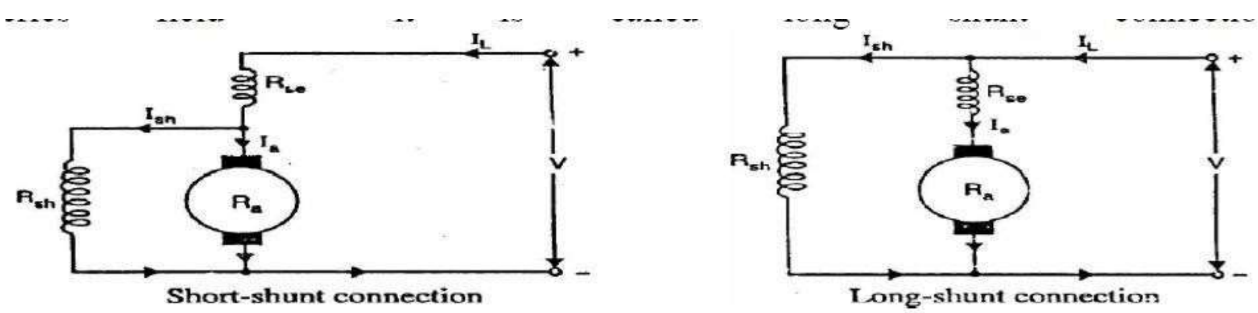


Figure 5.1.4 Long & Short Shunt Field

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 363]*

5.5 Retardation Test or Running Down on D.C Machines

In this article, we are going to discuss retardation test on dc machines. Retardation test is also called as running down test. This is the very efficient way to find out stray losses in dc shunt motors. In this test, we get total stray losses nothing but the combination of mechanical (friction & windage) and iron losses of the machine.

The circuit diagram of retardation test on dc machines shown below. A1, A2 are armature terminals.

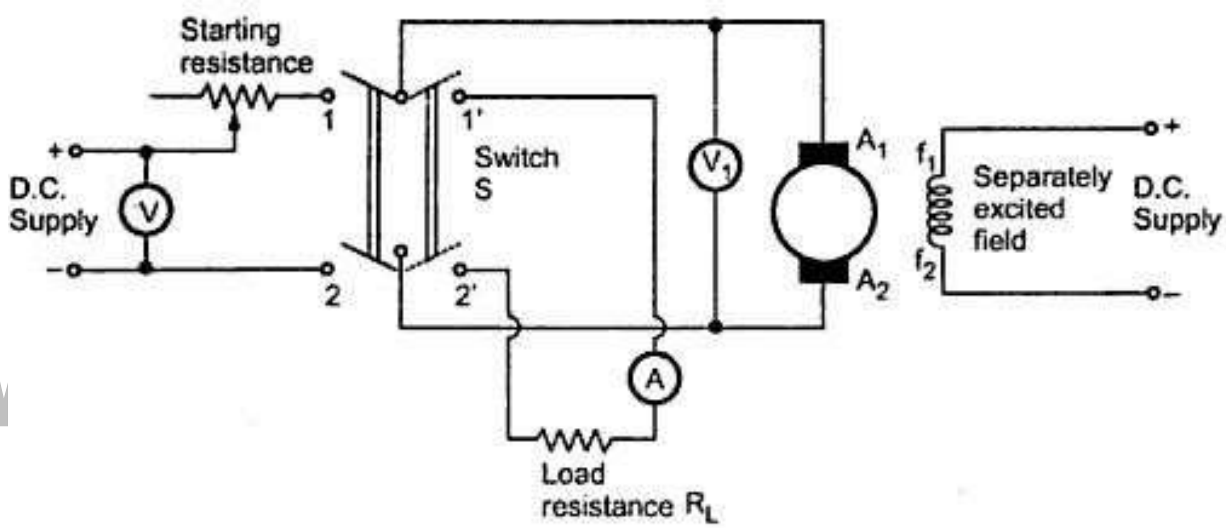


Figure 5.5.1 Retardation Test on D.C Machine

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 402]*

The procedure of Retardation Test on D.C Machines

The main points in the retardation or running down test are discussed below,

1. Now start the dc machine normally, run the machine slightly above the rated speed by adjusting resistance.

2. After achieving the rated speed just cut off the power supply to the armature, but keeping field normally excited.

3. Now wait for some time to fall down of speed below rated, then using the tachometer note down the values of speed (in rpm) and time (in the sec).

4. The armature consequently slows down and the amount of kinetic energy present in the armature is used to supply the rotational or stray losses which include iron, friction and winding loss. If I am the amount of inertia of the armature and is the angular velocity.

The kinetic energy of armature = $0.5\ I\omega^2$.

Rotational losses, W = Rate of change of kinetic energy.

$$W = \frac{d}{dt}\left(\frac{1}{2}I\omega^2\right) = I\omega\frac{d\omega}{dt}$$

I=Moment of inertia of the armature.

In retardation test of dc machines, the rotational losses are given by

Let N = normal speed in r.p.m.

ω = normal angular velocity in rad/s = $2\pi N/60$

$\therefore$ Rotational losses, W = Rate of loss of K.E. of armature

or $$W = \frac{d}{dt}\left(\frac{1}{2}I\omega^2\right) = I\omega\frac{d\omega}{dt}$$

Here I is the moment of inertia of the armature. As $\omega = 2\pi N/60$,

$$\therefore \quad W = I \times \frac{2\pi N}{60} \times \frac{d}{dt}\left(\frac{2\pi N}{60}\right) = \left(\frac{2\pi}{60}\right)^2 IN\frac{dN}{dt}$$

or $$W = 0.011\ IN\frac{dN}{dt}$$

Swinburne's Test

For a d.c shunt motor change of speed from no load to full load is quite small. Therefore, mechanical loss can be assumed to remain same from no load to full load. Also if field current is held constant during loading, the core loss too can be assumed to remain same.

In this test, the motor is run at rated speed under *no load* condition at rated voltage. The current drawn from the supply I_{L0} and the field current I_f are recorded.

Since the motor is operating under no load condition, net mechanical output power is zero. Hence the gross power developed by the armature must supply the core loss and friction & windage losses of the motor. Therefore,

$$P_{core} + P_{friction} = (V - I_{a0} r_a) I_{a0} = E_{b0} I_{a0}$$

Since, both *Pcore* and *Pfriction* for a shunt motor remains practically constant from no load to full load, the sum of these losses is called constant rotational loss

$$\text{constant rotational loss, } P_{rot} = P_{core} + P_{friction}$$

In the Swinburne's test, the constant rotational loss comprising of core and friction loss is estimated from the above equation.

After knowing the value of *Prot* from the Swinburne's test, we can fairly estimate the efficiency of the motor at any loading condition. Let the motor be loaded such that new current drawn from the supply is *IL* and the new armature current is *Ia*

The biggest advantage of Swinburne's test is that the shunt machine is to be run as motor under *no load* condition requiring little power to be drawn from the supply; based on the no load reading, efficiency can be predicted for any load current. However, this test is not sufficient if we want to know more about its performance (effect of armature reaction, temperature rise, commutation etc.) when it is actually loaded. Obviously the solution is to load the machine by connecting mechanical load directly on the shaft for motor or by connecting loading rheostat across the terminals for generator operation. This although sounds simple but difficult to implement in the laboratory for high rating machines (say above 20 kW), Thus the laboratory must have proper supply to deliver such a large power corresponding to the rating of the machine. Secondly, one should have loads to absorb this power.

Calculation of efficiency

Let field currents of the machines be are so adjusted that the second machine is acting as generator with armature current *Iag* and the first machine is acting as motor with armature current *Iam* as shown in figure 40.7. Also let us assume the current drawn from the supply be *I*1. Total power drawn from supply is *VI*1 which goes to supply all the losses (namely Cu losses in armature & field and rotational losses) of both the machines

$$
\begin{aligned}
\text{Power drawn from supply} &= VI_1 \\
\text{Field Cu loss for motor} &= VI_{fm} \\
\text{Field Cu loss for generator} &= VI_{fg} \\
\text{Armature Cu loss for motor} &= I_{am}^2 r_{am} \\
\text{Armature Cu loss for generator} &= I_{ag}^2 r_{ag} \\
\therefore \text{Rotational losses of both the machines} &= VI_1 - \left(VI_{fm} + VI_{fg} + I_{am}^2 r_{am} + I_{ag}^2 r_{ag}\right)
\end{aligned}
$$

Since speed of both the machines are same, it is reasonable to assume the rotational losses of both the machines are equal; which is strictly not correct as the field current of the generator will be a bit more than the field current of the motor, Thus, Once *Prot* is estimated for each machine we can proceed to calculate the efficiency of the machines as follows,

$$\text{Rotational loss of each machine, } P_{rot} = \frac{VI_1 - \left(VI_{fm} + VI_{fg} + I_{am}^2 r_{am} + I_{ag}^2 r_{ag}\right)}{2}$$

Efficiency of the motor

As pointed out earlier, for efficiency calculation of motor, first calculate the input power and then subtract the losses to get the output mechanical power as shown below,

$$
\begin{aligned}
\text{Total power input to the motor} &= \text{power input to its field} + \text{power input to its armature} \\
P_{inm} &= VI_{fm} + VI_{am} \\
\text{Losses of the motor} &= VI_{fm} + I_{am}^2 r_{am} + P_{rot} \\
\text{Net mechanical output power } P_{outm} &= P_{inm} - \left(VI_{fm} + I_{am}^2 r_{am} + P_{rot}\right) \\
\therefore \eta_m &= \frac{P_{outm}}{P_{inm}}
\end{aligned}
$$

Efficiency Of Generator

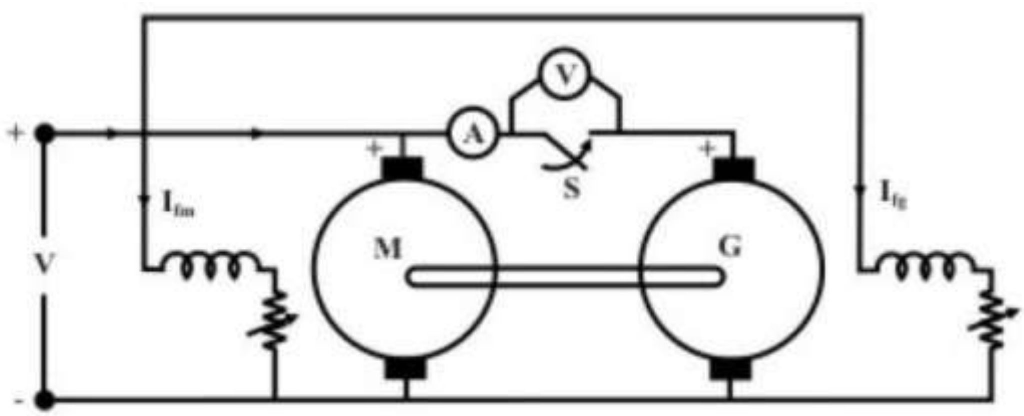
$$\text{Losses of the generator} = VI_{fg} + I_{ag}^2 r_{ag} + P_{rot}$$

$$\text{Input power to the generator, } P_{ing} = P_{outg} + \left(VI_{fg} + I_{ag}^2 r_{ag} + P_{rot}\right)$$

$$\therefore \eta_g = \frac{P_{outg}}{P_{ing}}$$

Hopkinson's Test

This as an elegant method of testing d.c machines. Here it will be shown that while power drawn from the supply only corresponds to no load losses of the machines, the armature physically carries any amount of current (which can be controlled with ease). Such a scenario can be created using two similar mechanically coupled shunt machines. Electrically these two machines are eventually connected in parallel and controlled in such a way that one machine acts as a generator and the other as motor. In other words two similar machines are required to carry out this testing which is not a bad proposition for manufacturer as large numbers of similar machines are manufactured.



ocedure

Figure 5.5.2 Hopkinson Test

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 411]*

Procedure

Connect the two similar (same rating) coupled machines as shown in figure 40.6. With switch S opened, the first machine is run as a shunt motor at rated speed. It may be noted that the second machine is operating as a separately excited generator because its field winding is excited and it is driven by the first machine. Now the question is what will be the reading of the voltmeter connected across the opened switch S? The reading may be (i) either close to twice supply voltage or (ii) small voltage. In fact the voltmeter practically reads the difference of the induced voltages in the armature of the machines. The upper armature terminal of the generator may have either + ve or negative polarity. If it happens to be +ve, then voltmeter reading will be small otherwise it will be almost double the supply voltage

Since the goal is to connect the two machines in parallel, we must first ensure voltmeter reading is small. In case we find voltmeter reading is high, we should switch off the supply, reverse the armature connection of the generator and start afresh. Now voltmeter is found to read small although time is still not ripe enough to close S for paralleling the machines. Any attempt to close the switch may result into large circulating current as the armature resistances are small. Now by adjusting the field current Ifg of the generator the voltmeter reading may be adjusted to zero ($Eg \approx Eb$) and S is now closed. Both the machines are now connected in parallel

Loading the machines

After the machines are successfully connected in parallel, we go for loading the machines i.e., increasing the armature currents. Just after paralleling the ammeter reading A will be close to zero as $Eg \approx Eb$. Now if Ifg is increased (by decreasing Rfg), then Eg becomes greater than Eb and both Iag and Iam increase, Thus by increasing field current of generator (alternatively decreasing field current of motor) one can make $Eg > Eb$ so as to make the second machine act as generator and first machine as motor. In practice, it is also required to control the field current of the motor Ifm to maintain speed constant at rated value. The interesting point to be noted here is that *Iag* and *Iam* do not reflect in the supply side line. Thus current drawn from supply remains small (corresponding to losses of both the machines). The loading is sustained by the output power of the generator running

Advantages of Hopkinson's Test

1. This test requires very small power compared to full- load power of the motor-generator coupled system. That is why it is economical.

2. Temperature rise and commutation can be observed and maintained in the limit because this test is done under full load condition.

3. Change in iron loss due to flux distortion can be taken into account due to the advantage of its full load condition

Disadvantages of Hopkinson's Test

The demerits of this test are

1. It is difficult to find two identical machines needed for Hopkinson's test.

2. Both machines cannot be loaded equally all the time.

3. It is not possible to get separate iron losses for the two machines though they are different because of their excitations.

4. It is difficult to operate the machines at rated speed because field currents vary widely.

39.8 Braking of d.c shunt motor: basic idea

It is often necessary in many applications to stop a running motor rather quickly. We know that any moving or rotating object acquires kinetic energy. Therefore, how fast we can bring the object to rest will depend essentially upon how quickly we can extract its kinetic energy and make arrangement to dissipate that energy somewhere else. If you stop pedaling your bicycle, it will eventually come to a stop eventually after moving quite some distance. The initial kinetic energy stored, in this case dissipates as heat in the friction of the road. However, to make the stopping faster, brake is applied with the help of rubber brake shoes on the rim of the wheels. Thus stored K.E now gets two ways of getting dissipated, one at the wheel-brake shoe interface (where most of the energy is dissipated) and the other at the road-tier interface. This is a good method no doubt, but regular maintenance of brake shoes due to wear and tear is necessary.

If a motor is simply disconnected from supply it will eventually come to stop no doubt, but will take longer time particularly for large motors having high rotational inertia. Because here the stored energy has to dissipate mainly through bearing friction and wind friction. The situation can be improved, by forcing the motor to operate as a generator during braking. The idea can be understood remembering that in motor mode electromagnetic torque acts along the direction of rotation while in generator the electromagnetic torque acts in the opposite direction of rotation. Thus by forcing the machine to operate as generator during the braking period, a torque opposite to the direction of rotation will be imposed on the shaft, thereby helping the machine to come to stop quickly. During braking action, the initial K.E stored in the rotor is either dissipated in an external resistance or fed back to the supply or both

5.2 MOTOR CHARACTERISTICS

Torque/Speed Curves

In order to effectively design with D.C. motors, it is necessary to understand their characteristic curves. For every motor, there is a specific Torque/Speed curve and Power curve

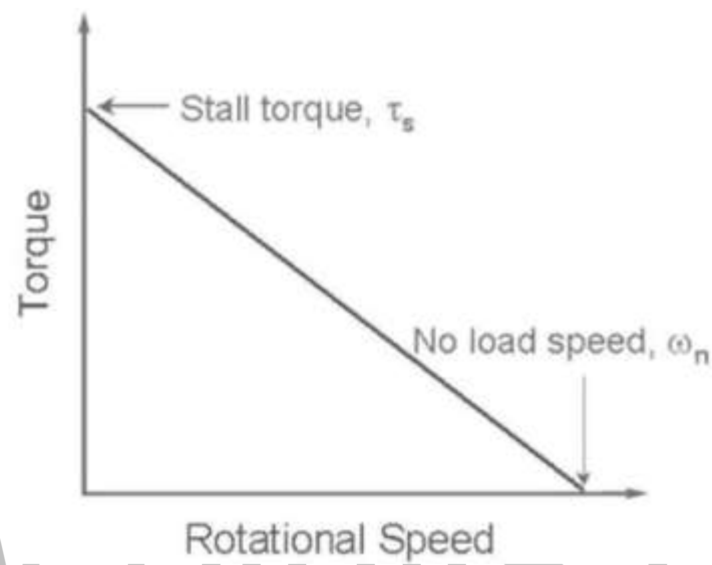


Figure 5.2.1 Speed Vs Torque Curve

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 365]*

The graph above shows a torque/speed curve of a typical D.C. motor. Note that torque is inversely proportional to the speed of the output shaft. In other words, there is a tradeoff between how much torque a motor delivers, and how fast the output shaft spins. Motor characteristics are frequently given as two points on this graph: The stall torque represents the point on the graph at which the torque is a maximum, but the shaft is not rotating.

The no load speed, is the maximum output speed of the motor (when no torque is applied to the output shaft). The linear model of a D.C. motor torque/speed curve is a very good approximation. The torque/speed curves shown below are actual curves for the green maxon motor (pictured at right) used by students in 2.007. One is a plot of empirical data, and the other was plotted mechanically using a device developed at MIT.

Note that the characteristic torque/speed curve for this motor is quite linear. This is generally true as long as the curve represents the direct output of the motor, or a simple gear reduced output. If the specifications are given as two points, it is safe to assume a linear curve.

Recall that earlier we defined power as the product of torque and angular velocity. This corresponds to the area of a rectangle under the torque/speed curve with one corner attheorigin and another corner at a point on the curve. Due to the linear inverse relationship between torque and speed, the maximum power occurs at the point where Recall that earlier we defined power as the product of torque and angular velocity.

Power/Torque and Power/Speed Curves

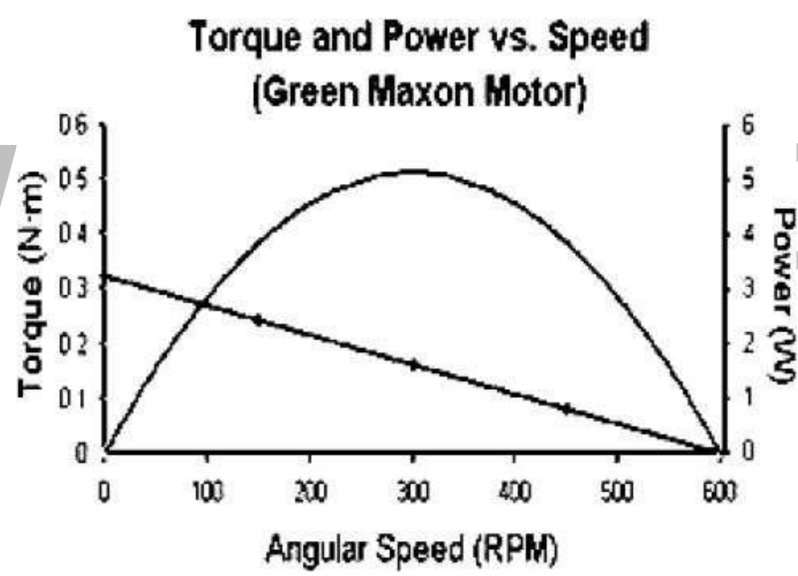


Figure 5.5 Power Vs Torque Curve

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 366]*

5.3 SPEED CONTROL OF DC SHUNT MOTOR

Where, Va is the voltage applied across the armature, N is the rotor speed and φ is the flux per pole and is proportional to the field current If. As explained earlier, armature current Ia is decided by the mechanical load present on the shaft. Therefore, by varying Va and If we can vary n. For fixed supply voltage and the motor connected as shunt we can vary Va by controlling an external resistance connected in series with the armature. If of course can be varied by controlling external field resistance Rf connected with the field circuit. Thus for. shunt motor we have essentially two methods for controlling speed, namely by:

1. Varying Armature Resistance
2. Varying Field Resistance

Speed Control by Varying Armature Resistance

The inherent armature resistance Ra being small, speed n versus armature current (Ia) characteristic will be a straight line with a small negative slope as shown in figure

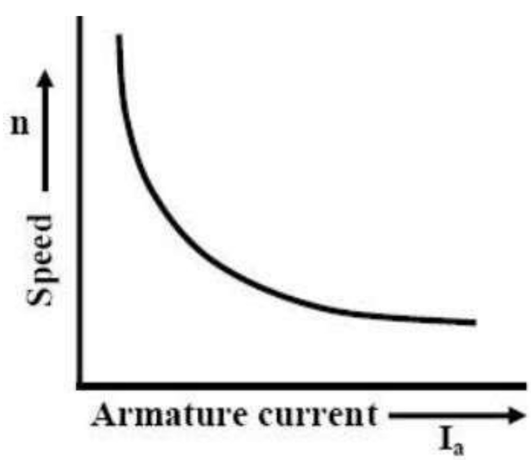


Figure 5.3.1 Speed Vs Armature Current

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 376]*

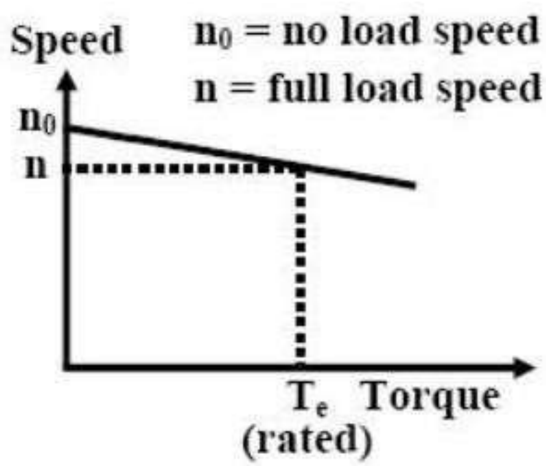


Figure 5.3.2 Speed Vs Torque

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 377]*

Note that for shunt motor voltage applied to the field and armature circuit are same and equal to the supply voltage V. However, as the motor is loaded, Ia Ra drop increase making speed a little less than the no load speed n0. For a well designed shunt motor this drop in speed is small and about 3 to 5% with respect to no load speed. This drop in speed from no load to full load condition expressed as a percentage of no load speed is called the inherent speed regulation of the motor. It is for this reason, a d.c shunt motor is said to be practically a constant speed motor since speed drops by a small amount from no load to full load condition.

From these characteristic it can be explained how speed control is achieved. Let us assume that the load torque TL is constant and field current is also kept constant. Therefore, since steady state operation demands Te = TL, Te= kIaφ too will remain constant; which means Ia will not change. Suppose Rest = 0, then at rated load torque, operating point will be at C and motor speed will be n. If additional resistance rext1 is introduced in the armature circuit, new steady state operating speed will be n1 corresponding to the operating point D.

This same load torque is supplied at various speed. Variation of the speed is smooth and speed will decrease smoothly if Rest is increased. Obviously, this method is suitable for controlling speed below the base speed and for supplying constant rated load torque which ensures rated armature current always. Although, this method provides smooth wide range speed control (from base speed down to zero speed), has a serious draw back since energy loss takes place in the external resistance Rest reducing the efficiency of the motor.

Speed Control by Varying Field Current

In this method field circuit resistance is varied to control the speed of a d.c shunt motor. Let us rewrite .the basic equation to understand the method.

If flux φ will change, hence speed will vary. To change If an external resistance is connected in series with the field windings. The field coil produces rated flux when no external resistance is connected and rated voltage is applied across field coil.

It should be understood that we can only decrease flux from its rated value by adding external resistance. Thus the speed of the motor will rise as we decrease the field current and speed control above the base speed will be achieved. Speed versus armature current characteristic is shown in figure for two flux values φ and φ1. Since φ1<φ, the no load speed no' for flux value φ1 is more than the no load speed no corresponding to φ.

However, this method will not be suitable for constant load torque .To make this point clear, let us assume that the load torque is constant at rated value. So from the initial steady condition, we have TL rated=Ta1= k=Ia rated .If load torque remains constant and flux is reduced to φ1, new armature current in the steady state is obtained from kI a1=TL rated . Therefore new armature current is but this fraction is less than 1. Hence new armature current will be greater than the rated armature current and the motor will be overloaded. This method therefore, will be suitable for a load whose torque demand decreases with the rise in speed keeping the output power constant as shown in figure. Obviously this method is based on flux weakening of the main field.

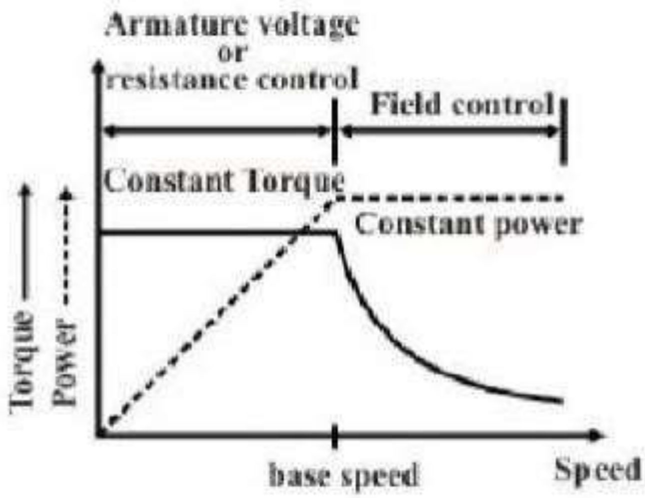


Figure 5.3.3 Constant Torque Power operation

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 379]*

Starting of DC Motors

The speed of the machine has to be increased from zero and brought to the operating speed. This is called starting of the motor. The operating speed itself should be varied as per the requirements of the load. This is called speed control. Finally, the running machine has to be brought to rest, by decelerating the same. This is called braking. At the instant of starting, rotor speed n = 0, hence starting armature current is Ist=V/ra. Since, armature resistance is quite small, starting current may be quite high (many times larger than the rated current). A large machine, characterized by large rotor inertia (J), will pick up speed rather slowly. Thus the level of high starting current may be maintained for quite some time so as to cause serious damage to the brush/commutator and to the armature winding. Also the source should be capable of supplying this burst of large current. The other loads already connected to the same source, would experience a dip in the terminal voltage, every time a D.C motor is attempted to start with full voltage. This dip in supply voltage is caused due to sudden rise in voltage drop in the source's internal resistance. The duration for which this drop in voltage will persist once again depends on inertia of the motor. Hence, for small D.C motors extra precaution may not be necessary during starting as large starting current will very quickly die down because of fast rise in the back emf. However, for large motor, a starter is to be used during starting.

A simple starter to limit the starting current, a suitable external resistance R is connected in series, as shown in the figure, with the armature so that Ist=V/(R+ra) At the time of starting, to have sufficient starting torque, field current is maximized by keeping external field resistance Rf to zero value. As the motor picks up speed,the value of R is gradually decreased to zero so that during running no external resistance remains in the armature circuit. But each time one has to restart the motor, the external armature resistance must be set to maximum value by moving the jockey manually. Now if the supply goes off, motor will come to a stop. All on a sudden, let us imagine, supply is restored.

This is then nothing but full voltage starting. In other words, one should be constantly alert to set the resistance to maximum value whenever the motor comes to a stop. This is one major limitation of a simple rheostatic starter

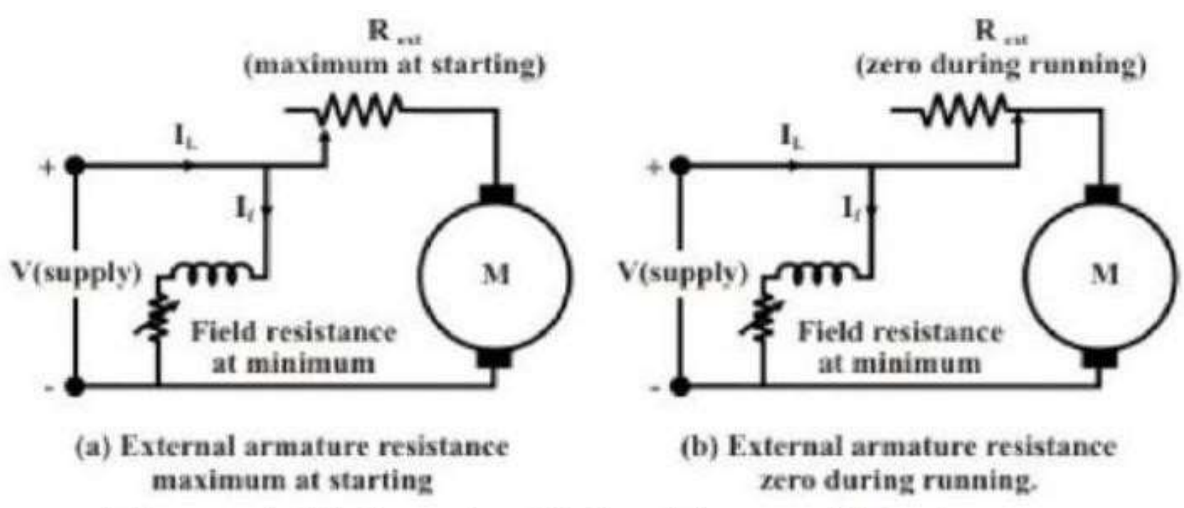


Figure 5.3.4 Starting using External resistance

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 381]*

Three Point Starter

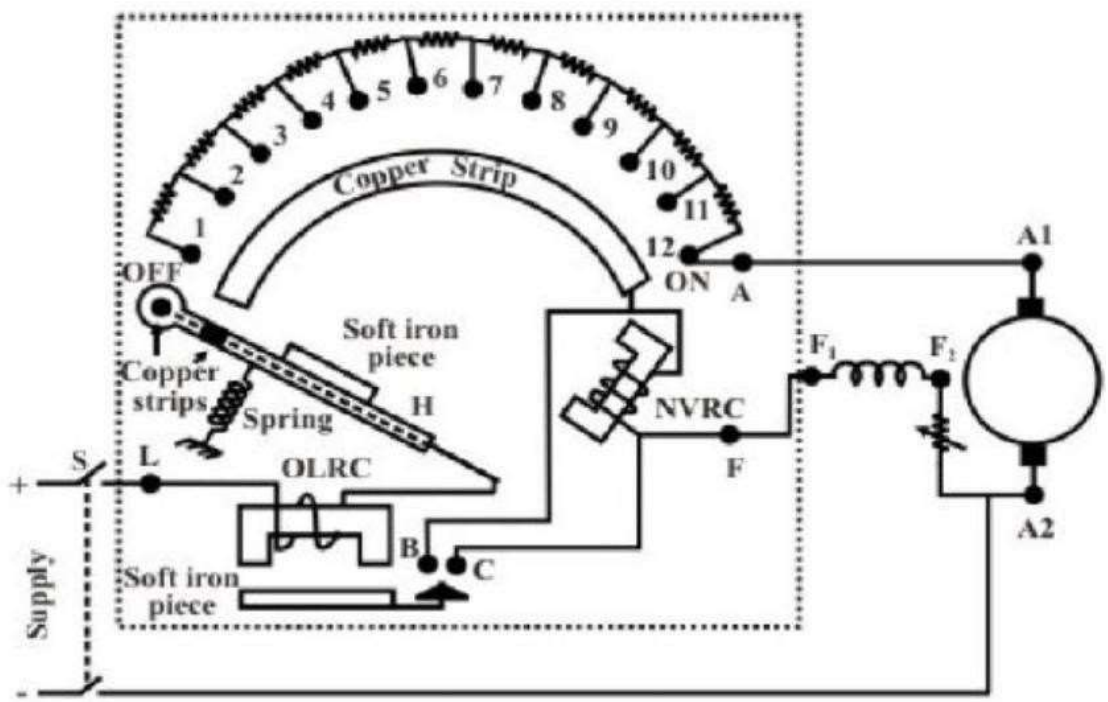


Figure 5.3.5 Three Point Starter

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman*, Page: 381]*

A "3-point starter" is extensively used to start a D.C shunt motor. It not only overcomes the difficulty of a plain resistance starter, but also provides additional protective features such as over load protection and no volt protection. The diagram of a 3-point starter connected to a shunt motor is shown in figure. Although, the circuit looks a bit clumsy at a first glance, the basic working principle is same as that of plain resistance starter. The starter is shown enclosed within the dotted rectangular box having three terminals marked as A, L and F for external connections. Terminal A is connected to one armature terminal Al of the motor. Terminal F is connected to one field terminal F1 of the motor and terminal L is connected to one supply terminal as shown. F2 terminal of field coil is connected to A2 through an external variable field resistance and the common point connected to supply (-ve). The external armatures resistances consist of several resistances connected in series and are shown in the form of an arc. The junctions of the resistances are brought out as terminals and marked. Just beneath the resistances, a continuous copper strip also in the form of an arc is present ,There is a handle which can be moved in the clockwise direction against the spring tension. The spring tension keeps the handle in the OFF position when no one attempts to move it. Now let us trace the circuit from terminal L (supply + ve). The wire from L passes through a small electro magnet called OLRC, (the function of which we shall discuss a little later) and enters through the handle shown by dashed lines. Near the end of the handle two copper strips are firmly connected with the wire.

The furthest strip is shown circular shaped and the other strip is shown to be rectangular. When the handle is moved to the right, the circular strip of the handle will make contacts with resistance terminals 1, 2 etc. Progressively. On the other hand, the rectangular strip will make contact with the continuous arc copper strip. The other end of this strip is brought as terminal F after going through an electromagnet coil (called NVRC). Terminal F is finally connected to motor field terminal Fl.

Working Principle

In the operation of the starter, initially the handle is in the OFF position. Neither armature nor the field of the motor gets supply. Now the handle is moved to stud number 1. In this position armature and all the resistances in series gets connected to the supply. Field coil gets full supply as the rectangular strip makes contact with arc copper strip. As the machine picks up speed handle is moved further to stud number 2. In this position the external resistance in the armature circuit is less as the first resistance is left out. Field however, continues to get full voltage by virtue of the continuous arc strip. Continuing in this way, all resistances will be left out when stud number 12 (ON) is reached. In this position, the electromagnet (NVRC) will attract the soft iron piece attached to the handle. Even if the operator removes his hand from the handle, it will still remain in the ON position as spring restoring force will be balanced by the force of attraction between

NVRC and the soft iron piece of the handle. The no volt release coil (NVRC) carries same current as that of the field coil. In case supply voltage goes off, field coil current will decrease to zero. Hence NVRC will be de-energized and will not be able to exert any force on the soft iron piece of the handle. Restoring force of the spring will bring the handle back in the OFF position.

The starter also provides over load protection for the motor. The other electromagnet, OLRC overload release coil along with a soft iron piece kept under it, is used to achieve this. The current flowing through OLRC is the line current IL drawn by the motor. As the motor is loaded, Ia hence IL increases. Therefore, IL is a measure of loading of the motor. This upward movement of the iron piece of OLRC is utilized to de-energize NVRC. To the iron a copper strip is attached. During over loading condition, this copper strip will also move up and put a short circuit between two terminals B and C. Carefully note that B and C are nothing but the two ends of the NVRC. In other words, when over load occurs a short circuit path is created across the NVRC. Hence NVRC will not carry any current now and gets de-energized. The moment it gets de-energized, spring action will bring the handle in the OFF position thereby disconnecting the motor from the supply. Three point starter has one disadvantage. If we want to run the machine at higher speed (above rated speed) by field weakening (i.e., by reducing field current), the strength of NVRC magnet may become so weak that it will fail to hold the handle in the ON position and the spring action will bring it back in the OFF position. Thus we find that a false disconnection of the motor takes place even when there is neither over load nor any sudden disruption of supply.

Four Point Starter

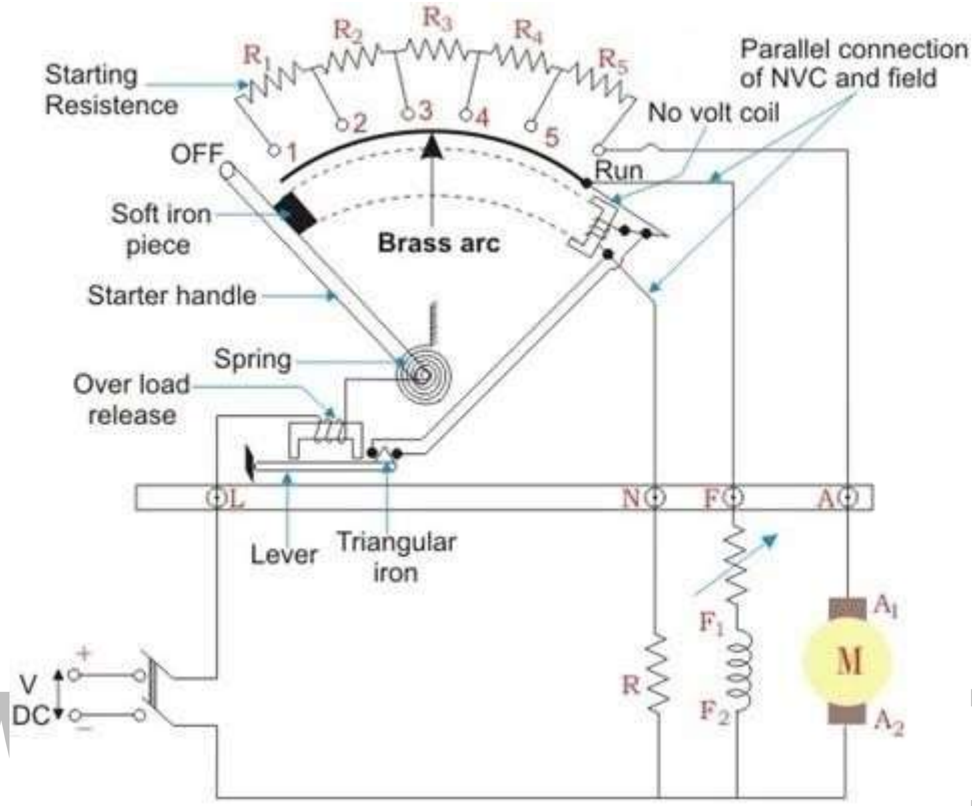


Figure 5.3.6 Four Point Starter

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 383]*

A 4 point starter protects the armature of a DC shunt motor or compound wound DC motor against the initially high starting current of the DC motor.The 4 point starter has a lot of constructional and functional similarity to a 3 point starter, but this special device has an additional point and coil in its construction (as the name suggests). This brings about some difference in its functionality, though the basic operational characteristic remains the same. The basic difference in the circuit of a 4 point starter as compared to 3 point starter is that the holding coil is removed from the shunt field current and is connected directly across the line with current limiting resistance in series.

A 4 point starter as the name suggests has 4 main operational points, namely

1. 'L' Line terminal (Connected to positive of supply.)
2. 'A' Armature terminal (Connected to the armature winding.)
3. 'F' Field terminal. (Connected to the field winding.)
4. Like in the case of the 3 point starter, and in addition to it there is, A 4th point N (Connected to the No Voltage Coil NVC)

The remarkable difference in case of a 4 point starter is that the No Voltage Coil is connected independently across the supply through the fourth terminal called 'N' in addition to the 'L', 'F' and 'A'. As a direct consequence of that, any change in the field supply current does not bring about any difference in the performance of the NVC. Thus it must be ensured that no voltage coil always produce a force which is strong enough to hold the handle in its 'RUN' position, against the force of the spring, under all the operational conditions. Such a current is adjusted through No Voltage Coil with the help of fixed resistance R connected in series with the NVC using fourth point 'N' as shown in the figure above.

Apart from this above mentioned fact, the 4 point and 3 point starters are similar in all other ways like possessing is a variable resistance, integrated into number of sections as shown in the figure above. The contact points of these sections are called studs and are shown separately as OFF, 1, 2, 3, 4, 5, RUN, over which the handle is free to be maneuvered manually to regulate the starting current with gathering speed.

Now to understand its way of operating let's have a closer look at the diagram given above. Considering that supply is given and the handle is taken stud No.1, then the circuit is complete and the line current that starts flowing through the starter. In this situation we can see that the current will be divided into 3 parts, flowing through 3 different points.

1. 1 part flows through the starting resistance (R_1+ R_2 + R_3…..) and then to the armature.
2. A 2nd part flowing through the field winding F.

3. And a 3rd part flowing through the no voltage coil in series with the protective resistance R.

So the point to be noted here is that with this particular arrangement any change in the shunt field circuit does not bring about any change in the no voltage coil as the two circuits are independent of each other.

This essentially means that the electromagnet pull subjected upon the soft iron bar of the handle by the no voltage coil at all points of time should be high enough to keep the handle at its RUN position, or rather prevent the spring force from restoring the handle at its original OFF position, irrespective of how the field rheostat is adjusted.