Speed Control of DC Motors: the speed of a motor is given by the relation

$N=\frac{V-I_aR_a}{Z\phi}\left(\frac{60A}{p}\right)=K\frac{V-I_aR_a}{\phi}$ where R_a= armature circuit resistance. It is obvious that the speed can be controlled by varying

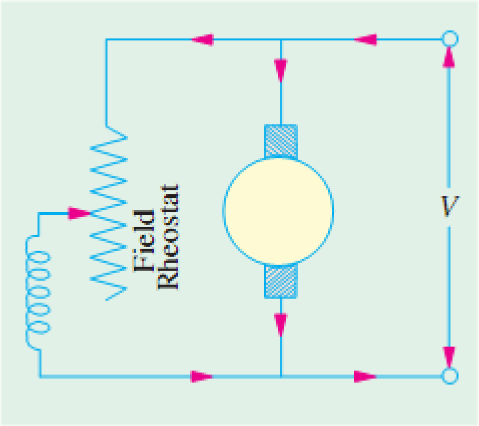
(*i*) Flux/pole, Φ (Flux Control)

(*ii*) Resistance R_a of armature circuit (Rheostatic Control) and

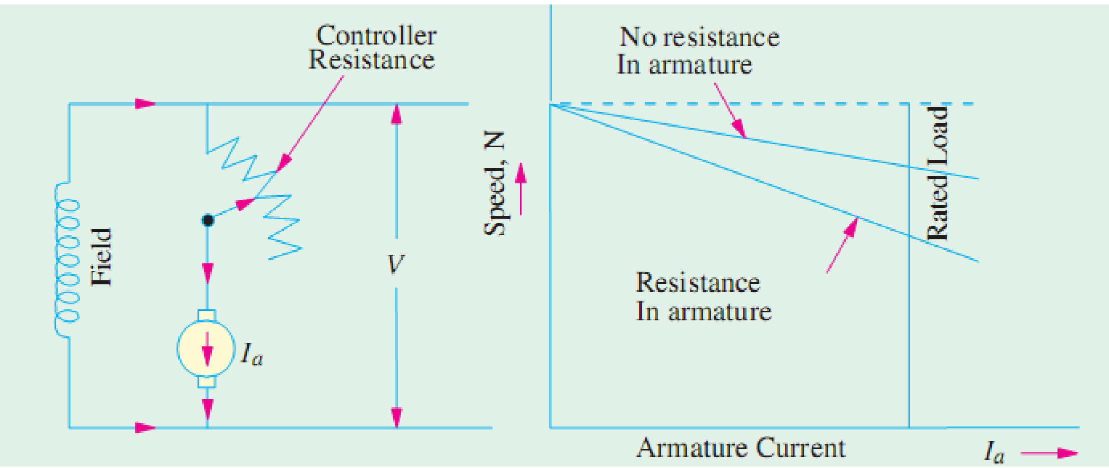
(*iii*) Applied voltage V (Voltage Control).

Speed Control of Shunt motor:

(*i*) Variation of Flux or Flux Control Method: By decreasing the flux, the speed can be increased and vice versa. The flux of a dc motor can be changed by changing I_{sh} with help of a shunt field rheostat. Since I_{sh} is relatively small, shunt field rheostat has to carry only a small current, which means $I^2_{sh}R$ loss is small, so that rheostat is small in size.



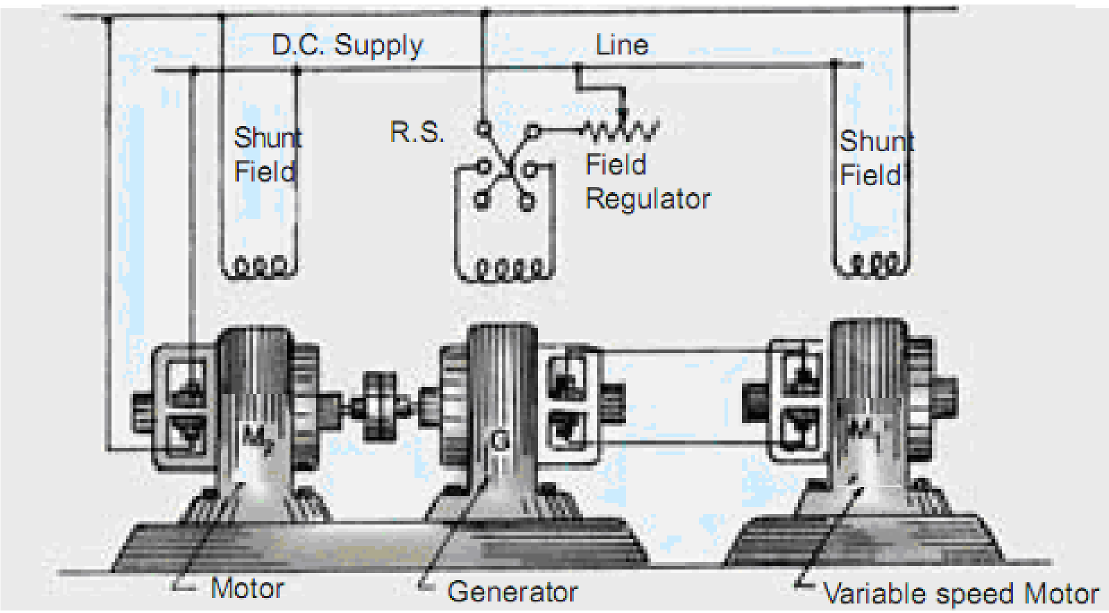
(ii) Armature or Rheostatic Control Method: This method is used when speeds below the no-load speed are required. As the supply voltage is normally constant, the voltage across the armature is varied by inserting a variable rheostat in series with the armature circuit. As controller resistance is increased, voltage across the armature is decreased, thereby decreasing the armature speed. For a load constant torque, speed is approximately proportional to the voltage across the armature. From the speed/armature current characteristic, it is seen that greater the resistance in the armature circuit, greater is the fall in the speed.



(iii) Voltage Control Method:

(a) Multiple Voltage Control: In this method, the shunt field of the motor is connected permanently to a fixed exciting voltage, but the armature is supplied with different voltages by connecting it across one of the several different voltages by means of suitable switchgear. The armature speed will be approximately proportional to these different voltages. The intermediate speeds can be obtained by adjusting the shunt field regulator.

(b) Ward-Leonard System: This system is used where an unusually wide and very sensitive speed control is required as for colliery winders, electric excavators, elevators and the main drives in steel mills and blooming and paper mills. M1 is the main motor whose speed control is required. The field of this motor is permanently connected across the dc supply lines. By applying a variable voltage across its armature, any desired speed can be obtained. This variable voltage is supplied by a motor-generator set which consists of either a dc or an ac motor M2 directly coupled to generator G. The motor M2 runs at an approximately constant speed. The output voltage of G is directly fed to the main motor M1. The voltage of the generator can be varied from zero up to its maximum value by means of its field regulator. By reversing the direction of the field current of G by means of the reversing switch RS, generated voltage can be reversed and hence the direction of rotation of M1. It should be remembered that motor generator set always runs in the same direction.

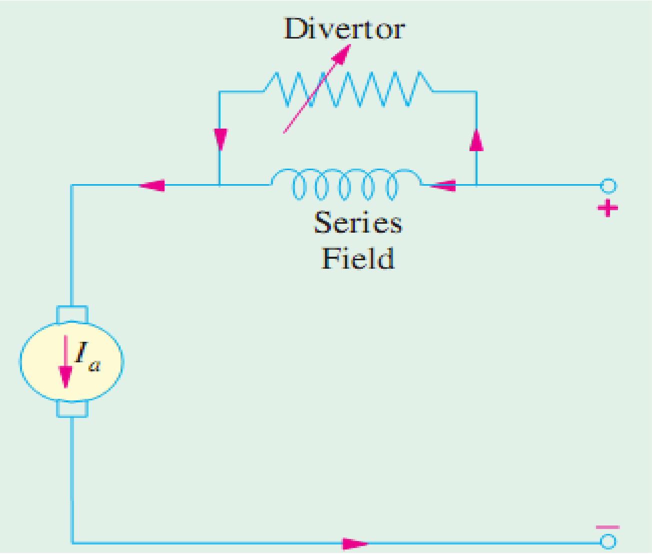


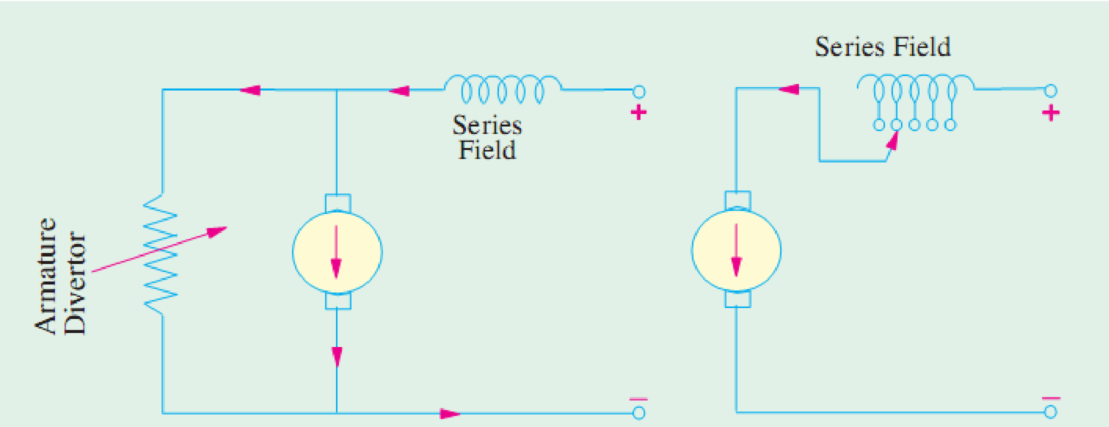
Speed Control of Series Motors:

1. Flux Control Method: Variations in the flux of a series motor can be brought about in any one of the following ways:

(a) Field Diverters: The series winding are shunted by a variable resistance known as field diverter. Any desired amount of current can be passed through the diverter by adjusting its resistance. Hence the flux can be decreased and consequently, the speed of the motor increased.

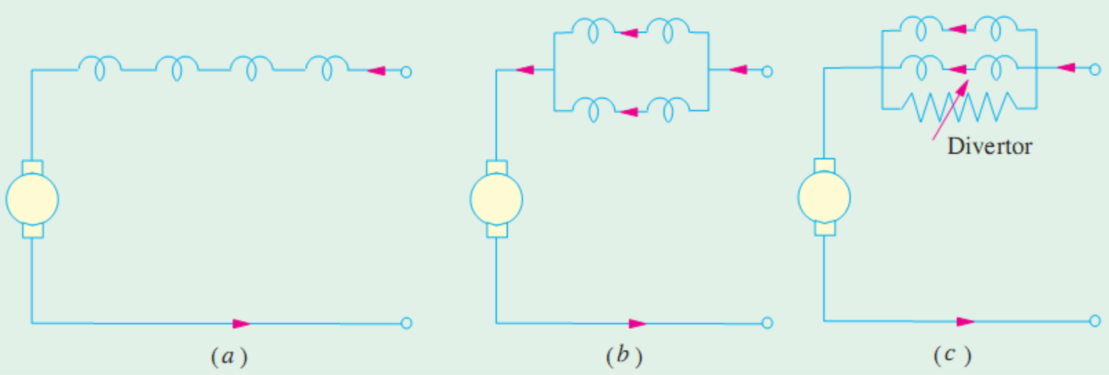
(b) Armature Diverter: A diverter across the armature can be used for giving speeds lower than the normal speed. For a given constant load torque, if I_a is reduced due to armature diverter, the ϕ must increase ($\because T_a \propto \phi I_a$) This results in an increase in current taken from the supply (which increases the flux and a fall in speed ($N \propto I/\phi$)). The variation in speed can be controlled by varying the diverter resistance.



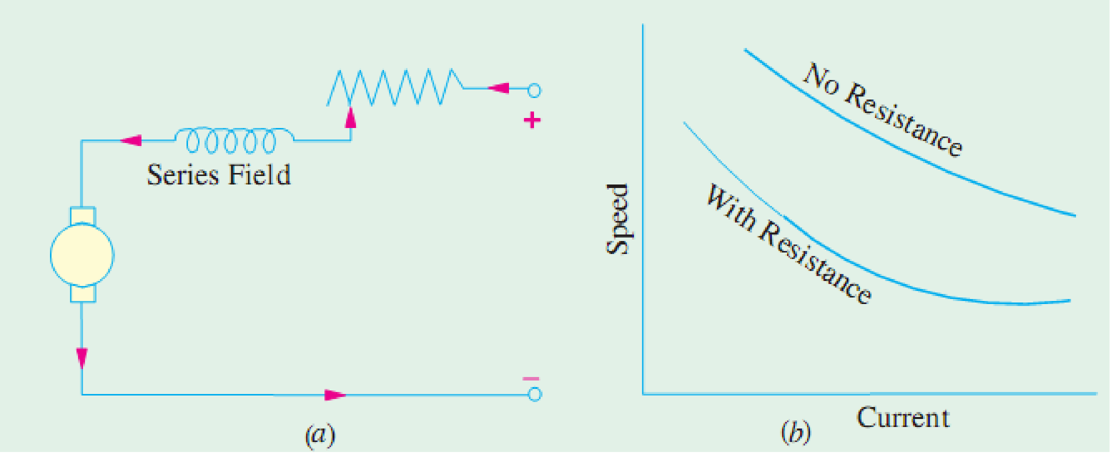


(c) Trapped Field Control Field: This method is often used in electric traction. The number of series filed turns in the circuit can be changed. With full field, the motor runs at its minimum speed which can be raised in steps by cutting out some of the series turns.

(d) Paralleling Field coils: this method used for fan motors, several speeds can be obtained by regrouping the field coils. It is seen that for a 4-pole motor, three speeds can be obtained easily.



2. Variable Resistance in Series with Motor: By increasing the resistance in series with the armature the voltage applied across the armature terminals can be decreased. With reduced voltage across the armature, the speed is reduced. However, it will be noted that since full motor current passes through this resistance, there is a considerable loss of power in it.



Problems 4

1- *A 230 V dc shunt motor runs at 800 rpm and takes armature current of 50 A. Find resistance to be added to the field circuit to increase speed to 1000 rpm at an armature current of 80 A. Assume flux proportional to field current. Armature resistance = 0.15 Ω and field winding resistance = 250 Ω.*

2- *A 250 V, dc shunt motor has an armature resistance of 0.5 Ω and a field resistance of 250 Ω. When driving a load of constant torque at 600 rpm, the armature current is 20 A. If it is desired to raise the speed from 600 to 800 rpm, what resistance should be inserted in the shunt field circuit? Assume that the magnetic circuit is unsaturated.*

3- *A dc shunt motor takes an armature current of 20 A from a 220 V supply. Armature circuit resistance is 0.5 ohm. For reducing the speed by 50%, calculate the resistance required in the series, with the armature, if (a) the load torque is constant (b) the load torque is proportional to the square of the speed.*

4- *A 7.48 kW, 220 V, 990 rpm shunt motor has a full load efficiency of 88%, the armature resistance is 0.08 ohm and shunt field current is 2 A. If the speed of this motor is reduced to 450 rpm by inserting a resistance in the armature* *circuit, find the motor output, the armature current, external resistance to be inserted in the armature circuit and overall efficiency. Assume the load torque to remain constant.*

5- *A 250 V dc shunt motor has armature circuit resistance of 0.5 Ω and a field circuit resistance of 125 Ω. It drives a load at 1000 rpm and takes 30 A. The field circuit resistance is then slowly increased to 150 Ω. If the flux and field current can be assumed to be proportional and if the load torque remains constant, calculate the final speed and armature current. [1186 rpm. 33.6 A]*

6- *A shunt-wound motor has a field resistance of 400 Ω and an armature resistance of 0.1 Ω and runs off 240 V supply. The armature current is 60 A and the motor speed is 900 rpm; Assuming a straight line magnetization curve, calculate (a) the additional resistance in the field to increase the speed to 1000 rpm for the same armature current and (b) the speed with the original field current of 200 A. [(a) 44.4 Ω (b) 842.5 rpm]*

7- *A 250-V shunt motor has an armature current of 20 A when running at 1000 rpm against full load torque. The armature resistance is 0.5 Ω. What resistance must be inserted in series with the armature to reduce the speed to 500 rpm at the same torque and what will be the speed if the load torque is halved with this resistance in the circuit? Assume the flux to remain constant throughout and neglect brush contact drop.*

8- *A 7.46 kW, 220 V, 900 rpm shunt motor has a full-load efficiency of 88 per cent, an armature resistance of 0.08 Ω and shunt field current of 2 A. If the speed of this motor is reduced to 450 rpm by inserting a resistance in the armature circuit, the load torque remaining constant, find the motor output, the armature current, the external resistance and the overall efficiency.*

9- *A 200 V, dc series motor takes 40 A when running at 700 rpm. Calculate the speed at which the motor will run and the current taken from the supply if the field is shunted by a resistance equal to the field resistance and the load torque is increased by 50%. Armature resistance = 0.15 Ω, field resistance = 0.1 Ω It may be assumed that flux per pole is proportional to the field.*

10- *A 4-pole, 250 V dc series motor takes 20 A and runs at 900 rpm each field coil has resistance of 0.025 ohm and the resistance of the armature is 0.1 ohm. At what speed will the motor run developing the same torque if : (i) a diverter of 0.2 ohm is connected in parallel with the series field (ii) rearranging the* *field coils in two series and parallel groups Assume unsaturated magnetic operation.*

11- *A 200V, dc series motor runs at 500rpm when taking a line current of 25A. The resistance of the armature is 0.2Ω and that of the series field 0.6Ω. At what speed will it run when developing the same torque when armature diverter of 10Ω is used? Assume a straight line magnetization curve*.[**314rpm]**

Electric Braking: A motor and its load may be brought to rest quickly by using either (i) Friction Braking or (ii) Electric Braking. Mechanical brake has one drawback: it is difficult to achieve a smooth stop because it depends on the condition of the braking surface as well as on the skill of the operator. The excellent electric braking methods are available which eliminate the need of brake lining levers and other mechanical gadgets. Electric braking, both for shunt and series motors, is of the following three types:

(i) Rheostatic or dynamic braking

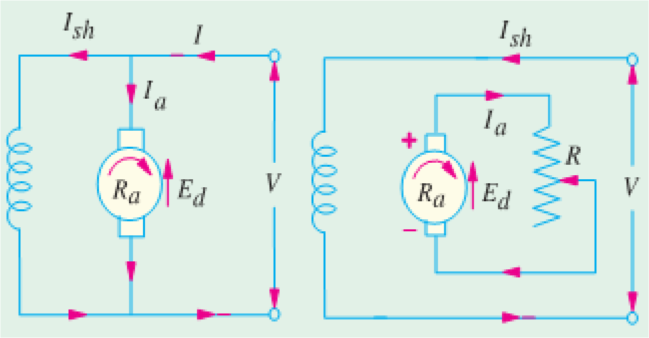
(ii) Plugging i.e., reversal of torque so that armature tends to rotate in the opposite direction.

(iii) Regenerative braking.

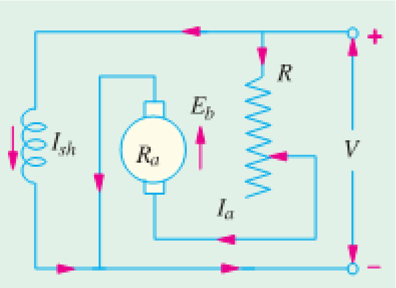
Obviously, friction brake is necessary for holding the motor even after it has been brought to rest.

Electric Braking of Shunt Motors:

(a) Rheostatic or Dynamic Braking: In this method, the armature of the shunt motor is disconnected from the supply and is connected across a variable resistance R. The field winding is left connected across the supply. The braking effect is controlled by varying the series resistance R. Obviously, this method makes use of generator action in a motor to bring it to rest.



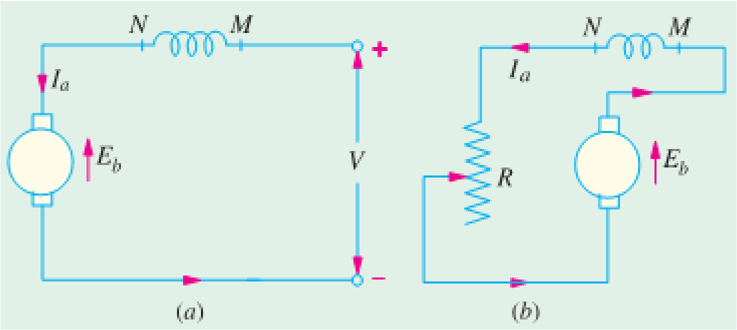
(b) Plugging or Reverse Current Braking: This method is commonly used in controlling elevators, rolling mills, printing presses and machine tools etc. In this method, connections to the armature terminals are reversed so that motor tends to run in the opposite direction. Due to the reversal of armature connections, applied voltage V and E start acting in the same direction around the circuit. In order to limit the armature current to a reasonable value, it is necessary to insert a resistor in the circuit while reversing armature connections.



(c) Regenerative Braking: This method is used when the load on the motor has over-hauling characteristic as in the lowering of the cage of a hoist or the downgrade motion of an electric train. Regeneration takes place when E_b becomes grater than V. This happens when the overhauling load acts as a prime mover and so drives the machines as a generator. Consequently, direction of Ia and hence of armature torque is reversed and speed falls until E becomes lower than V. It is obvious that during the slowing down of the motor, power is returned to the line which may be used for supplying another train on an upgrade, thereby relieving the powerhouse of part of its load.

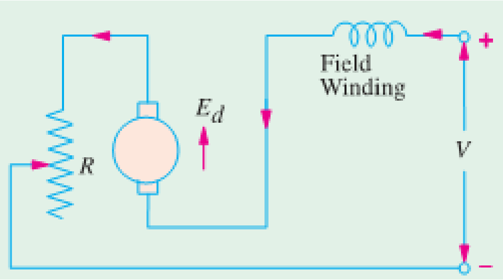
Electric Braking of Series Motor:

(a) Rheostatic (or dynamic) Braking: The motor is disconnected from the supply, the field connections are reversed and the motor is connected in series with a variable resistance R. Obviously, now, the machine is running as a generator. The field connections are reversed to make sure that current through field winding flows in the same direction as before (i.e., from M to N) in order to assist residual magnetism. In practice, the variable resistance employed for starting purpose is itself used for braking purposes.



(a) (b)

(b) Plugging or Reverse Current Braking: As in the case of shunt motors, in this case also the connections of the armature are reversed and a variable resistance R is put in series with the armature.



(c) Regenerative Braking: This type of braking of a series motor is not possible without modification because reversal of I_a would also mean reversal of the field and hence of Eb. However, this method is sometimes used with traction motors, special arrangements being necessary for the purpose.

Starter of DC Motors: the current drawn by a motor armature is given by the relation where V is the supply voltage, the back emf and R the armature resistance. When the motor is at rest, there is no back emf developed in the armature. If, now, full supply voltage is applied across the stationary armature, it will draw a very large current because armature resistance is relatively small. This excessive current will blow out the fuses and, prior to that, it will damage the commutator and brushes etc. To avoid this happening, a resistance is introduced in series with the armature (for the duration of starting period only, say 5 to 10 seconds) which limits the starting current to a safe value. The starting resistance is gradually cut out as the motor gains speed and develops the back emf which then regulates its speed. Very small motors may, however, be started from rest by connecting them directly to the supply lines. It does not result in any harm to the motor for the following reasons:

1- Such motors have a relatively higher armature resistance than large motors; hence their starting current is not so high.

2- Being small, they have low moment of inertia, hence they speed up quickly.

3- The momentary large starting current taken by them is not sufficient to produce a large disturbance in the voltage regulation of the supply lines.

12- A 10 hp (7.46kW) 200 V shunt motor has full-load efficiency of 85%. The armature has a resistance of 0.25Ω. Calculate the value of the starting resistance necessary to limit the starting current to 1.5 times the full-load current at the moment of first switching on. The shunt current may be neglected. Find also the back emf of the motor, when the current has fallen to its full load value, assuming that the whole of the starting resistance is still in circuit.

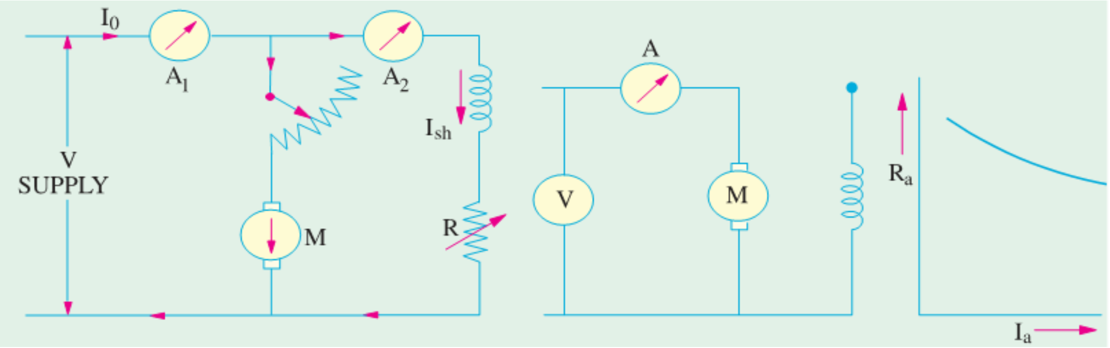
Swinburne's Test: It is a simple method in which losses are measured separately and from their knowledge, efficiency at any desired load can be predetermined in advance. The only running test needed is no-load test. However, this test is applicable to those machines in which flux is practically constant i.e. shunt and compound-wound machines. The machine is running as a motor on no-load at its rated voltage. The speed is adjusted to the rated speed with the help of shunt regulator. The no-load current I is measured by the ammeter A1 whereas shunt field current I_{sh} is given by ammeter A2. The no-load armature current is (I_0-I_{sh}) or I_{a0}.

Let, supply voltage = V, No-load input power = VI_0

$\therefore$ Power input to armature=$V(I_0-I_{sh})$; Power input to shunt = VI_{sh}

No-load power input to armature supplies the following losses : (i) Iron losses in core (ii) friction loss (iii) windage loss and(iv) armature Cu loss,$(I_0-I_{sh})^2Ra$ or $I_{a0}{}^2R_a$

In calculating armature Cu loss, ‘hot’ resistance of armature should be used. A stationary measurement of armature circuit resistance at the room-temperature (15C°) is made by passing current through the armature from a low voltage dc supply.



Then, the ‘hot’ resistance, allowing a temperature rise of 50C° is found thus: $R_{15} = R_o\,(1 + 15\alpha_0)$; $R_{65} = R_o\,(1 + 65\alpha_0)$, $R_{65} = R_{15} \times \dfrac{1+65\alpha_o}{1+15\alpha_o}$

If we subtract from the total input the no-load armature Cu loss, then we get constant losses.

$\therefore$ Constant losses $W_c = VI_0 - (I_0 - I_{sh})^2 R_a$

Knowing the constant losses of the machine, its efficiency at any other load can be determined as given below. Let I = load current at which efficiency is required.

Then, armature current is $I_a = I - I_{sh}$ ...if machine is motoring

$= I + I_{sh}$ ...if machine is generating

Efficiency when running as a motor

Input = VI, Armature Cu loss = $I_a^2 R_a = (I - I_{sh})^2 R_a$

Constant losses = Wc

$\therefore$ Total losses = $(I - I_{sh})^2 R_a + W_c$; $\eta_m = \frac{input - losses}{input} = \frac{VI - (I - I_{sh})^2 R_a - W_c}{VI}$

Efficiency when running as a generator

Output = VI ; Armature Cu loss = $(I + I_{sh})^2 R_a$; constant loss=W_c

$\therefore$ Total losses = $(I + I_{sh})^2 R + W_c$; $\eta_g = \frac{output}{output + losses} = \frac{VI}{VI + (I + I_{sh})^2 R_a + W_c}$

Advantages of Swinburne's Test:

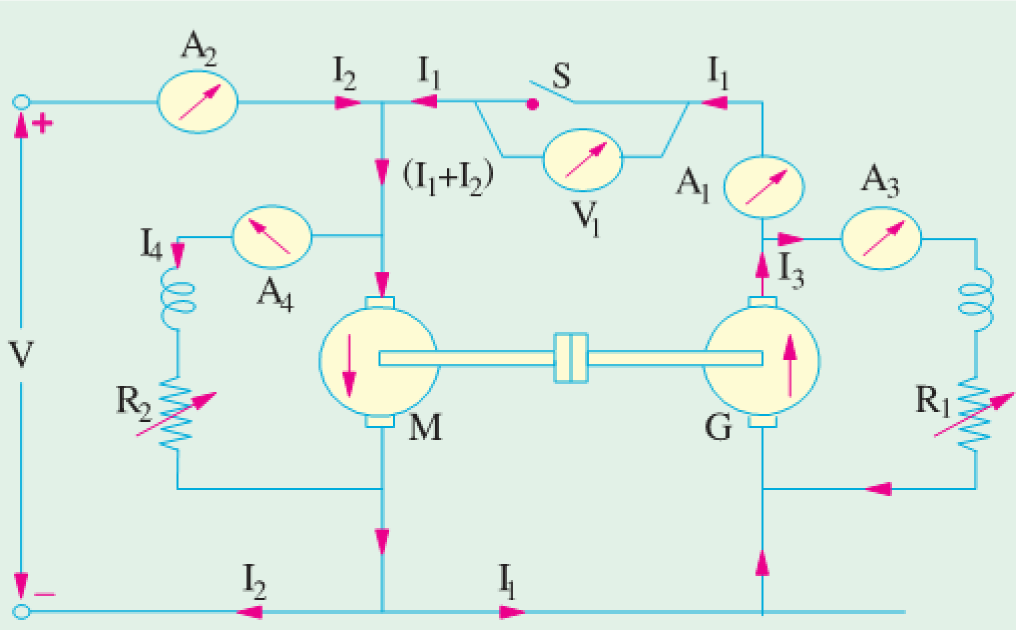
1. It is convenient and economical because power required to test a large machine is small i.e. only no-load input power.
2. The efficiency can be predetermined at any load because constant-losses are known.

Main Disadvantages

1. No account is taken of the change in iron losses from no-load to full-load. At full-load, due to armature reaction, flux is distorted which increases the iron losses in some cases by as much as 50%.
2. As the test is on no-load, it is impossible to know whether commutation would be satisfactory at full-load and whether the temperature rise would be within the specified limits.

Regenerative or Hopkinson's Test (Back to Back Test): By this method, full-load test can be carried out on two shunt machines, preferably identical ones, without wasting their outputs. The two machines are mechanically coupled and are so adjusted electrically that one of them runs as a motor and the other as a generator. The mechanical output of the motor drives the generator and the electrical output of generator is used in supplying the greater part of input to the motor. If there were no losses in the machines, they would have run without any external power supply. But due to these losses, generator output is not sufficient to drive the motor and vice-versa. The losses are supplied either by an extra motor which is belt-connected to the motor-generator set, or by electrically from the supply mains. The two shunt machines are connected in parallel. They are, to begin with, started as unloaded motors. Then, the field of one is weakened and that of the other is strengthened so that the former runs as a motor and the latter as a generator. The usual method of procedure is as follows: Machine M is started up from the supply mains with the help of a starter (not shown) whereas main switch S of the other machine is kept open. Its speed is adjusted to normal value by means of its field regulator. Machine M drives machine G as a generator and its voltage is read on voltmeter V. The voltage of G is adjusted by its field regulator until voltmeter V1 reads zero, thereby showing that its voltage is the same, both in polarity and magnitude as that of the main supply. Thereafter, S is closed to parallel the machines. By adjusting the respective field regulators, any load can now be thrown on to the machines. Generator current I_1 can be adjusted to any desired value by increasing the excitation of G or by reducing the excitation of M and the corresponding values of different ammeters are read. The electrical output of the generator plus the small power taken from the supply, is taken by the motor and is given out as a mechanical power after supplying the motor losses. If supply voltage is V, then

Motor input=$V(I_1+I_2)$, where I_2 is the current taken from the supply. Generator output = VI_1



Assuming that both machines have the same efficiency η.

Output of motor = η × input = η $V(I_1+I_2)$ = generator input

Output of generator=η×input=η×η$V(I_1+I_2)$=$\eta^2V(I_1 + I_2)$

$$\therefore \eta^2V(I_1 + I_2)=VI_1 \text{ or } \eta = \sqrt{\frac{I_1}{I_1+I_2}}$$

However, it is not quite correct to assume equal efficiencies for two machines because their armature currents as well as excitations are different. We will not find the efficiencies separately.

Let R_a= armature resistance of each machine

I_3= exciting current of the generator

I_4= exciting current of the motor

Armature Cu loss in generator = $(I_1+I_3)^2R_a$

Armature Cu loss in motor = $(I_1+I_2-I_4)^2R_a$

Shunt Cu loss in generator = VI_3

Shunt Cu loss in motor = VI_4

But total motor and generator losses are equal to the power supplied by the mains. Power drawn from supply = VI_2

If we subtract the armature and shunt Cu losses from this, we get the stray losses of both machines.

Total stray losses for the set= $VI_2-[(I_1+I_3)^2R_a+(I_1+I_2-I_4)^2R_a+VI_3+VI_4]=W$

Making one assumption that stray losses are equally divided between the two machines, we have Stray loss per machine = W/2

For Generator

Total losses = $(I_1+I_3)^2R_a+VI_3+W/2=W_g$

Output=VI_1 $\therefore \eta_g = \dfrac{VI_1}{VI_1+W_g}$

For Motor

Total losses = $(I_1+I_2-I_4)^2R_a+VI_4+W/2=W_m$

Input = $V(I_1+I_2)$ $\therefore \eta_m = \dfrac{V(I_1+I_2)-W_m}{V(I_1+I_2)}$

Alternative Connections for Hopkinson's Test: the following figure shows in slightly different method of connecting the two machines to the supply. Here, the main difference is that the shunt windings are directly connected across the lines. Hence, the line input current is I_1 excluding the field currents. The efficiencies can be calculated as detailed below:

Motor armature Cu loss = $(I_1+I_2)^2R_a$

Generator armature Cu loss = $I_2^2R_a$

Power drawn from the supply =W_{input} =VI_1

Total stray losses i.e. iron, friction and windage losses for the two machines are = $VI_1-[(I_1+I_2)^2R_a- I_2^2 R_a] = W$

$\therefore$ Stray loss for each machine = W/2

Motor Efficiency

Motor input = armature input + shunt field input = $V (I_1+I_2)+VI_3+W_{input}$

Motor losses=armature Cu loss+shunt Cu loss+stray losses

$$=(I_1+I_2)^2R_a+VI_3+W/2=W_m$$

Motor efficiency $= \eta = \frac{W_{input} - W_m}{W_{input}} \times 100\%$

Generator Efficiency:

Generator output = VI_2

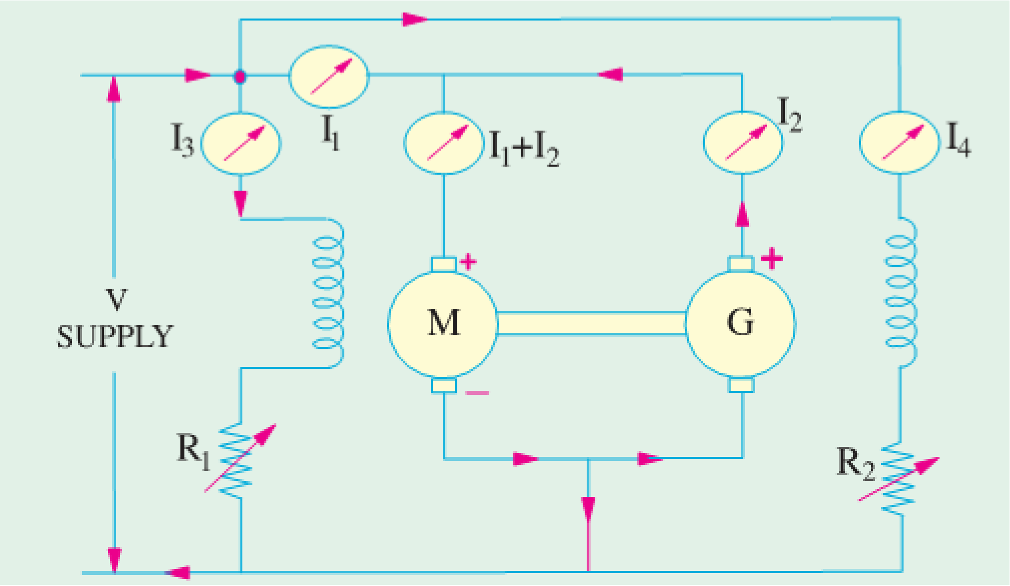
Generator losses = $I_2{}^2R_aVI_4+W/2=W_g$

$\therefore$ Generator efficiency$= \eta = \frac{VI_2}{VI_2 + W_g}$

Advantages and Disadvantages of Hopkinson's Test

1. Power required for the test is small as compared to the full-load powers of the two machines.
2. As machines are being tested under full-load conditions, the temperature rise and the commutation qualities of the machines can be observed.
3. Because of full-load conditions, any change in iron loss due to flux distortion at full-load, is being taken into account.

The only disadvantage is with regard to the availability of two identical machines.



13- The no-load test of a 44.76 kW, 220 V dc shunt motor gave the following figures: Input current=13.25 A; field current=2.55 A; resistance of armature at 75C^o = 0.032Ω and brush drop =2 V. Estimate the full-load current and efficiency.[90%]

14- A 250V, 14.92 kW shunt motor has a maximum efficiency of 88% and a speed of 700 rpm when delivering 80% of its rated output. The resistance of its shunt field is 100Ω. Determine the efficiency and speed when the motor draws a current of 78 A from the mains.[86.9%, 680 rpm]

15- The Hopkinson's test on two similar shunt machines gave the following full-load data: Line voltage=110V Field currents are 3A and 3.5A Line current = 48A Armature resistance of each is 0.035Ω Motor armature current=230A Calculate the efficiency of each machine assuming a brush contact drop of 1 volt per brush.[88.8%, 89.4%]

16- The Hopkinson's test on two shunt machines gave the following results for full-load: Line voltage=250V; current taken from supply system excluding field currents =50A; motor armature current = 380 A; field currents 5A and 4.2A. Calculate the efficiency of the machine working as a generator. Armature resistance of each machine is 0.2 Ω.[92.02%]