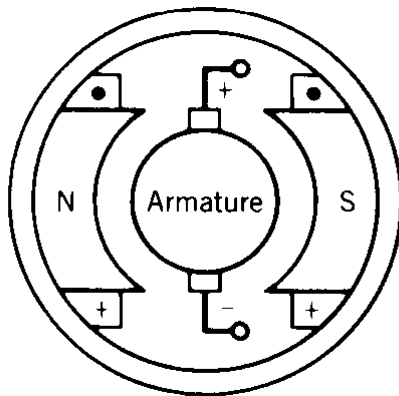


DC Machines

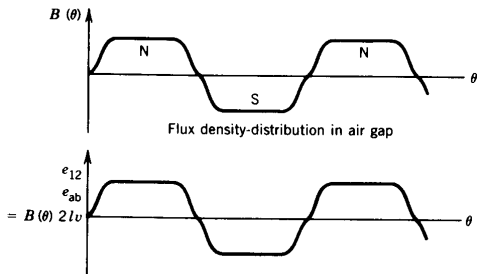
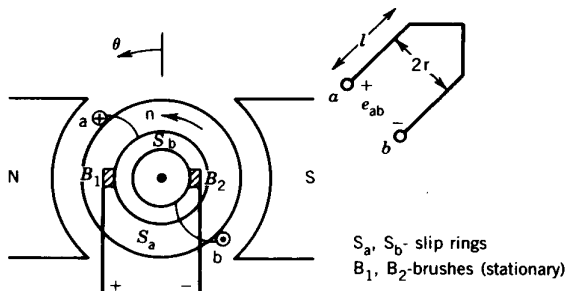


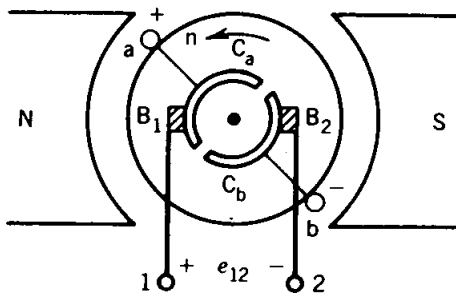
Construction

1. Stator - Field Winding
2. Rotor - Armature Winding

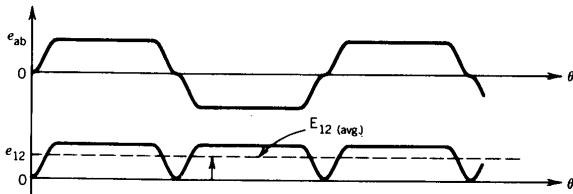
Field Winding is concentrated. However Armature winding is distributed over slots.

DC Generator





C_a, C_b -commutator
segment



DC Motor

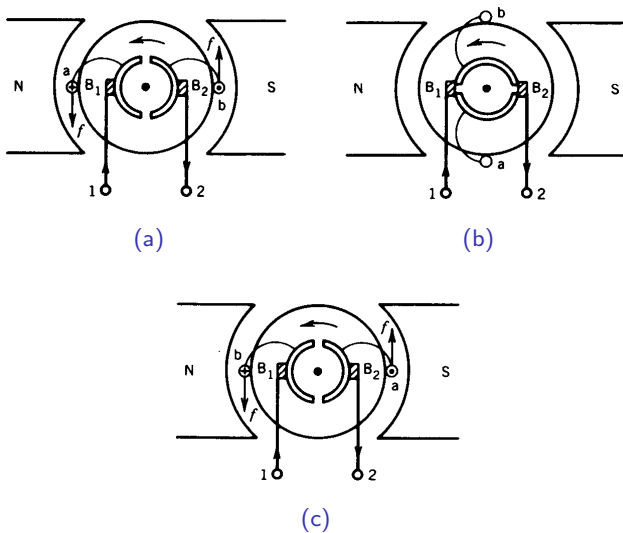


Figure: Current reversal in a DC Motor

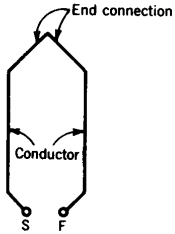
Generator

1. When armature rotates in the stationary field, emf is induced in it. But this is alternating.
2. Commutators convert the alternating emf to unidirectional one.
3. DC voltage is obtained across the brushes.

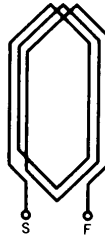
Motor

1. When the armature is connected to a DC supply through brushes, it experiences Torque.
2. Commutators reverse the current in the conductors so that there is steady Torque.

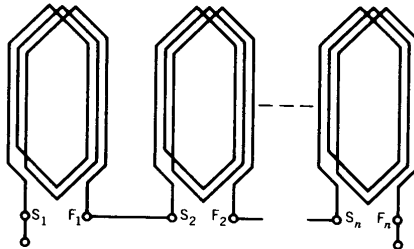
Winding



(a) Turn

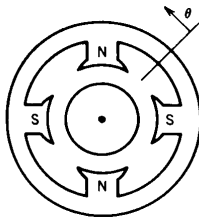


(b) Coil

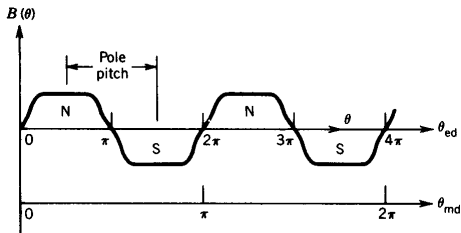


(c) Winding

Mechanical and Electrical Angles



(a) 4 Pole DC Machine



(b) Flux Density Distribution

- ▶ For a P pole machine,

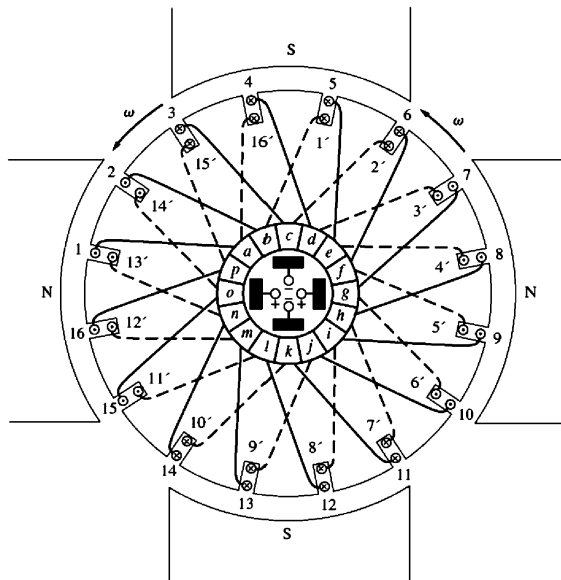
$$\theta_e = \frac{P}{2} \theta_m$$

- ▶ Pole pitch is the distance between the centers of two adjacent poles.

One Pole pitch = 180° electrical degree

- ▶ Coil pitch is the distance between two sides of a coil.
- ▶ If the coil pitch is equal to one pole pitch, it is called a full pitch coil.
- ▶ if the coil pitch is less than one pole pitch, it is called a short pitch coil.

Armature Winding - Lap

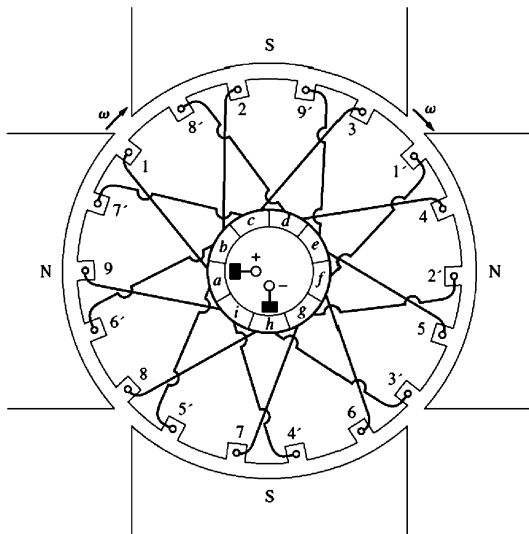


Source: Stephan Chapman

Lap Winding

- ▶ The distance (in number of segments) between the commutator segments to which the two ends of a coil are connected is called the commutator pitch.
- ▶ In a lap winding, the commutator pitch is either 1 or -1.
- ▶ If the commutator pitch is +1, it is called a progressive lap winding.
- ▶ If the commutator pitch is -1, it is called a retrogressive lap winding.
- ▶ There is one coil between two commutator segments.
- ▶ There are $\frac{1}{P} \times$ total number of coils between two adjacent poles.
- ▶ In a lap winding, the number of parallel paths (A) is always equal to the number of poles (P) and also to the number of brushes.

Armature Winding - Wave



Source: Stephan Chapman

Wave Winding

- ▶ In a wave winding, the commutator pitch is $\frac{C \pm 1}{P/2}$ where C is the total number of coils.
- ▶ If $+$ is used, it is called a progressive wave winding.
- ▶ If $-$ is used, it is called a retrogressive wave winding.
- ▶ There are $\frac{P}{2}$ coils between two commutator segments.
- ▶ There are $\frac{1}{2}$ of the total number of coils between two adjacent poles.
- ▶ In a wave winding, the number of parallel paths (A) is always equal to 2 and there may be two or more brushes.

Lap

- ▶ Number of parallel paths is number of poles ($A = P$)
- ▶ Since there are more parallel paths, this is preferred for Low Voltage and High Current applications.

Wave

- ▶ Number of parallel paths is always 2 ($A = 2$)
- ▶ Since there are less parallel paths, this is preferred for High Voltage and Low Current applications.

Induced EMF

The induced EMF in a conductor is

$$e = Blv = Bl\omega_m r \text{ Volt}$$

where

l = length of the conductor in the slot

B = flux density

ω_m = mechanical speed

r = radius of the armature

The flux per pole

$$\phi = B \times \frac{2\pi rl}{P}$$

$$e = \phi \frac{P}{2\pi rl} r l \omega_m$$

$$e = \frac{P}{2\pi} \phi \omega_m$$

Let Z be the total number of conductors and A be the number of parallel paths.

The induced EMF in the armature is

$$E = e \times \frac{Z}{A} = \frac{PZ}{2\pi A} \phi \omega_m$$

$$E = K \phi \omega_m \text{ volt}$$

where $K = \frac{PZ}{2\pi A}$.

$$E \propto \phi \omega_m$$

- ▶ In Generator, it is called Generated EMF (E_g)
- ▶ In Motor, it is called Back EMF (E_b)

Developed Torque

The developed torque in armature is

$$T = \frac{EI_a}{\omega_m}$$

$$T = K\phi I_a \text{ Nm}$$

$$\boxed{T \propto \phi I_a}$$

- ▶ In Generator, the developed Torque opposes rotation.
- ▶ In Motor, the developed torque sustains the motion.

For steady operation in any machine,

$$T_e = T_m$$

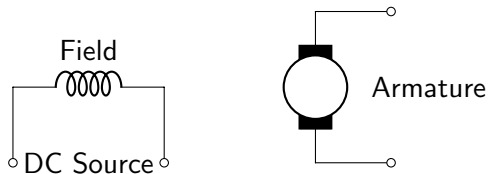
where

T_e = electrical (developed) torque in Nm

T_m = mechanical torque in Nm

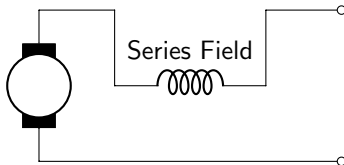
Classification

1. Separately Excited

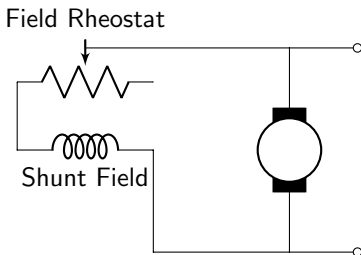


2. Self Excited

► Series



► Shunt



► Compound

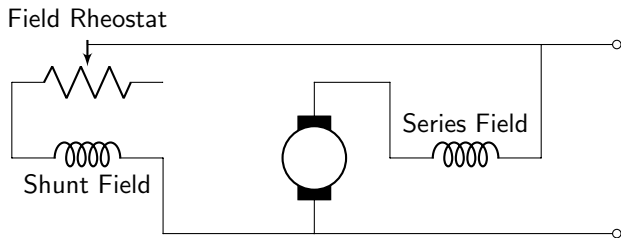


Figure: Long Shunt

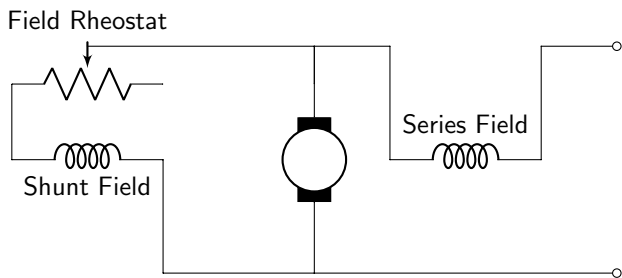
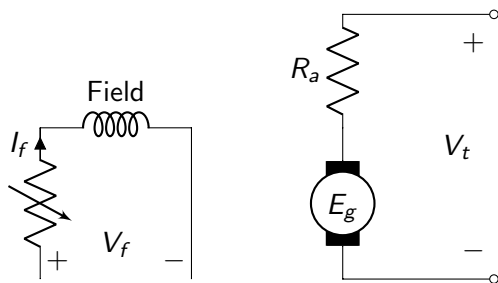


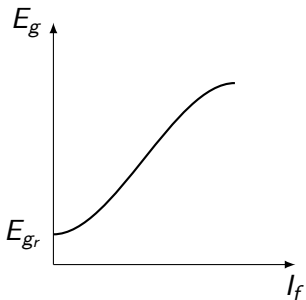
Figure: Short Shunt

Generator

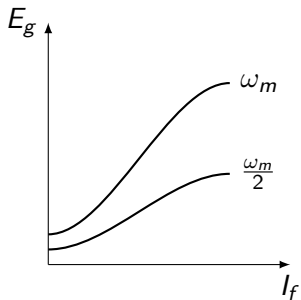


Since there is no load, $I_a = 0$.

$$V_t = E_g$$



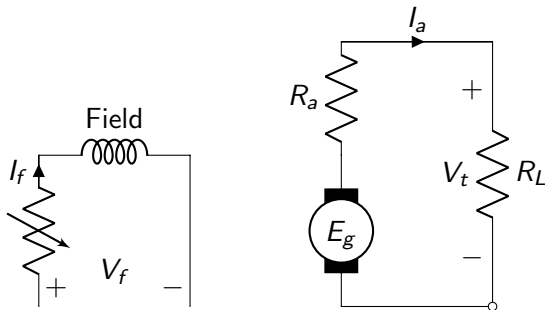
(a) Open Circuit Characteristics



(b) At different Speed

E_{gr} is the residual voltage.

When it supplies load,



$$V_t = E_g - I_a R_a$$

Armature Reaction (AR)

When the current flows in the armature winding, it produces its own field. This field will disturb the main field. Hence there is a net reduction in the flux.

Armature Reaction

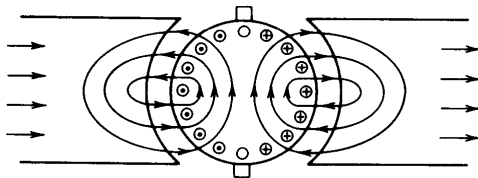


Figure: Armature Reaction

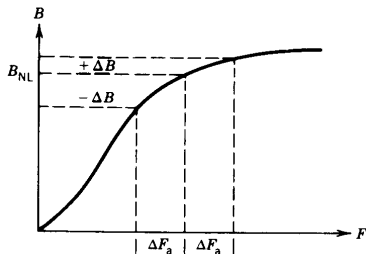


Figure: B-H Curve

$$\text{Net mmf} = \text{Field mmf} - \text{AR}$$

$$N_f I_{f_{\text{eff}}} = N_f I_f - N_f I_{f_{\text{AR}}}$$

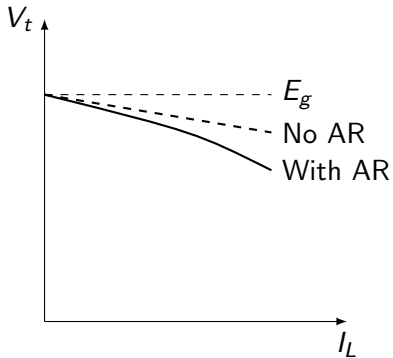
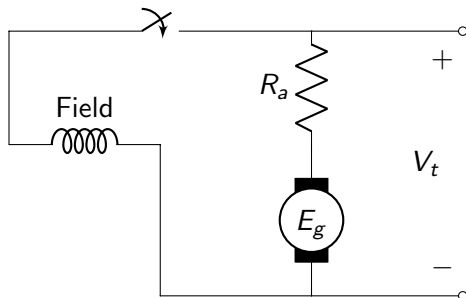


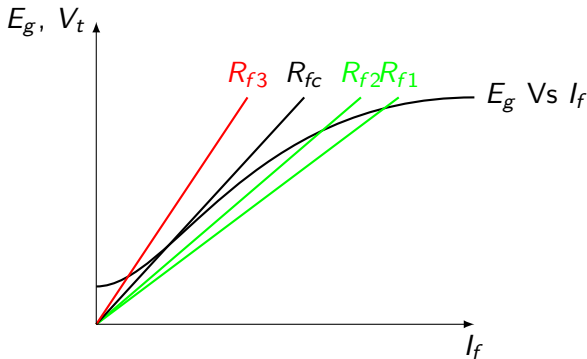
Figure: Terminal Characteristics

Shunt Generator



For voltage buildup

1. Residual magnetism must be present in the machine.
2. Field winding mmf should aid the residual magnetism.
3. Field circuit resistance should be less than the critical field resistance.



In order the machine to develop voltage,

$$R_f < R_{fc}$$

The generator voltage build up will increase until two curves intersect.

► Shunt

$$I_a = I_L + I_f$$

$$V_t = E_g - I_a R_a$$

$$I_f = \frac{V_t}{R_{sh}}$$

► Series

$$I_L = I_a$$

$$V_t = E_g - I_a(R_a + R_{ser})$$

► Compound (long shunt)

$$I_a = I_L + I_f$$

$$V_t = E_g - I_a(R_a + R_{ser})$$

► Compound (short shunt)

$$I_a = I_L + I_f$$

$$V_t = E_g - I_a R_a - I_L R_{ser}$$

In Compound machines, there are two field windings (Both shunt and series).

1. When these two fluxes aid each other, the machine is called a *cumulative compound machine*.
2. When they oppose each other, the machine is called a *differential compound machine*.

The total effective mmf per pole is

$$F_{\text{eff}} = F_{\text{sh}} \pm F_{\text{ser}} - F_{\text{AR}}$$

$$N_f I_{f_{\text{eff}}} = N_f I_f \pm N_{\text{ser}} I_{\text{ser}} - N_f I_{f_{\text{AR}}}$$

where

N_f = number of turns per pole of the shunt field winding

N_{ser} = number of turns per pole of the series field winding

F_{AR} = mmf of the armature reaction

$$I_{f_{\text{eff}}} = I_f \pm \frac{N_{\text{ser}}}{N_f} I_{\text{ser}} - I_{f_{\text{AR}}}$$

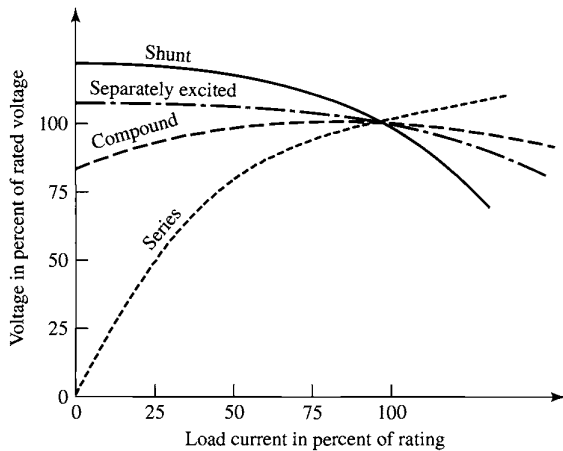


Figure: Terminal Characteristics of DC Generators

Source : "Electric Machinery" A. E. Fitzgerald et. al.

DC Machine Example ¹:

A 25 kW 125 V separately excited dc machine is operated at a constant speed of 3000 rpm with a constant field current such that the open circuit terminal voltage is 125 V. $R_a = 0.02 \Omega$.

1. The machine is acting as a generator with $V_t = 124$ V and $P_t = 24$ kW. Find the speed.
2. The machine is acting as a motor with $V_t = 123$ V and $P_t = 21.9$ kW. Find the speed.

1.

$$I_a = \frac{P_t}{V_t} = 193.54 \text{ A}$$

$$E_a = V_t + I_a R_a = 127.87 \text{ V}$$

Since $E_a \propto \phi \omega_m$ and $\phi = \text{constant}$,

$$n = \frac{3000 \times 127.87}{125} = 3069 \text{ rpm}$$

2.

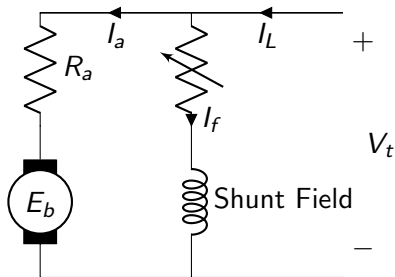
$$I_a = \frac{P_t}{V_t} = 178 \text{ A}$$

$$E_a = V_t - I_a R_a = 119.4 \text{ V}$$

$$n = \frac{3000 \times 119.4}{125} = 2866 \text{ rpm}$$

Motor

Shunt :



$$I_L = I_a + I_f$$

$$E_b = V_t - I_a R_a$$

$$T_a = \frac{E_b I_a}{\omega_m}$$

We know,

$$E_b = K\phi\omega_m ; T_a = K\phi I_a$$

To study ω Vs T characteristics,

$$\omega_m = \frac{E_b}{K\phi}$$

$$\omega_m = \frac{V_t - I_a R_a}{K\phi}$$

$$\omega_m = \frac{V_t}{K\phi} - \frac{R_a}{(K\phi)^2} T_a$$

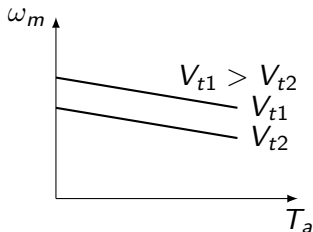


Figure: Speed - Torque Characteristics

If Armature Reaction is taken into account, the speed will increase (because of reduction in flux) as load increases.

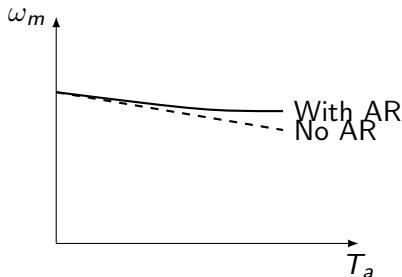
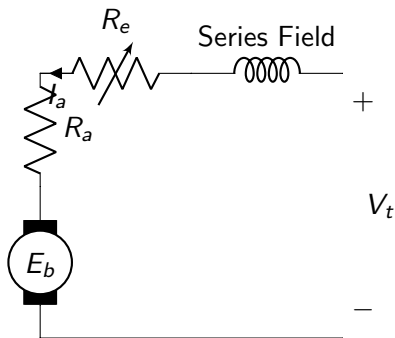


Figure: Speed - Torque Characteristics

DC Shunt motor is almost a constant speed motor.

It is used in Fans, Pumps, blowers and conveyors.

Series:



$$I_L = I_a = I_f$$

$$E_b = V_t - I_a(R_{\text{ser}} + R_e + R_a)$$

We know,

$$E_b = K\phi\omega_m ; T_a = K\phi I_a$$

If magnetic linearity is assumed, $\phi \propto I_a$,

$$E_b = K_{se} I_a \omega_m$$

$$T_a = K_{se} I_a^2$$

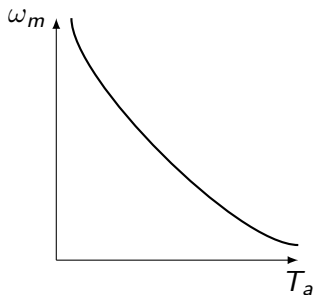
We get

$$\omega_m = \frac{V_t - I_a(R_{ser} + R_e + R_a)}{K_{se} I_a}$$

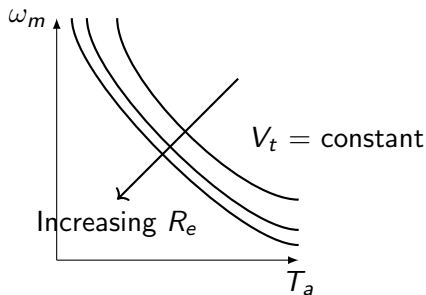
$$\omega_m = \frac{V_t}{\sqrt{K_{se}} \sqrt{T_a}} - \frac{R_{ser} + R_e + R_a}{K_{se}}$$

If there is no load, ω will be very high.

DC Series motors should never be started without load.



(a) ω Vs T_a

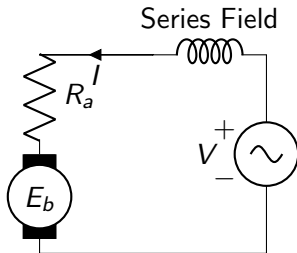


(b) For different R_e

Series motors are used where large starting torques are required. For example, automobile starters, traction, cranes and locomotives.

Check yourself

If a DC series motor is supplied with AC, will it run?



In DC Series motor, $T_a \propto I_a^2$ (Assuming Magnetic linearity).
The instantaneous torque is

$$T_a \propto (I_m \sin(\omega t - \phi))^2 = \frac{1}{2}(1 - \cos 2(\omega t - \phi))$$

Since there is average torque, the motor will run. (But pulsating....)

Since it works on both AC and DC, it is called a **universal motor**.
It is used in blender, dryer and vacuum cleaner.

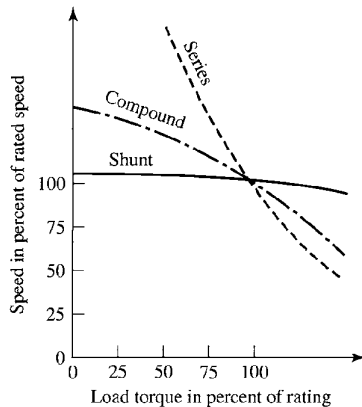
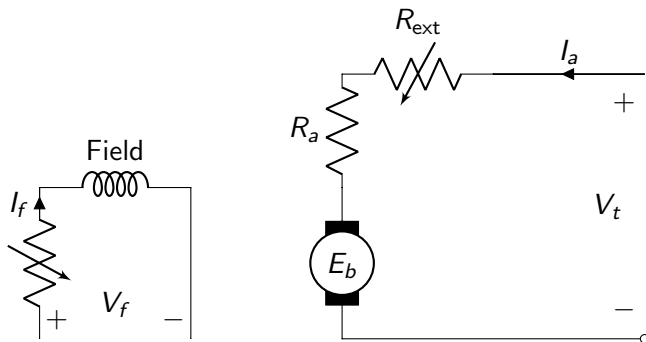


Figure: Speed - Torque Characteristics of DC Motors

Source : "Principles of Electric Machines and Power Electronics" P C Sen

Speed Control of DC Shunt Motor



$$\omega_m = \frac{E_b}{\phi} = \frac{V_t - I_a(R_a + R_{ext})}{\phi}$$

The speed control in a DC machine can be achieved by the following methods:

1. Armature voltage control (V_t).
2. Field control (ϕ).
3. Armature resistance control (R_{ext}).

Assume the motor is driving a fan load ($T_L \propto \omega_m^2$).

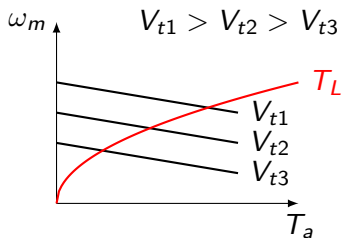


Figure: Armature Voltage Control

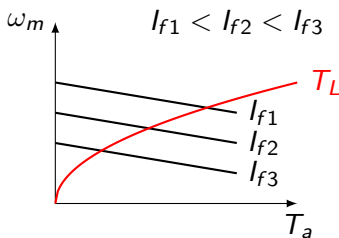
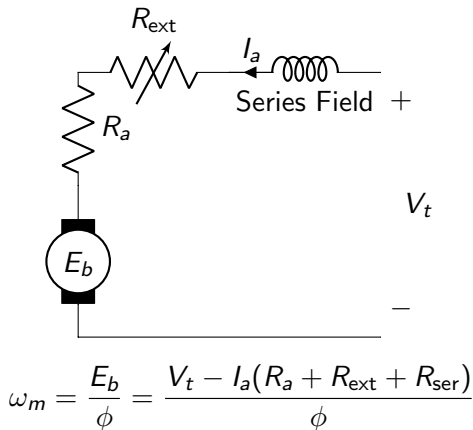


Figure: Field Control

DC Series Motor - Speed Control



The speed can be controlled by changing

1. the external resistance (R_{ext}).
2. the terminal voltage (V_t).

Assume the motor is driving a fan load ($T_L \propto \omega_m^2$).

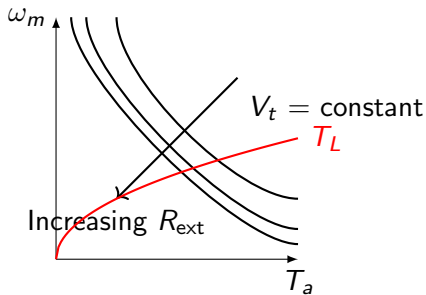
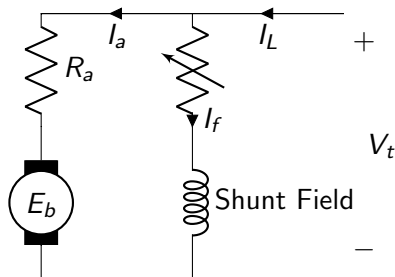


Figure: For different R_{ext}

Starting of DC Motors



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

When the motor is about to start, $E_b = 0$.

$$I_a = \frac{V_t}{R_a}$$

Since R_a is small, I_a is very large. To limit it,

1. Insert an external resistance at start (Three point starter).
2. Use a low V_t at start. (Variable DC supply is required).

DC Motor - Example 2:

A 220 V, 7 hp series motor is mechanically coupled to a fan and draws 25 A and runs at 300 rpm when connected to a 220 V supply with no external resistance connected to the armature circuit. The torque required by the fan is directly proportional to the square of the speed. $R_a = 0.6\Omega$ and $R_{ser} = 0.4\Omega$. Neglect armature reaction and rotational loss.

1. Determine the power delivered to the fan and torque developed by the motor.
2. The speed is to be reduced to 200 rpm by inserting a resistance (R_{ext}) in the armature circuit. Determine R_{ext} and the power delivered to the fan.

1.

$$E_a = V_t - I_a(R_a + R_{ser}) = 220 - 25 \times (1) = 195 \text{ V}$$

$$P = E_a I_a = 195 \times 25 = 4880 \text{ W}$$

$$T = \frac{P}{\omega_m} = \frac{4880}{2 \times \pi \times 300/60} = 155.2 \text{ Nm}$$

2. In DC series motor, $T_a \propto I_a^2$. It is given that $T_L \propto \omega_m^2$.

$$\frac{I_{a1}^2}{I_{a2}^2} = \frac{N_1^2}{N_2^2}$$

$$I_{a2} = \frac{25 \times 200}{300} = 16.67 \text{ A}$$

We also know that $E_a \propto \phi \omega_m$. However in series motor,
 $\phi \propto I_a$.

$$\frac{E_{a1}}{E_{a2}} = \frac{I_{a1} \omega_{m1}}{I_{a2} \omega_{m2}}$$

$$E_{a2} = \frac{195 \times 200 \times 16.67}{25 \times 300} = 86.68 \text{ V}$$

$$86.68 = 220 - 16.67(1 + R_{\text{ext}})$$

$$R_{\text{ext}} \approx 7 \Omega$$

$$P = 86.68 \times 16.67 = 1444.96 \text{ Watts}$$