DC Machines

Module 9

DC Machines

Lesson 39

D.C Motors

Contents

39.1 Goals of the lesson

In this lesson aspects of starting and speed control of d.c motors are discussed and explained. At the end principles of electric braking of d.c. shunt motor is discussed. After going through the lesson, the reader is expected to have clear ideas of the following.

1. The problems of starting d.c motors with full rated voltage.
2. Use and selection of variable resistance as a simple starter in the armature circuit of a d.c motor.
3. Superiority of commercial starter (3-point starter) over resistance starter. Various protective features incorporated in a commercial starter.
4. Various strategies (namely-armature resistance control, armature voltage control and field current control) adopted for controlling speed of d.c motors.
5. Importance of characteristics such as (i) speed vs. armature current and (ii) speed vs. torque which are relevant for clear understanding of speed control technique.
6. Principle of electric braking – qualitative explanation.

39.2 Introduction

Although in this section we shall mainly discuss *shunt* motor, however, a brief descriptions of (i) D.C shunt, (ii) separately excited and (iii) series motor widely used are given at the beginning.

The armature and field coils are connected in parallel in a d.c shunt motor as shown in figure 39.1 and the parallel combination is supplied with voltage V. I_L, I_a and I_f are respectively the current drawn from supply, the armature current and the field current respectively. The following equations can be written by applying KCL, and KVL in the field circuit and KVL in the armature circuit.

$$
\begin{aligned}
I_L &= I_a + I_f \text{ applying KCL} \\
I_f &= \frac{V}{R_f} \text{ from KVL in field circuit} \\
I_a &= \frac{V - E_b}{r_a} \text{ from KVL in the armature circuit} \\
&= \frac{V - k\phi n}{r_a}
\end{aligned}
$$

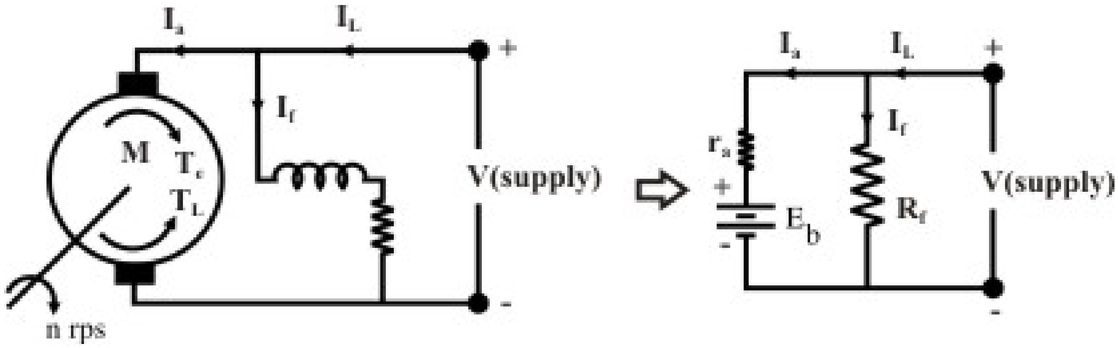


Figure 39.1: D.C shunt motor connection & its circuit representation.

39.3 Important Ideas

We have learnt in the previous lecture (37), that for motor operation:

1. Electromagnetic torque $T_e = k\phi I_a$ developed by the motor acts along the direction of rotation.
2. The load torque T_L acts in the opposite direction of rotation or in opposition to T_e.
3. If $T_e = T_L$, motor operates with *constant* speed. .
4. If at any time $T_e > T_L$, the motor will *accelerate*.
5. If at any time $T_e < T_L$, the motor will *decelerate*.

Although our main focus of study will be the operation of motor under steady state condition, a knowledge of "how motor moves from one steady state operating point to another steady operating point" is important to note. To begin with let us study, how a motor from rest condition settles to the final operating point. Let us assume the motor is absolutely under no-load condition which essentially means T_L = 0 and there is friction present. Thus when supply is switched on, both $I_a = V/r_a$ and ϕ will be established developing T_e. As T_L = 0, motor should pick up speed due to acceleration. As motor speed increases, armature current decreases since back emf E_b rises. The value of T_e also progressively decreases. But so long T_e is present, acceleration will continue, increasing speed and back emf. A time will come when supply voltage and E_b will be same making armature current I_a zero. Now T_e becomes zero and acceleration stops and motor continues to run steadily at constant speed given by $n = V/(k\phi)$ and drawing no armature current. Note that input power to the armature is zero and mechanical output power is zero as well.

Let us bring a little reality to the previous discussion. Let us not neglect frictional torque during acceleration period from rest. Let us also assume frictional torque to be constant and equal to T_{fric}. How the final operating point will be decided in this case? When supply will be switched on T_e will be developed and machine will accelerate if T_e > T_{fric}. With time T_e will decrease as I_a decreases. Eventually, a time will come when T_e becomes equal to T_L and motor will continue to run at constant steady no load speed n_0. The motor in the final steady state however will continue to draw a definite amount of armature current which will produce T_e just enough to balance T_{fric}.

Suppose, the motor is running steadily at no load speed n_0, drawing no load armature I_{a0} and producing torque T_{e0} (= T_{fric}). Now imagine, a constant load torque is suddenly imposed on the shaft of the motor at $t = 0$. Since speed can not change instantaneously, at $t = 0^+$, $I_a(t = 0^+) = I_{a0}$ and $T_e(t = 0^+) = T_{e0}$. Thus, at $t = 0^+$, opposing torque is $(T_L + T_{fric}) < T_{e0}$. Therefore, the motor should start decelerating drawing more armature current and developing more T_e. Final steady operating point will be reached when, $T_e = T_{fric} + T_L$ and motor will run at a new speed lower than no load speed n_0 but drawing I_a greater than the no load current I_{a0}.

In this section, we have learnt the mechanism of how a D.C motor gets loaded. To find out steady state operating point, one should only deal with steady state equations involving torque and current. For a shunt motor, operating point may change due to (i) change in field current or ϕ, (ii) change in load torque or (iii) change in both. Let us assume the initial operating point to be:

$$\begin{aligned}
\text{Armature current} &= I_{a1} \\
\text{Field current} &= I_{f1} \\
\text{Flux per pole} &= \phi_1 \\
\text{Speed in rps} &= n_1 \\
\text{Load torque} &= T_{L1} \\
T_{e1} &= k\phi_1 I_{a1} = T_{L1} \qquad (39.1) \\
E_{b1} &= k\phi_2 n_2 = V - I_{a1} r_a \qquad (39.2)
\end{aligned}$$

Now suppose, we have changed field current and load torque to new values I_{f2} and T_{L2} respectively. Our problem is to find out the new steady state armature current and speed. Let,

$$\begin{aligned}
\text{New armature current} &= I_{a2} \\
\text{New field current} &= I_{f2} \\
\text{New flux per pole} &= \phi_2 \\
\text{Speed in rps} &= n_2 \\
\text{New load torque} &= T_{L2} \\
T_{e2} &= k\phi_2 I_{a2} = T_{L2} \qquad (39.3) \\
E_{b2} &= k\phi_2 n_2 = V - I_{a2} r_a \qquad (39.4)
\end{aligned}$$

Now from equations 39.1 and 39.3 we get:

$$\frac{T_{e2}}{T_{e1}} = \frac{T_{L2}}{T_{L1}} = \frac{k\phi_2 I_{a2}}{k\phi_1 I_{a1}} \qquad (39.5)$$

From equation 39.5, one can calculate the new armature current I_{a2}, the other things being known. Similarly using equations 39.2 and 39.4 we get:

$$\frac{E_{b1}}{E_{b2}} = \frac{k\phi_2 n_2}{k\phi_1 n_1} = \frac{V - I_{a1} r_a}{V - I_{a2} r_a} \qquad (39.6)$$

Now we can calculate new steady state speed n_2 from equation 39.6.

39.4 Starting of D.C shunt motor

39.4.1 Problems of starting with full voltage

We know armature current in a d.c motor is given by

$$I_a = \frac{V - E_b}{r_a} = \frac{V - k\phi n}{r_a}$$

At the instant of starting, rotor speed $n = 0$, hence starting armature current is $I_{ast} = \frac{V}{r_a}$. 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 (size) 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.

39.4.2 A simple starter

To limit the starting current, a suitable external resistance R_{ext} is connected in series (Figure 39.2(a)) with the armature so that $I_{ast} = \frac{V}{R_{ext} + r_a}$. At the time of starting, to have sufficient starting torque, field current is maximized by keeping the external field resistance R_f, to zero value. As the motor picks up speed, the value of R_{ext} 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. Imagine, the motor to be running with $R_{ext} = 0$ (Figure 39.2(b)).

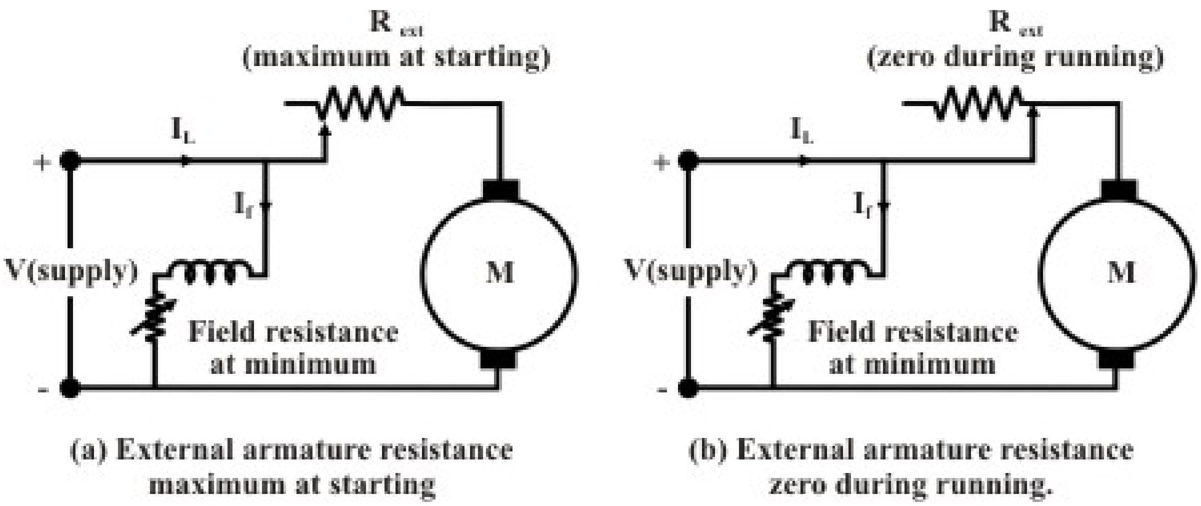


Figure 39.2: A simple starter in the form of external armature resistance.

Now if the supply goes off (due to some problem in the supply side or due to load shedding), 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.

39.4.3 3-point starter

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 39.3. 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 (called studs) and marked as 1,2,.. .12. 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.

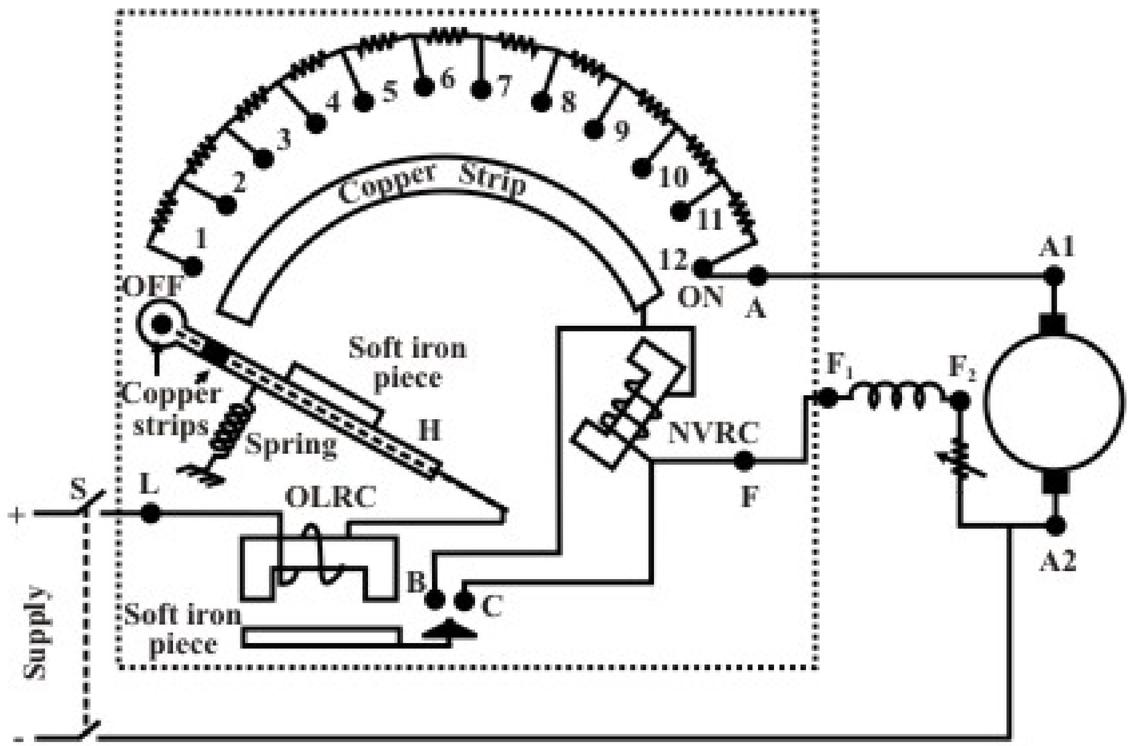


Figure 39.3: A 3-point starter.

Working principle

Let us explain 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 deenergised 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 I_L drawn by the motor. As the motor is loaded, I_a hence I_L increases. Therefore, I_L is a measure of loading of the motor. Suppose we want that the motor should not be over loaded beyond rated current. Now gap between the electromagnet and the soft iron piece is so adjusted that for $I_L \leq I_{rated}$, the iron piece will not be pulled up. However, if $I_L \leq I_{rated}$ force of attraction will be sufficient to pull up iron piece. This upward movement of the iron piece of OLRC is utilized to de-energize NVRC. To the iron a copper strip (Δ shaped in figure) 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 deenergised. The moment it gets deenergised, 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*.

39.5 Speed control of shunt motor

We know that the speed of shunt motor is given by:

$$n = \frac{V_a - I_a r_a}{k\phi}$$

where, V_a is the voltage applied across the armature and ϕ is the flux per pole and is proportional to the field current I_f. As explained earlier, armature current I_a is decided by the mechanical load present on the shaft. Therefore, by varying V_a and I_f we can vary n. For fixed supply voltage and the motor connected as shunt we can vary V_a by controlling an external resistance connected in series with the armature. I_f of course can be varied by controlling external field resistance R_f 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.

39.5.1 Speed control by varying armature resistance

The inherent armature resistance r_a being small, speed n versus armature current I_a characteristic will be a straight line with a small negative slope as shown in figure 39.4. In the discussion to follow we shall not disturb the field current from its rated value. At no load (i.e., $I_a = 0$) speed is highest and $n_0 = \frac{V_a}{k\phi} = \frac{V}{k\phi}$. 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, $I_a r_a$ drop increases making speed a little less than the no load speed n_0. 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.

$$\text{Inherent \% speed regulation} = \frac{n - n_0}{n_0} \times 100$$

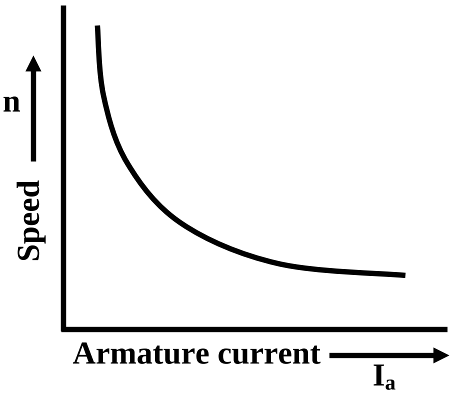


Figure 39.4: Speed vs. armature current characteristic.

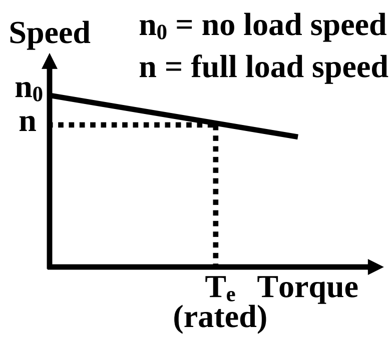


Figure 39.5: Speed vs. torque characteristic.

It is for this reason, a d.c shunt motor is said to be practically a constant speed motor (with no external armature resistance connected) since speed drops by a small amount from no load to full load condition.

Since $T_e = k\phi I_a$, for constant ϕ operation, T_e becomes simply proportional to I_a. Therefore, speed vs. torque characteristic is also similar to speed vs. armature current characteristic as shown in figure 39.5.

The slope of the n vs I_a or n vs T_e characteristic can be modified by deliberately connecting external resistance r_{ext} in the armature circuit. One can get a family of speed vs. armature curves as shown in figures 39.6 and 39.7 for various values of r_{ext}. From these characteristic it can be explained how speed control is achieved. Let us assume that the load torque T_L is constant and field current is also kept constant. Therefore, since steady state operation demands $T_e = T_L$, $T_e = k\phi I_a$ too will remain constant; which means I_a will not change. Suppose $r_{ext} = 0$, then at rated load torque, operating point will be at C and motor speed will be n. If additional resistance r_{ext1} is introduced in the armature circuit, new steady state operating speed will be n_1 corresponding to the operating point D. In this way one can get a speed of n_2 corresponding to the operating point E, when r_{ext2} is introduced in the armature circuit. This same load torque is supplied at various speed. Variation of the speed is smooth and speed will decrease smoothly if r_{ext} 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 r_{ext} reducing the efficiency of the motor.

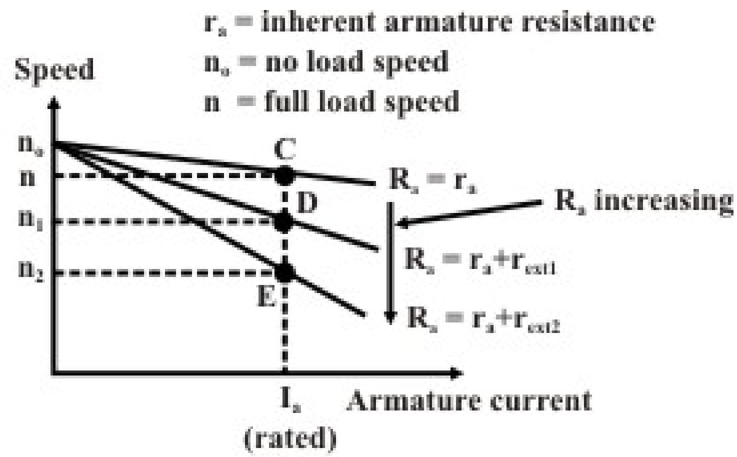


Figure 39.6: Family of speed vs. armature current characteristic.

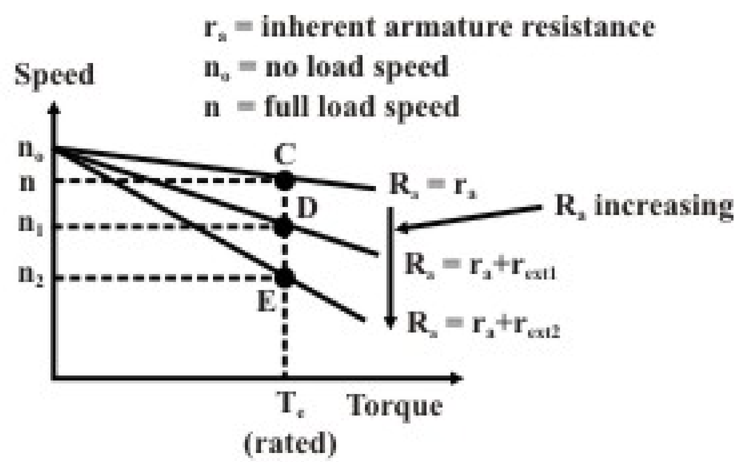


Figure 39.7: Family of speed vs. Torque current characteristic.

39.5.2 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.

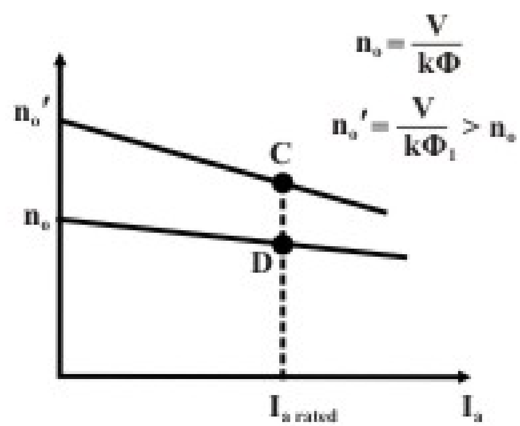
$$n = \frac{V - I_a r_a}{k\phi}$$

If we vary I_f, flux ϕ will change, hence speed will vary. To change I_f 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 39.8 for two flux values ϕ and ϕ_1. Since $\phi_1 < \phi$, the no load speed $n_o^{'}$ for flux value ϕ_1 is more than the no load speed n_o 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 $T_{L\,rated} = T_{e1} = k\phi I_{a\,rated}$. If load torque remains constant and flux is reduced to ϕ_1, new armature current in the steady state is obtained from $k\phi_1 I_{a1} = T_{L\,rated}$. Therefore new armature current is

$$I_{a1} = \frac{\phi}{\phi_1} I_{a\ rated}$$

But the fraction, $\frac{\phi}{\phi_1} > 1$; 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 39.9. Obviously this method is based on *flux weakening* of the main field. Therefore at higher speed main flux may become so weakened, that armature reaction effect will be more pronounced causing problem in commutation.



At C, higher speed but less torque
At D, lower speed but higher torque

Figure 39.8: Family of speed vs. armature current characteristic.

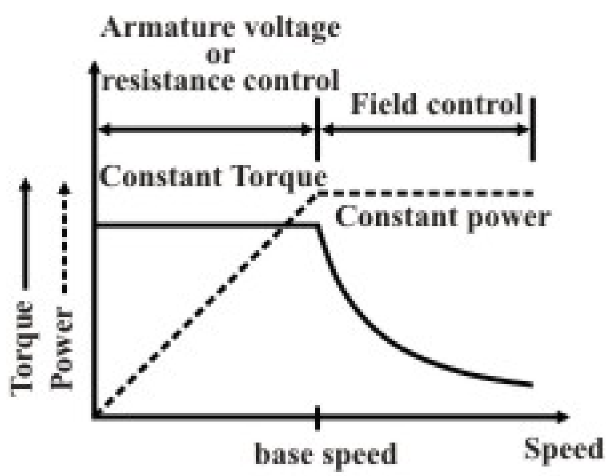


Figure 39.9: Constant torque & power operation.

39.5.3 Speed control by armature voltage variation

In this method of speed control, armature is supplied from a separate variable d.c voltage source, while the field is separately excited with fixed rated voltage as shown in figure 39.10. Here the armature resistance and field current are not varied. Since the no load speed $n_0 = \frac{V_a}{k\phi}$, the speed versus I_a characteristic will shift parallely as shown in figure 39.11 for different values of V_a.

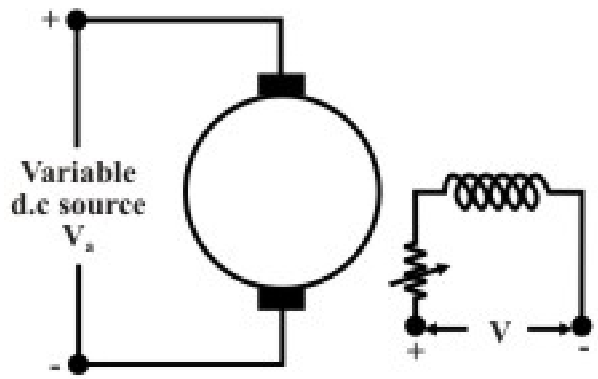


Figure 39.10: Speed control by controlling armature voltage.

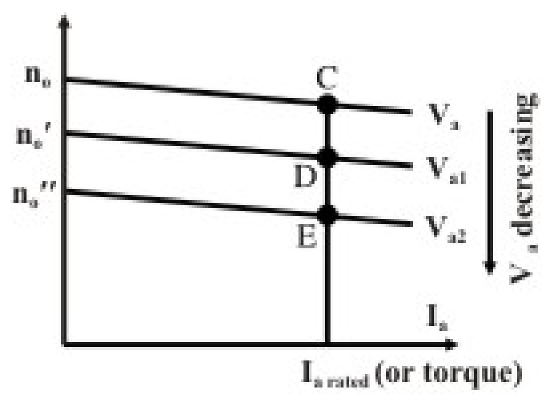


Figure 39.11: Family of n VS. I_a characteristics.

As flux remains constant, this method is suitable for constant torque loads. In a way armature voltage control method is similar to that of armature resistance control method except that the former one is much superior as no extra power loss takes place in the armature circuit. Armature voltage control method is adopted for controlling speed from base speed down to very small speed as one should not apply across the armature a voltage which is higher than the rated voltage.

39.5.4 Ward Leonard method: combination of V_a and I_f control

In this scheme, both field and armature control are integrated as shown in figure 39.12. Arrangement for field control is rather simple. One has to simply connect an appropriate rheostat in the field circuit for this purpose. However, in the pre power electronic era, obtaining a *variable* d.c supply was not easy and a separately excited d.c generator was used to supply the motor armature. Obviously to run this generator, a *prime mover* is required. A 3-phase induction motor is used as the prime mover which is supplied from a 3-phase supply. By controlling the field current of the generator, the generated emf, hence V_a can be varied. The potential divider connection uses two rheostats in parallel to facilitate reversal of generator field current.

First the induction motor is started with generator field current zero (by adjusting the jockey positions of the rheostats). Field supply of the motor is switched on with motor field rheostat set to zero. The applied voltage to the motor V_a, can now be gradually increased to the rated value by slowly increasing the generator field current. In this scheme, no starter is required for the d.c motor as the applied voltage to the armature is gradually increased. To control the speed of the d.c motor below base speed by armature voltage, excitation of the d.c generator is varied, while to control the speed above base speed field current of the d.c motor is varied maintaining constant V_a. Reversal of direction of rotation of the motor can be obtained by adjusting jockeys of the generator field rheostats. Although, wide range smooth speed control is achieved, the cost involved is rather high as we require one additional d.c generator and a 3-phase induction motor of simialr rating as that of the d.c motor whose speed is intended to be controlled.

In present day, variable d.c supply can easily be obtained from a.c supply by using controlled rectifiers thus avoiding the use of additional induction motor and generator set to implement Ward leonard method.

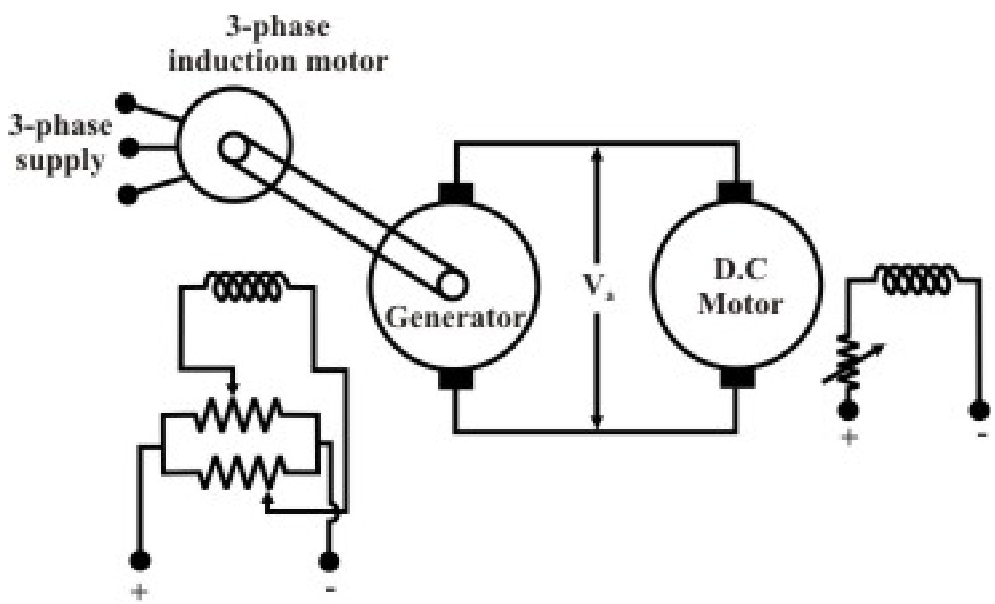


Figure 39.12: Scheme for Ward Leonard method.

39.6 Series motor

In this motor the field winding is connected in series with the armature and the combination is supplied with d.c voltage as depicted in figure 39.13. Unlike a shunt motor, here field current is not independent of armature current. In fact, field and armature currents are equal i.e., $I_f = I_a$. Now torque produced in a d.c motor is:

$$\begin{aligned} T &\propto \phi I_a \\ &\propto I_f I_a \\ &\propto I_a^2 \text{ before saturation sets in i.e., } \phi \propto I_a \\ &\propto I_a \text{ after saturation sets in at large } I_a \end{aligned}$$

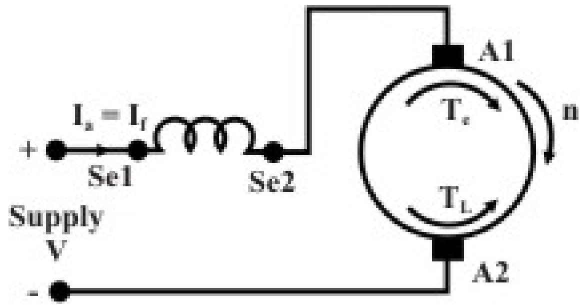


Figure 39.13: Series motor.

Since torque is proportional to the square of the armature current, starting torque of a series motor is quite high compared to a similarly rated d.c shunt motor.

39.6.1 Characteristics of series motor

Torque vs. armature current characteristic

Since $T \propto I_a^2$ in the linear zone and $T \propto I_a$ in the saturation zone, the T vs. I_a characteristic is as shown in figure 39.14

speed vs. armature current

From the KVL equation of the motor, the relation between speed and armature current can be obtained as follows:

$$
\begin{aligned}
V &= I_a\left(r_a + r_{se}\right) + E_b \\
&= I_a r + k\phi n \\
\text{or, } n &= \frac{V - I_a r}{k\phi} \\
\text{In the linear zone } n &= \frac{V - I_a r}{k' I_a} \\
&= \frac{V}{k' I_a} - \frac{r}{k'} \\
\text{In the saturation zone } n &= \frac{V - I_a r}{k' \phi_{sat}}
\end{aligned}
$$

The relationship is inverse in nature making speed dangerously high as $I_a \to 0$. Remember that the value of I_a, is a measure of degree of loading. Therefore, a series motor should never be operated under no load condition. Unlike a shunt motor, a series motor has no finite no load speed. Speed versus armature current characteristic is shown in figure nvsia:side: b.

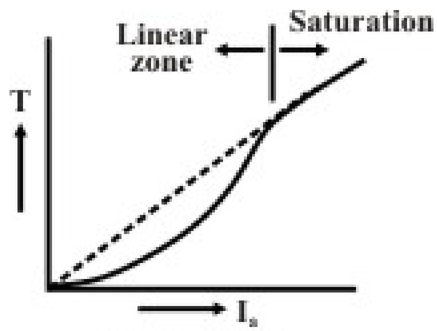


Figure 39.14

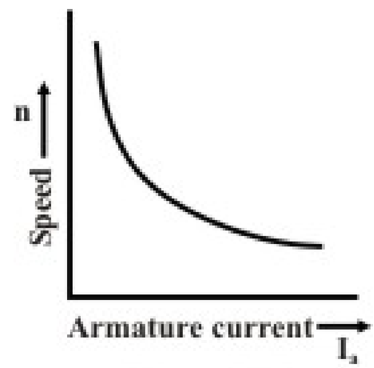


Figure 39.15

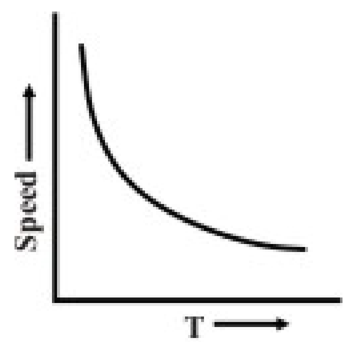


Figure 39.16

speed vs. torque characteristic

Since $I_a \propto \sqrt{T}$ in the linear zone, the relationship between speed and torque is

$$\frac{V}{k''\sqrt{T}} - \frac{r}{k'}$$

k'' and k' represent appropriate constants to take into account the proportionality that exist between current, torque and flux in the linear zone. This relation is also inverse in nature indicating once again that at light load or no load $(T \to 0)$ condition; series motor speed approaches a dangerously high value. The characteristic is shown in figure 39.16. For this reason, a series motor is never connected to mechanical load through belt drive. If belt snaps, the motor becomes unloaded and as a consequence speed goes up unrestricted causing mechanical damages to the motor.

39.7 Speed control of series motor

39.7.1 Speed control below base speed

For constant load torque, steady armature current remains constant, hence flux also remains constant. Since the machine resistance $r_a + r_{se}$ is quite small, the back emf E_b is approximately equal to the armature terminal voltage V_a. Therefore, speed is proportional to V_a. If V_a is reduced, speed too will be reduced. This V_a can be controlled either by connecting external resistance in series or by changing the supply voltage.

Series-parallel connection of motors

If for a drive two or more (even number) of identical motors are used (as in traction), the motors may be suitably connected to have different applied voltages across the motors for controlling speed. In series connection of the motors shown in figure 39.17, the applied voltage across each motor is $V/2$ while in parallel connection shown in figure 39.18, the applied voltage across each motor is V. The back emf in the former case will be approximately half than that in the latter case. For same armature current in both the cases (which means flux per pole is same), speed will be half in series connection compared to parallel connection.

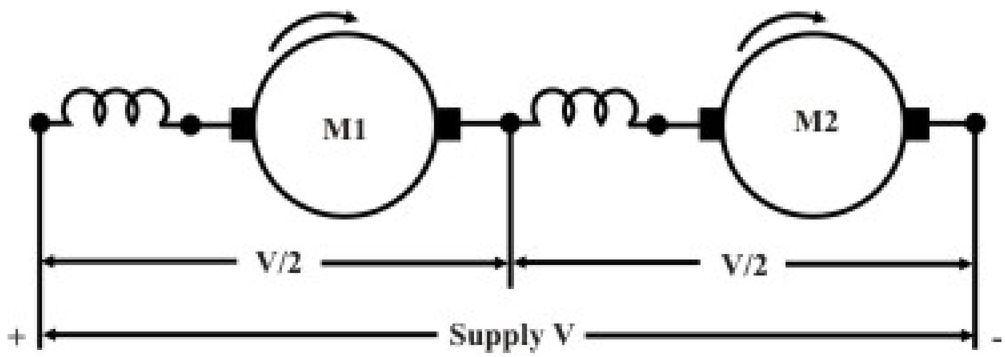


Figure 39.17: Motors connected in series.

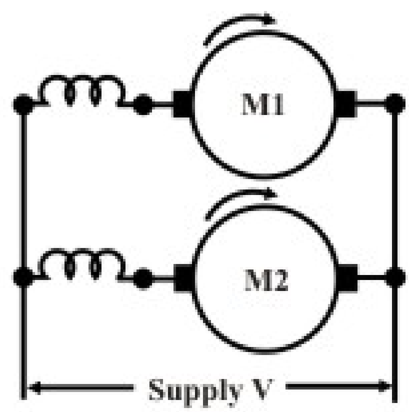


Figure 39.18: Motors connected in parallel.

39.7.2 Speed control above base speed

Flux or field current control is adopted to control speed above the base speed. In a series motor, independent control of field current is not so obvious as armature and field coils are in series. However, this can be achieved by the following methods:

1. **Using a *diverter* resistance connected across the field coil.**
   In this method shown in figure 39.19, a portion of the armature current is diverted through the diverter resistance. So field current is now not equal to the armature current; in fact it is less than the armature current. Flux weakening thus caused, raises the speed of the motor.

2. **Changing number of turns of field coil provided with tapings.**
   In this case shown figure 39.20, armature and field currents are same. However provision is kept to change the number of turns of the field coil. When number of turns changes, field mmf $N_{se}I_f$ changes, changing the flux hence speed of the motor.

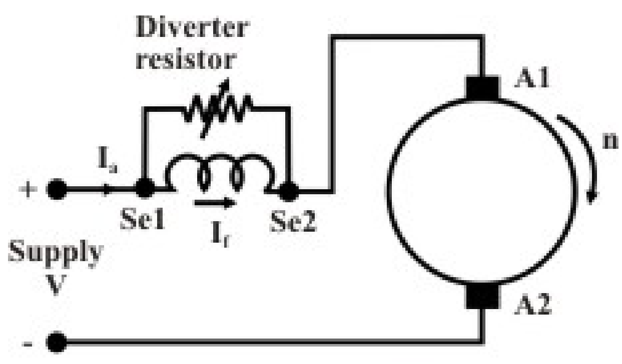


Figure 39.19: Field control with diverter.

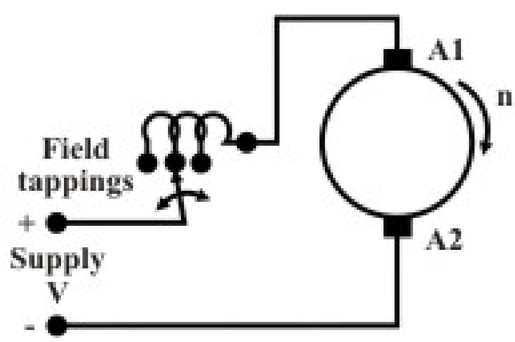


Figure 39.20: Field control with tappings.

3. **Connecting field coils wound over each pole in series or in. parallel.**
   Generally the field terminals of a d.c machine are brought out after connecting the field coils (wound over each pole) in series. Consider a 4 pole series motor where there will be 4 individual coils placed over the poles. If the terminals of the individual coils are brought out, then there exist several options for connecting them. The four coils could be connected in series as in figure 39.21; the 4 coils could be connected in parallel or parallel combination of 2 in series and other 2 in series as shown in figure 39.22. n figure For series connection of the coils (figure 39.21) flux produced is proportional to I_a and

for series-parallel connection (figure 39.22) flux produced is proportional to $\frac{I_a}{2}$. Therefore, for same armature current I_a, flux will be doubled in the second case and naturally speed will be approximately doubled as back emf in both the cases is close to supply voltage V. Thus control of speed in the ratio of 1:2 is possible for series parallel connection.

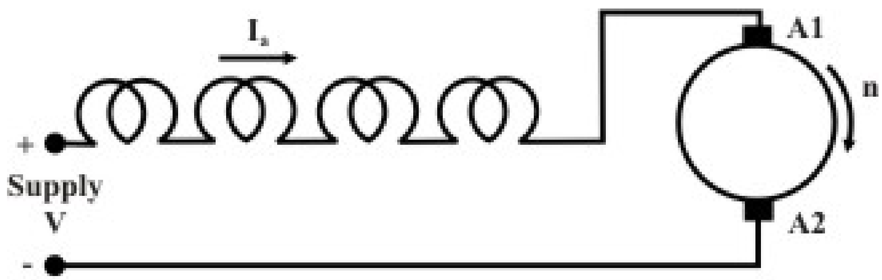


Figure 39.21: coils in series.

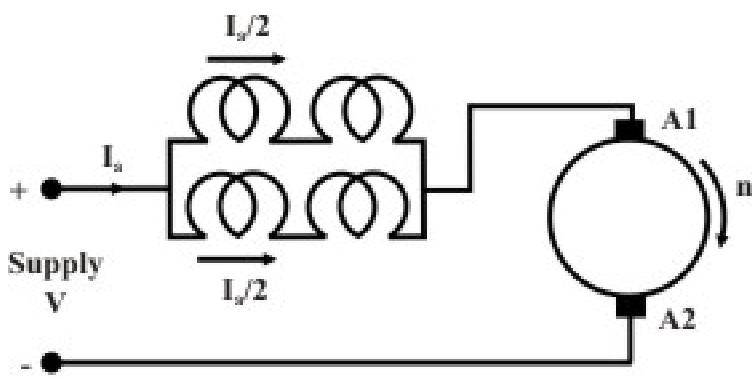


Figure 39.22: Series-parallel connection of coils.

In a similar way, reader can work out the variation of speed possible between (i) all coils connected in series and (ii) all coils connected in parallel.

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.

39.8.1 Rheostatic braking

Consider a d.c shunt motor operating from a d.c supply with the switch S connected to position 1 as shown in figure 39.23. S is a *single pole double throw switch* and can be connected either to position 1 or to position 2. One end of an external resistance R_b is connected to position 2 of the switch S as shown.

Let with S in position 1, motor runs at n rpm, drawing an armature current I_a and the back emf is $E_b = k\phi\, n$. Note the polarity of E_b which, as usual for motor mode in opposition with the supply voltage. Also note T_e and n have same clock wise direction.

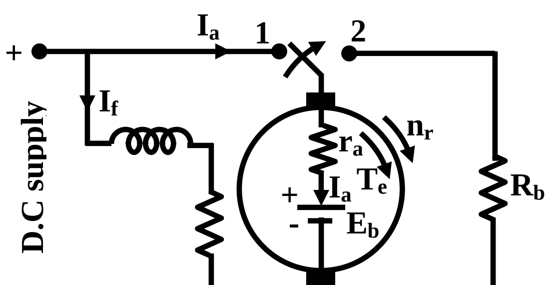


Figure 39.23: Machine operates as motor

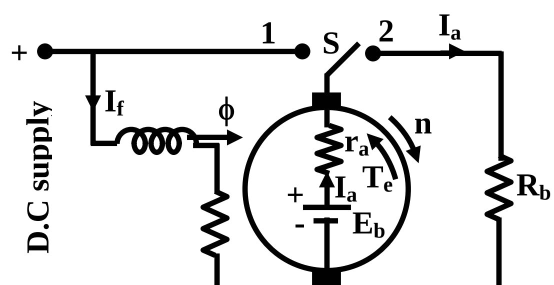


Figure 39.24: Machine operates as generator during braking

Now if S is suddenly thrown to position 2 at $t = 0$, the armature gets disconnected from the supply and terminated by R_b with field coil remains energized from the supply. Since speed of the rotor can not change instantaneously, the back emf value E_b is still maintained with same polarity prevailing at $t = 0_-$. Thus at $t = 0_+$, armature current will be $I_a = E_b/(r_a + R_b)$ and with reversed direction compared to direction prevailing during motor mode at $t = 0_-$.

Obviously for $t > 0$, the machine is operating as generator dissipating power to R_b and now the electromagnetic torque T_e must act in the opposite direction to that of n since I_a has changed direction but ϕ has not (recall $T_e \propto \phi\, I_a$). As time passes after switching, n decreases reducing K.E and as a consequence both E_b and I_a decrease. In other words value of braking torque will be highest at $t = 0_+$, and it decreases progressively and becoming zero when the machine finally come to a stop.

39.8.2 Plugging or dynamic braking

This method of braking can be understood by referring to figures 39.25 and 39.26. Here S is a double pole double throw switch. For usual motoring mode, S is connected to positions 1 and 1'. Across terminals 2 and 2', a series combination of an external resistance R_b and supply voltage with polarity as indicated is connected. However, during motor mode this part of the circuit remains inactive.

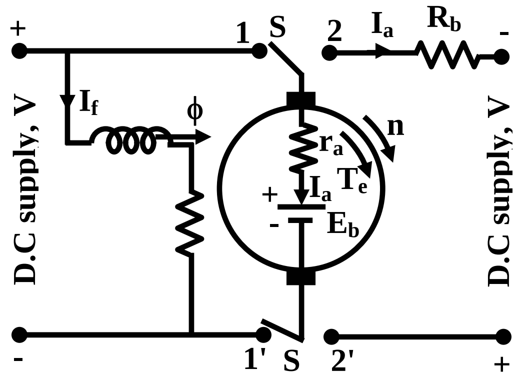


Figure 39.25: Machine operates as motor

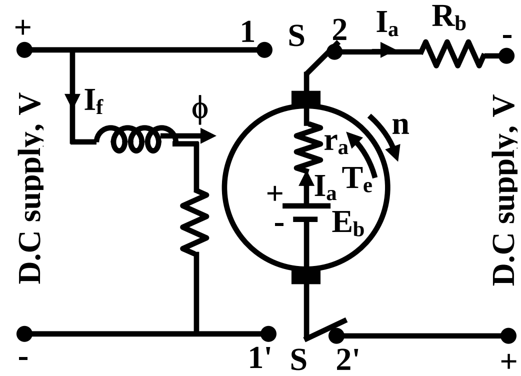


Figure 39.26: Machine operates as generator during braking (plugging).

To initiate braking, the switch is thrown to position 2 and 2' at $t = 0$, thereby disconnecting the armature from the left hand supply. Here at $t = 0_+$, the armature current will be $I_a = (E_b + V)/(r_a + R_b)$ as E_b and the right hand supply voltage have additive polarities by virtue of the connection. Here also I_a reverses direction producing T_e in opposite direction to n. I_a decreases as E_b decreases with time as speed decreases. However, I_a can not become zero at any time due to presence of supply V. So unlike rheostatic braking, substantial magnitude of braking torque prevails. Hence stopping of the motor is expected to be much faster then rheostatic breaking. But what happens, if S continuous to be in position 1' and 2' even after zero speed has been attained? The answer is rather simple, the machine will start picking up speed in the reverse direction operating as a motor. So care should be taken to disconnect the right hand supply, the moment armature speed becomes zero.

39.8.3 Regenerative braking

A machine operating as motor may go into regenerative braking mode if its speed becomes sufficiently high so as to make back emf greater than the supply voltage i.e., $E_b > V$. Obviously under this condition the direction of I_a will reverse imposing torque which is opposite to the direction of rotation. The situation is explained in figures 39.27 and 39.28. The normal motor operation is shown in figure 39.27 where armature motoring current I_a is drawn from the supply and as usual $E_b < V$. Since $E_b = k\phi\, n_1$. The question is how speed on its own become large enough to make $E_b < V$ causing regenerative braking. Such a situation may occur in practice when the mechanical load itself becomes active. Imagine the d.c motor is coupled to the wheel of locomotive which is moving along a plain track without any gradient as shown in figure 39.27. Machine is running as a motor at a speed of n_1 rpm. However, when the track has a downward gradient (shown in figure 39.28), component of gravitational force along the track also appears which will try to accelerate the motor and may increase its speed to n_2 such that $E_b = k\phi\, n_2 >$ V. In such a scenario, direction of I_a reverses, feeding power back to supply. Regenerative braking here will not stop the motor but will help to arrest rise of dangerously high speed.

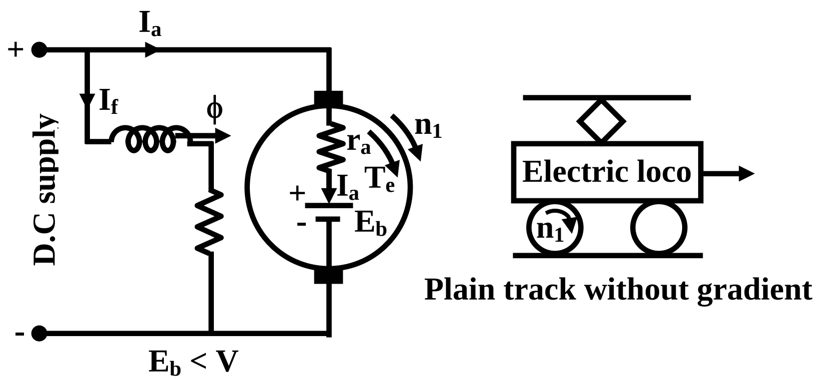


Figure 39.27: Machine operates as motor

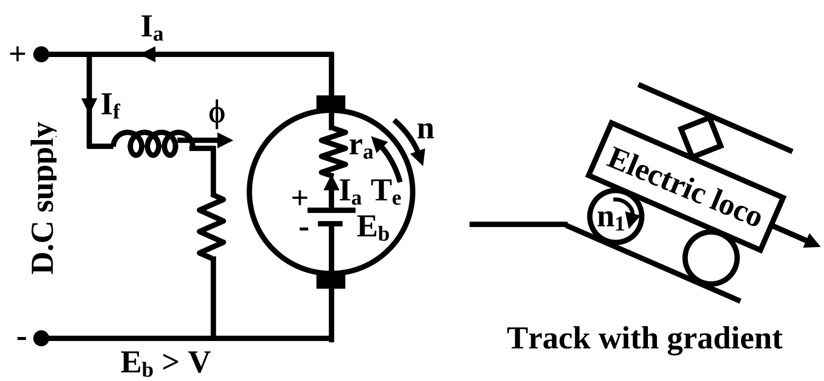


Figure 39.28: Machine enters regenerative braking mode.

39.9 Tick the correct answer

1. A 200 V, 1000 rpm, d.c shunt motor has an armature resistance of 0.8 Ω and its rated armature current is 20 A. Ratio of armature starting current to rated current with full voltage starting will be:

   (A) 1 V (B) 12.5 V (C) 25 V (D) 16 V

2. A 200 V, 1000 rpm, d.c shunt motor has an armature resistance of 0.8 Ω and found to run from a 200 V supply steadily at 950 rpm with a back emf of 190 V. The armature current is:

   (A) 237.5 A (B) 10 A (C) 250 A (D) 12.5 A

3. A d.c 220 V, shunt motor has an armature resistance of 1 Ω and a field circuit resistance of 150 Ω. While running steadily from 220 V supply, its back emf is found to be 209 V. The motor is drawing a line current of:

   (A) 11 A (B) 12.47 A (C) 221.47 A (D) 9.53 A

4. A 220 V, d.c shunt motor has r_a = 0.8 Ω and draws an armature current of 20 A while supplying a constant load torque. If flux is suddenly reduced by 10%, then immediately the armature current will become:

(A) 45.5 A and the new steady state armature current will be 22.2 A.
(B) 20 A and the new steady state armature current will be 22.2 A.
(C) 22.2 A and the new steady state armature current will be 45.5 A.
(D) 20 A and the new steady state armature current will be 25 A.

5. A 220 V, d.c shunt motor has r_a = 0.8 Ω and draws an armature current of 20 A while supplying a constant load torque. If a 4.2 Ω resistance is inserted in the armature circuit suddenly, then immediately the armature current will become:

   (A) 20 A and the new steady state armature current will be 3.2 A.
   (B) 3.2 A and the new steady state armature current will be 20 A.
   (C) 47.2 A and the new steady state armature current will be 3.2 A.
   (D) 3.2 A and the new steady state armature current will be 47.2 A.

6. A separately excited 220 V, d.c generator has r_a = 0.6 Ω and while supplying a constant load torque, draws an armature current of 30 A at rated voltage. If armature supply voltage is reduced by 20%, the new steady state armature current will be:

   (A) 24 A (B) 6 A (C) 30 A (D) 36 A

7. A 250 V, d.c shunt motor having negligible armature resistance runs at 1000 rpm at rated voltage. If the supply voltage is reduced by 25%, new steady state speed of the motor will be about:

   (A) 750 rpm (B) 250 rpm (C) 1000 rpm (D) 1250 rpm

39.10 Solve the following

1. A d.c motor takes an armature current of 50A at 220V. The resistance of the armature is 0.2Ω. The motor has 6 poles and the armature is lap wound with 430 conductors. The flux per pole is 0.03Wb. Calculate the speed at which the motor is running and the electromagnetic torque developed.

2. A 10KW, 250V, 1200 rpm d.c shunt motor has a full load efficiency of 80%, r_a = 0.2Ω and R_f = 125Ω. The machine is initially operating at full load condition developing full load torque.

   i. What extra resistance should be inserted is the armature circuit if the motor speed is to be reduced to 960 rpm?
   ii. What additional resistance is to be inserted in the field circuit in order to raise the speed to 1300 rpm?

Note that for both parts (i) and (ii) the initial condition is the same full load condition as stated in the *first paragraph* and load torque remains constant throughout. Effect of saturation and armature reaction may be neglected.