DC Machines

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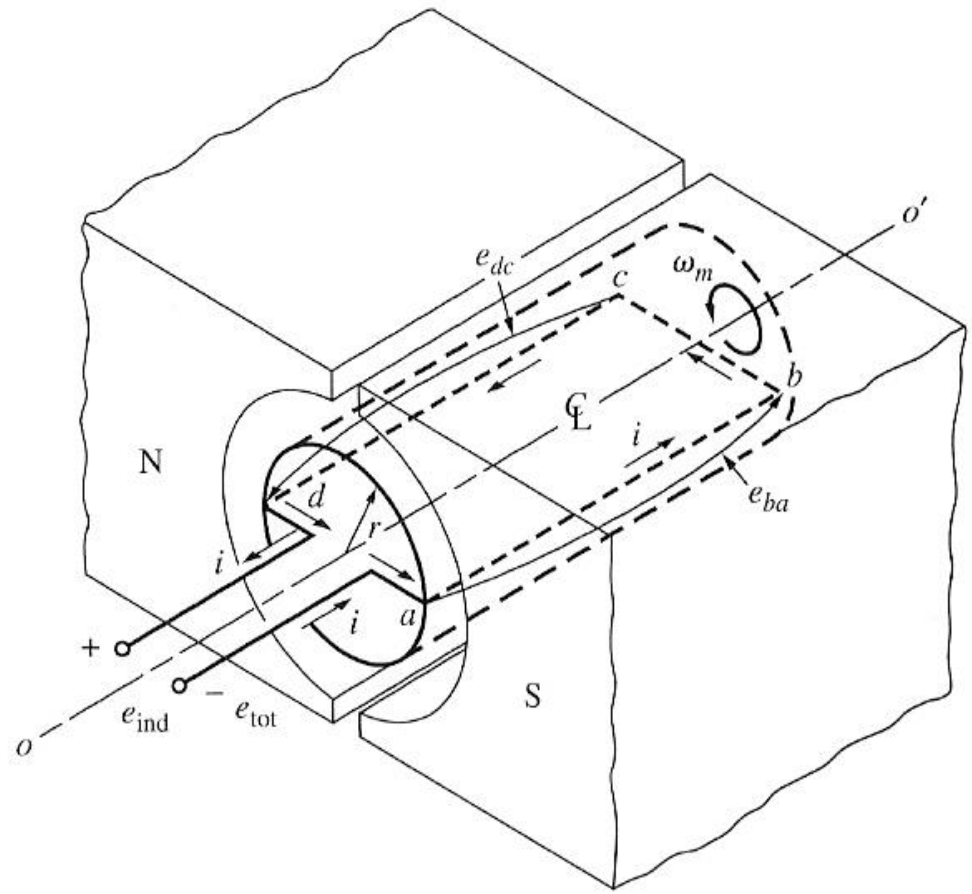
DC Machines

- DC Machine Construction
- Basic Principles
- Armature winding of DC machines
- Armature Reaction
- Equivalent Circuit
- Power & Torque
- Operation characteristics of DC generators
- Speed control of DC machines
- Starting of DC machines

Basic Principles of DC machines

DC MACHINERY

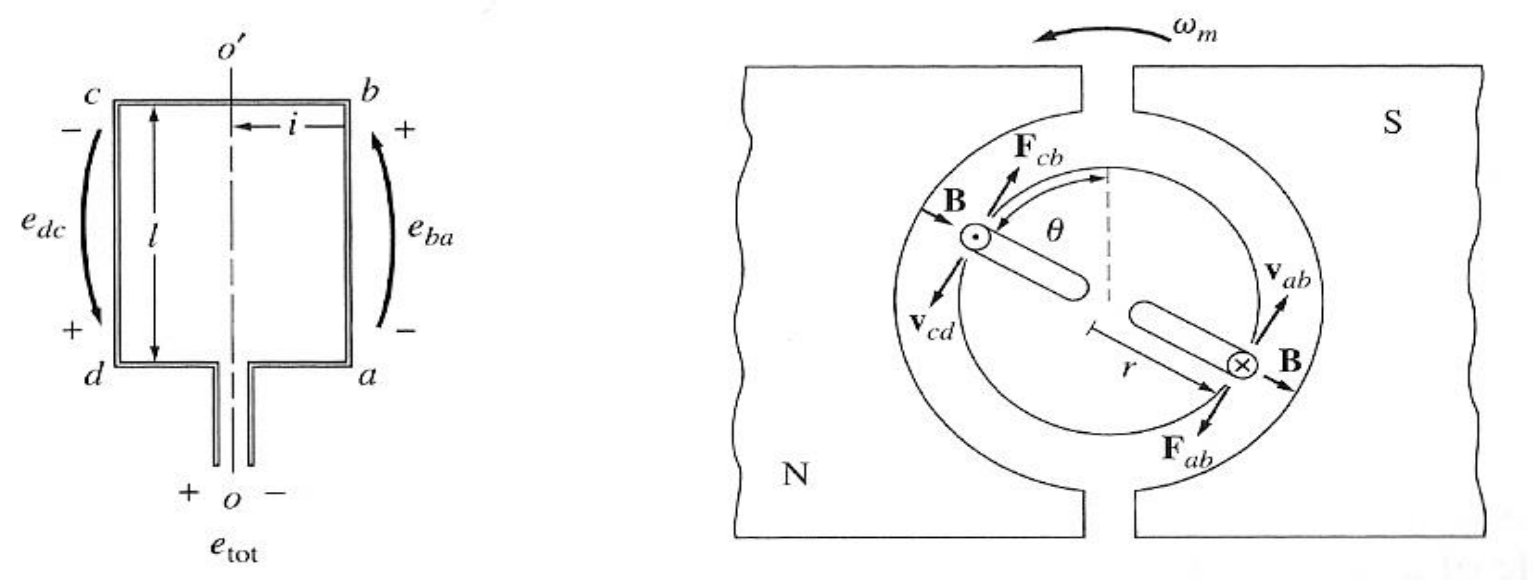
- The simplest rotating dc machine is shown below:



(a)

VOLTAGE INDUCED IN A LOOP

- If the rotor is rotated, a voltage will be induced in the wire loop
- To determine the magnitude and shape of the voltage, examine the figure below:



(c) (d)

VOLTAGE INDUCED IN A LOOP

- To determine the total voltage e_{tot} on the loop, examine each segment of the loop separately and sum all the resulting voltages. The voltage on each segment is given by:

$$e_{\text{ind}} = \left(v \times \boldsymbol{B}\right) \cdot \boldsymbol{I}$$

- Thus, the total induced voltage on the loop is:

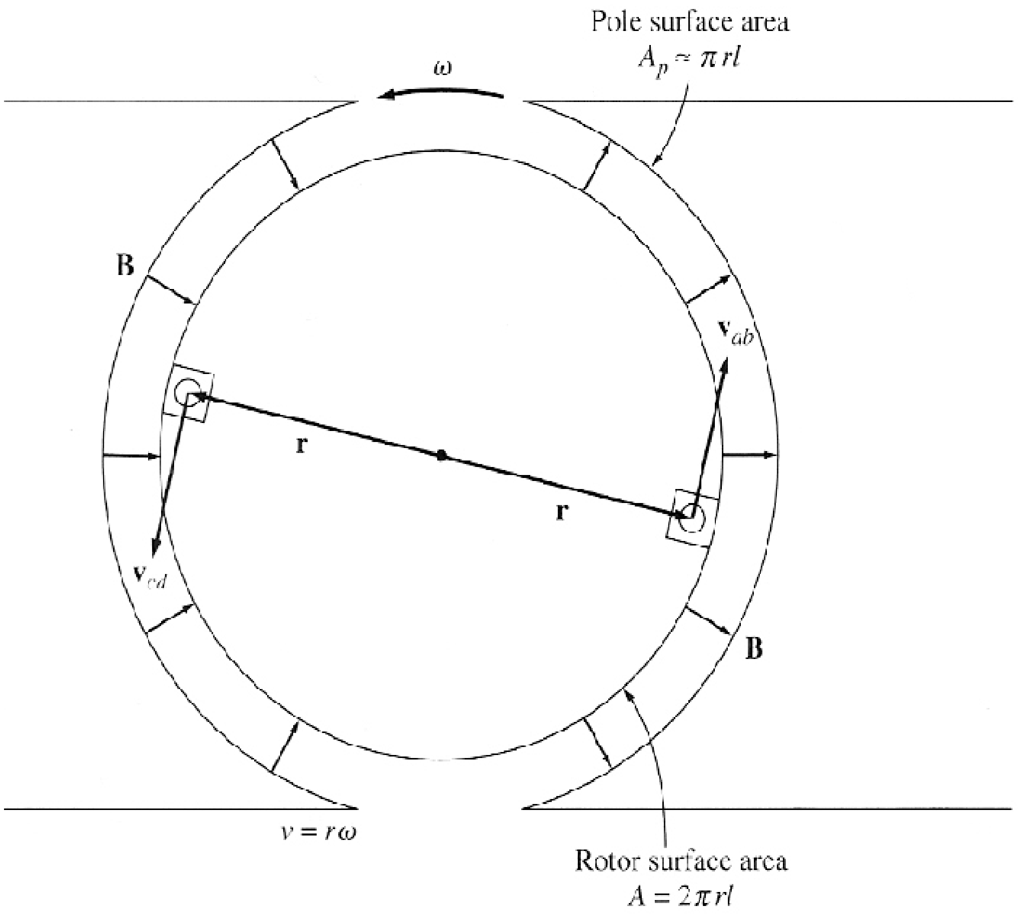
$$e_{\text{ind}} = 2v\boldsymbol{BI}$$

- **When the loop rotates through 180°, segment *ab* is under the north pole face instead of the south pole face, at that time, the direction of the voltage on the segment reverses, but its magnitude remains constant. The resulting voltage e_{tot} is shown next**

VOLTAGE INDUCED IN A LOOP

- There is an alternative way to express the e_{ind} equation, which clearly relates the behaviour of the single loop to the behaviour of larger, real dc machines.
- Examine the figure

➔



- The tangential velocity v of the edges of the loop can be expressed as $v = r\omega$ Substituting this expression into the e_{ind} equation before, gives:

$$e_{\text{ind}} = 2r\omega BI$$

VOLTAGE INDUCED IN A LOOP

- The rotor surface is a cylinder, so the area of the rotor surface A is equal to $2\pi rl$
- Since there are 2 poles, the area under each pole is $A_p = \pi rl$. Thus,

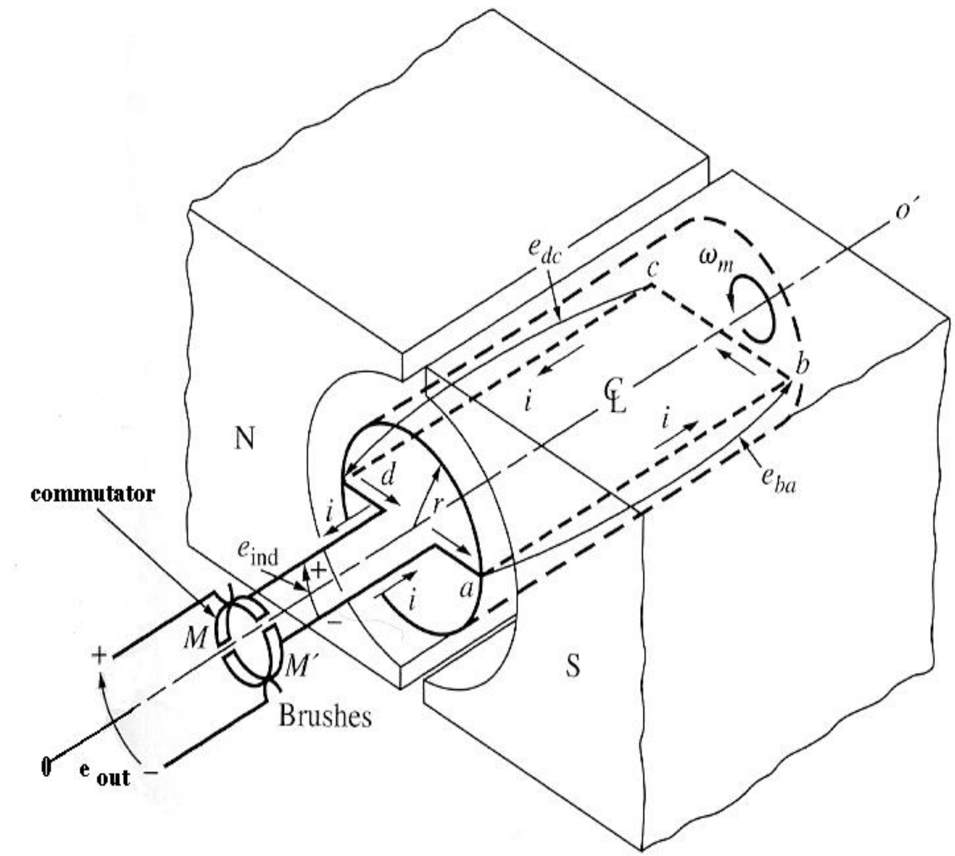
$$e_{\text{ind}} = \frac{2}{\pi} A_p B\omega$$

- the flux density B is constant everywhere in the air gap under the pole faces, the total flux under each pole is $\phi = A_p B$. Thus, the final form of the voltage equation is:

$$e_{\text{ind}} = \frac{2}{\pi} \phi\omega$$

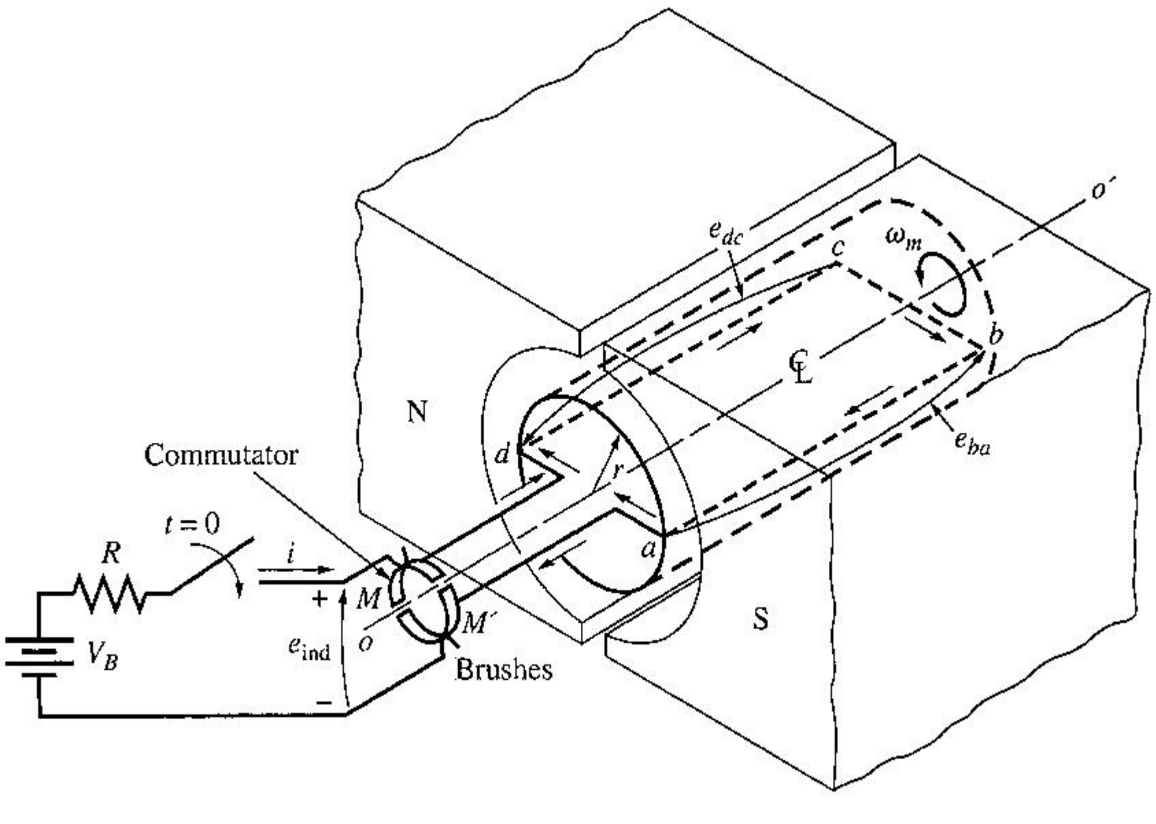
VOLTAGE INDUCED IN A LOOP
HOW TO GET IT OUT

- Thus, every time the voltage of the loop switches direction, the contacts also switches connections, & the output of the contacts is always built up in the same way
- This connection-switching process is known as **commutation** - The rotating semicircular segments are called commutator segments, and the fixed contacts are called brushes



Induced Torque in the Rotating Loop

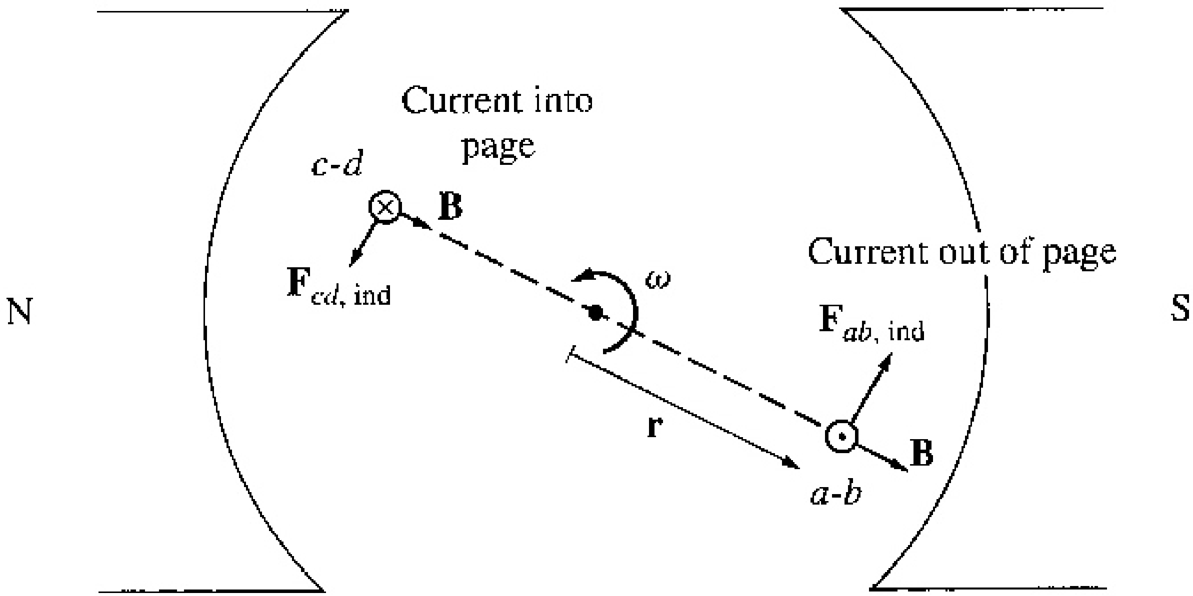
- Suppose a battery is now connected to the machine as shown here, together with the resulting configuration



(a)

Induced Torque in the Rotating Loop

- How much torque will be produced in the loop when the switch is closed?



(b)

- approach to take is to examine one segment of the loop at a time and then sum the effects of all the individual segments

Induced Torque in the Rotating Loop

- The force on a segment of the loop is given by

$$F = i(I \times B)$$

and the torque on the segment is

$$\tau = rF\sin\theta$$

- The resulting total induced torque in the loop is:

$$\tau_{\text{ind}} = 2rilB$$

- By using the fact that $A_p = \pi rl$ and $\phi = A_p B$, the torque expression can be reduced to:

$$\tau_{\text{ind}} = \frac{2}{\pi}\varphi i$$

- In general, torque in any real machine will depend on the following 3 factors:

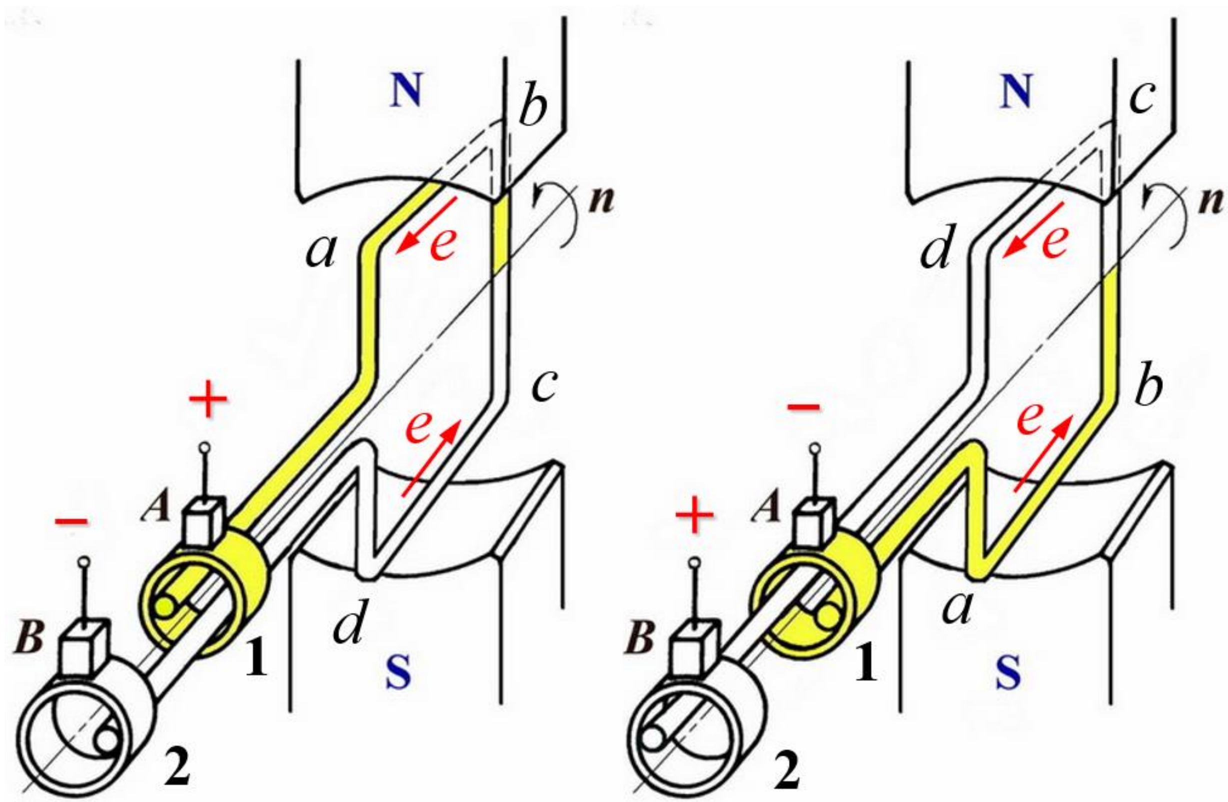
1- The flux in the machine

2- The current in the machine

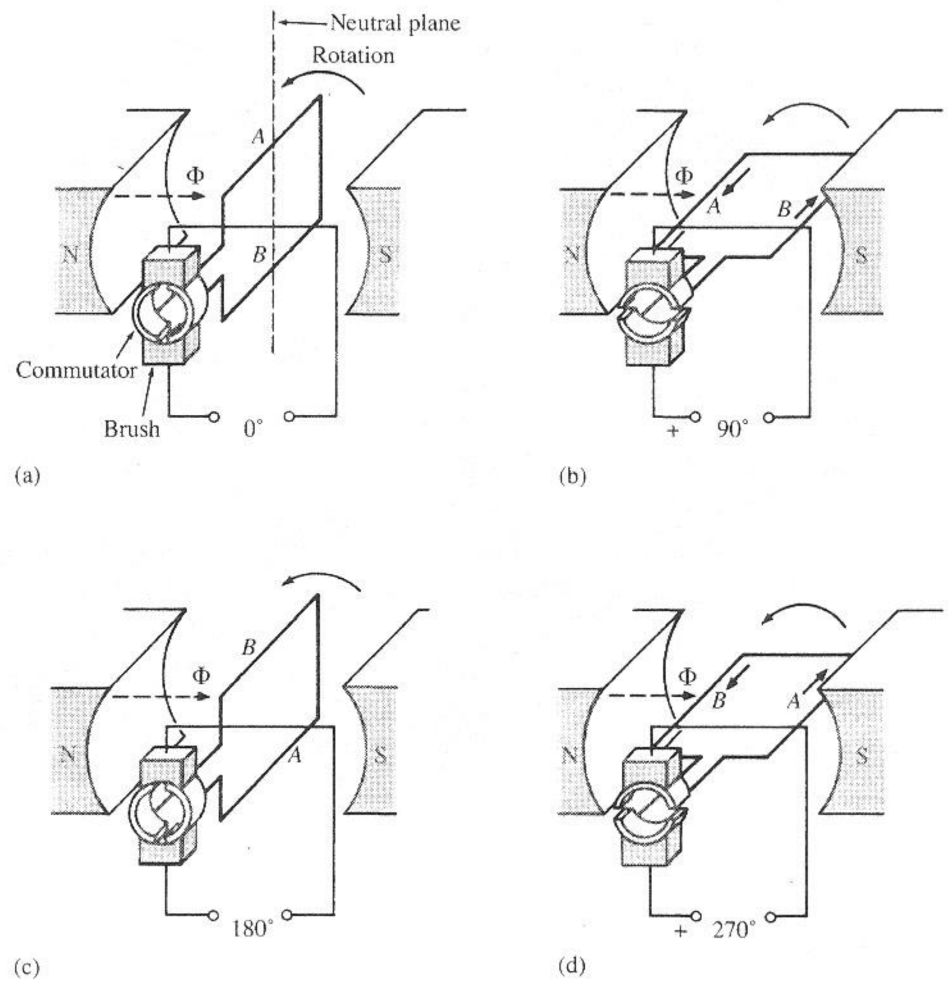
3- A constant representing the construction of the machine

DC Machine Construction

Field winding of AC machines

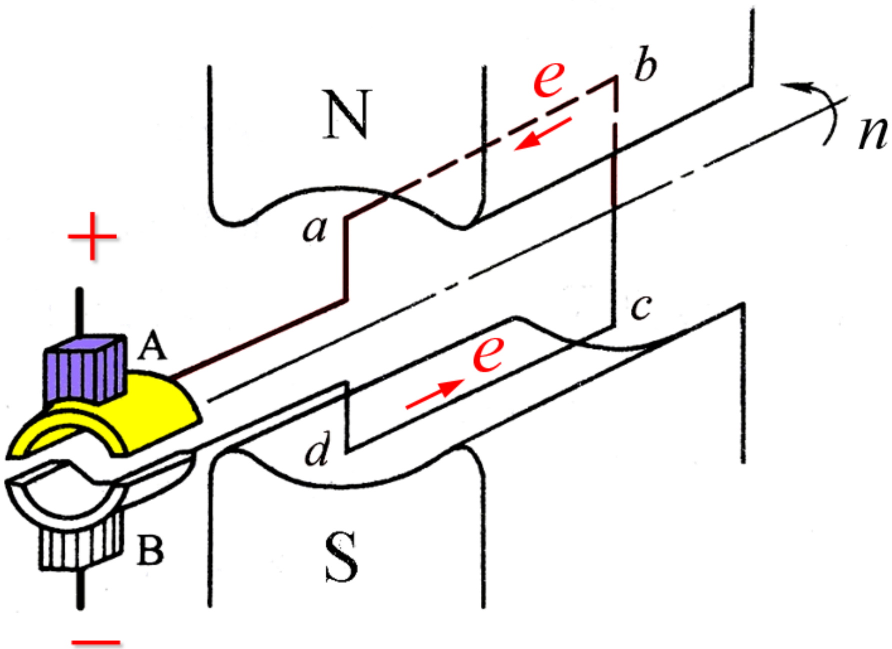


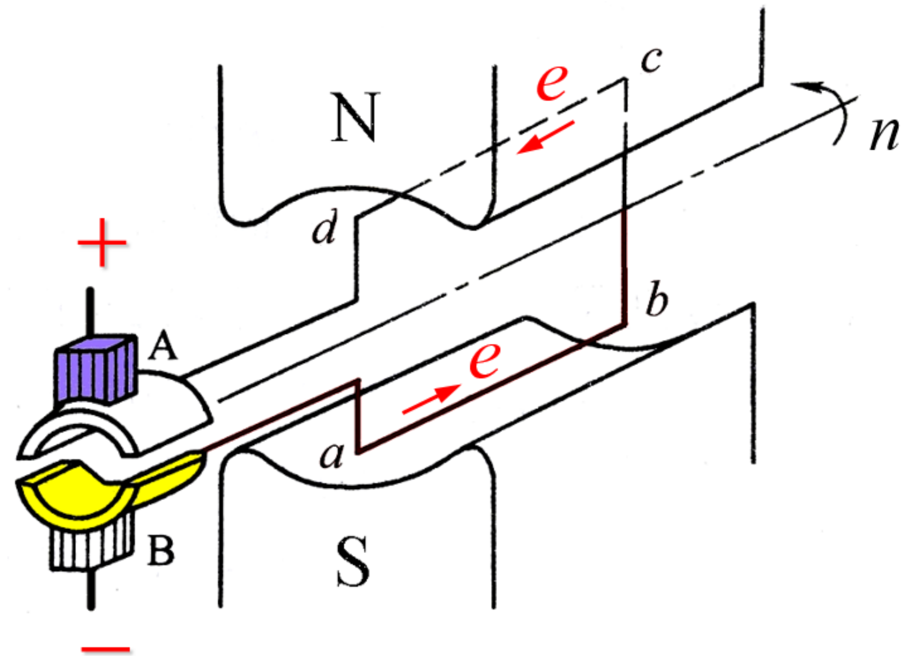
Commutator



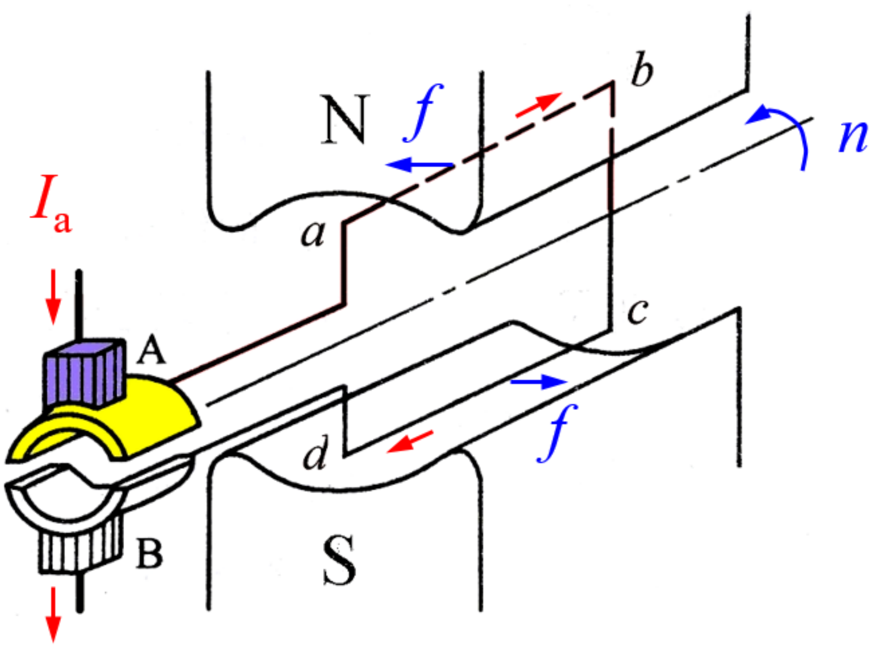
Neutral plane
Rotation
Φ
A
B
N
S
Commutator
Brush
0°
(a)
90°
+
(b)
180°
(c)
270°
(d)

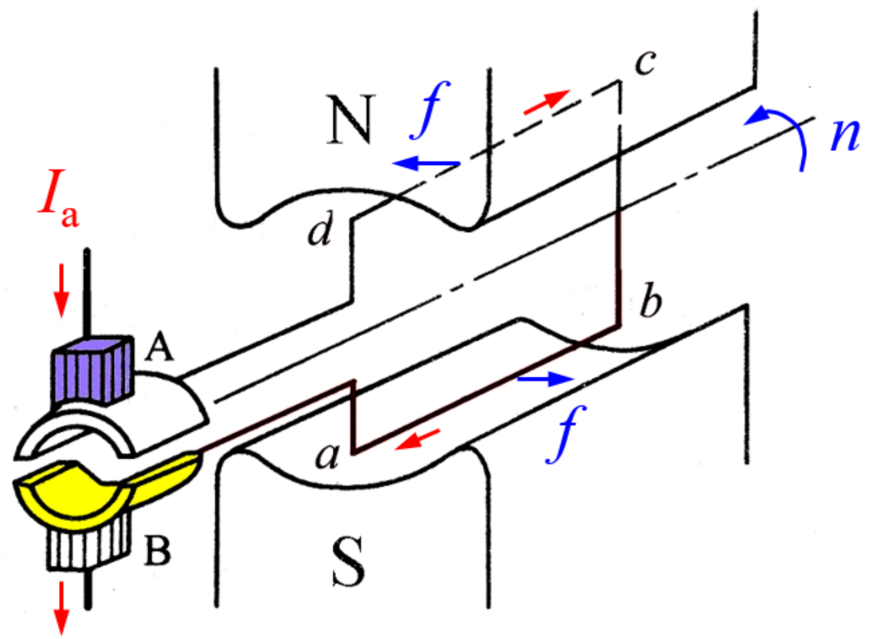
Commutator of DC generators



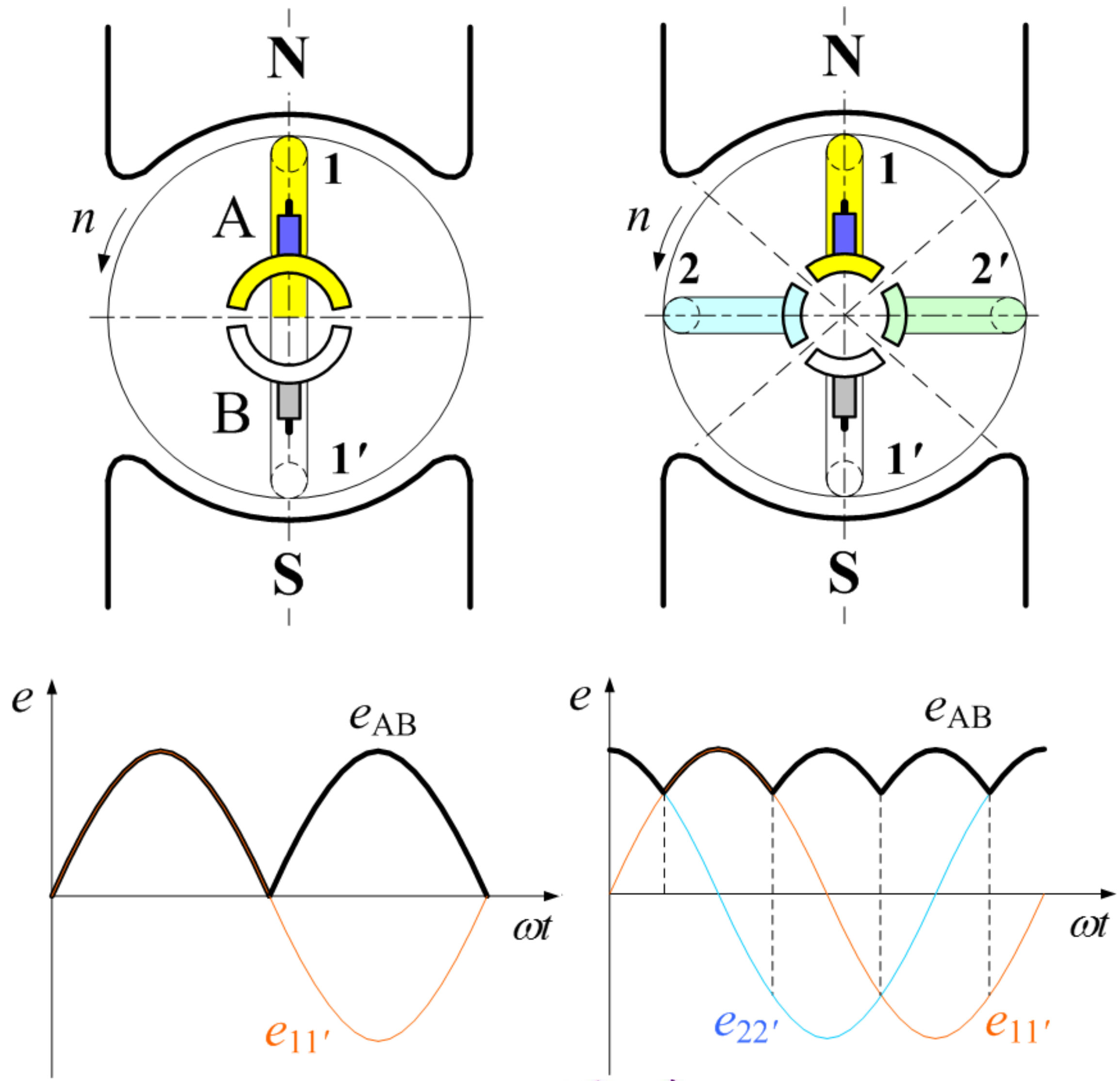


Commutator of DC motors

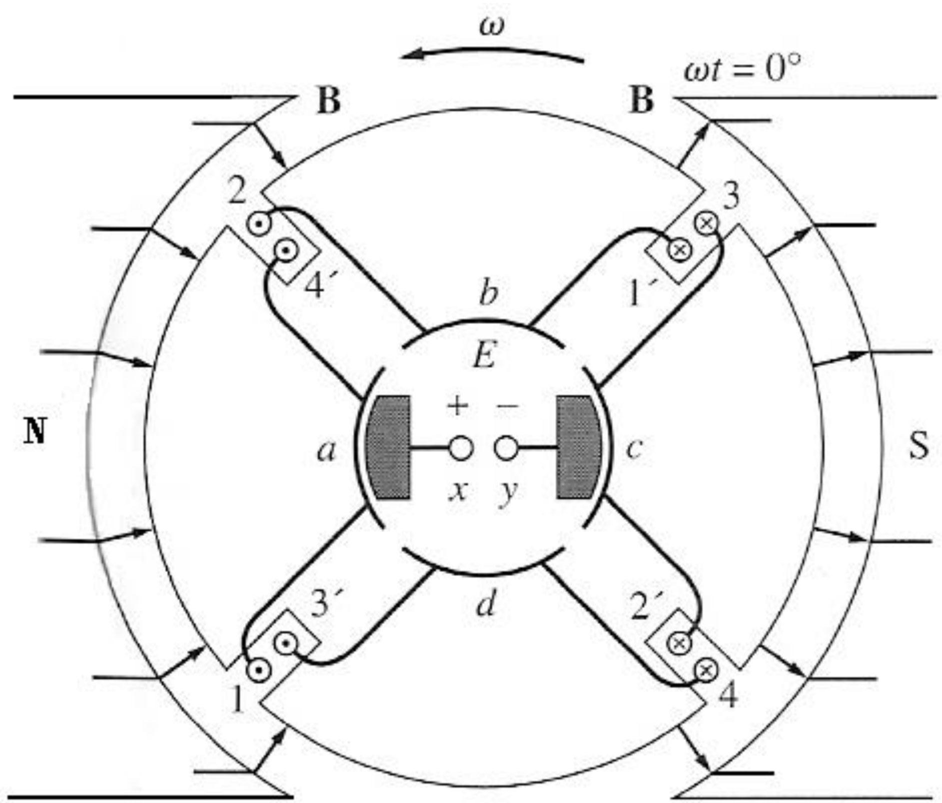




Reduce Voltage Harmonics

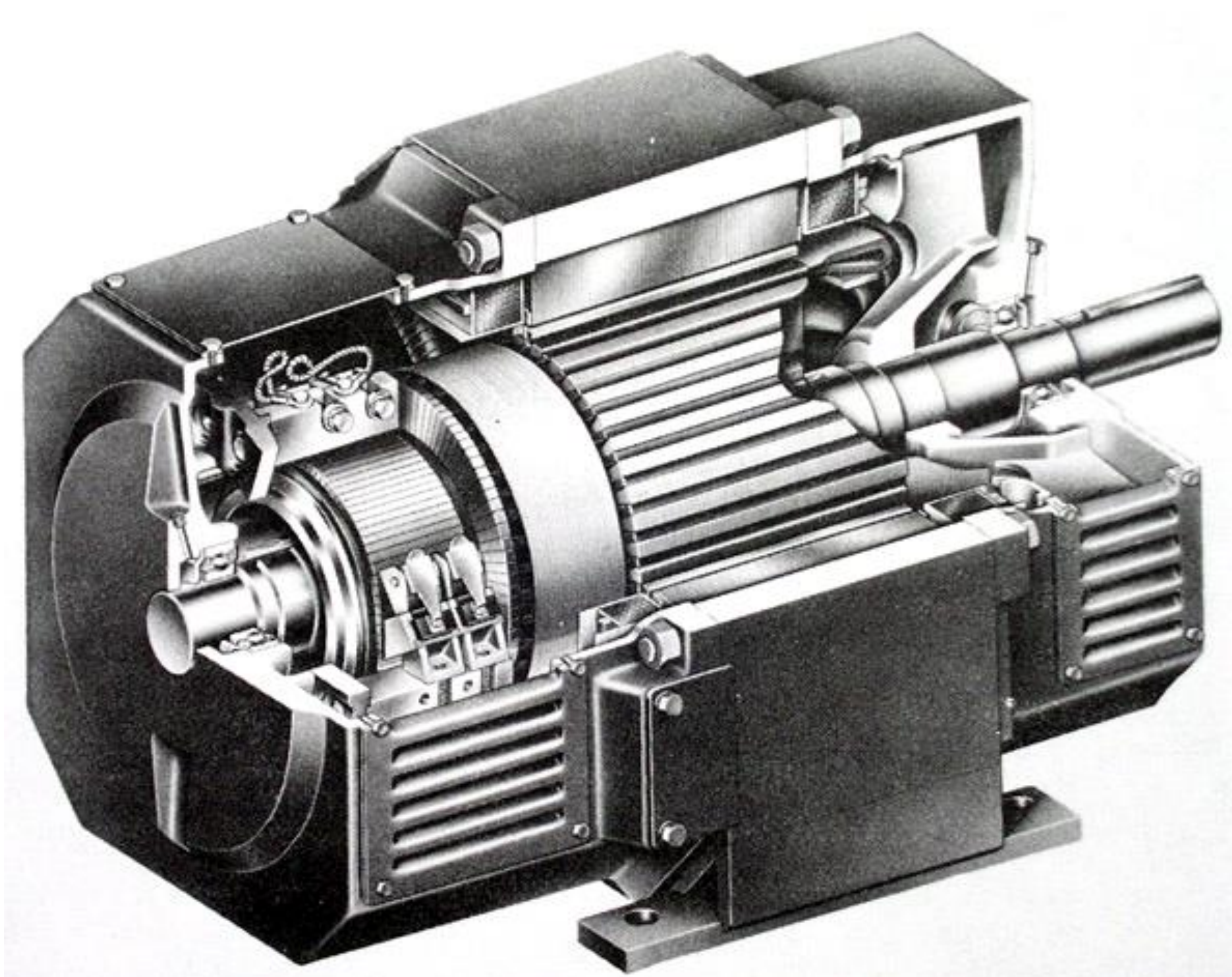


Cross section of a DC machine

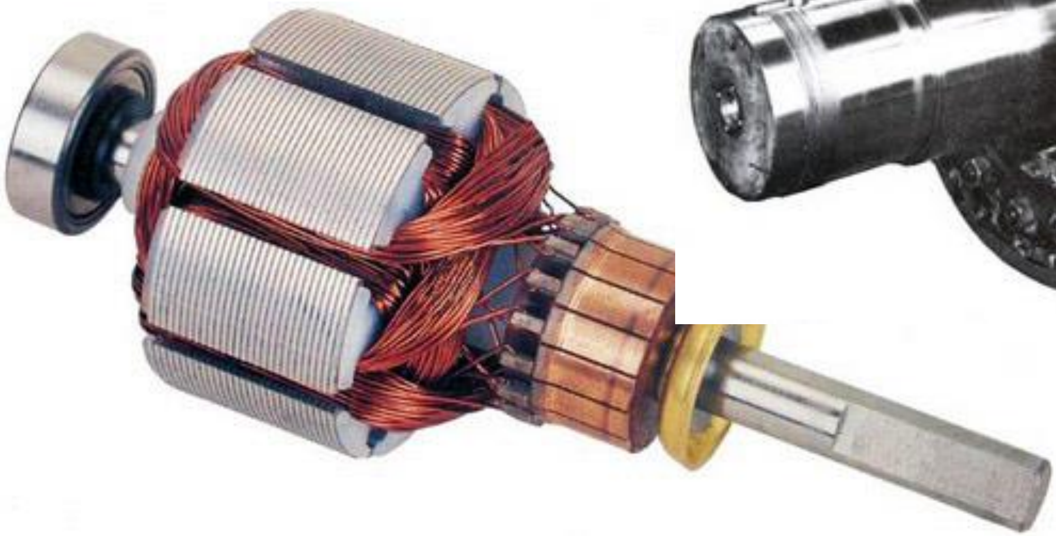


(a)

Construction of DC machines

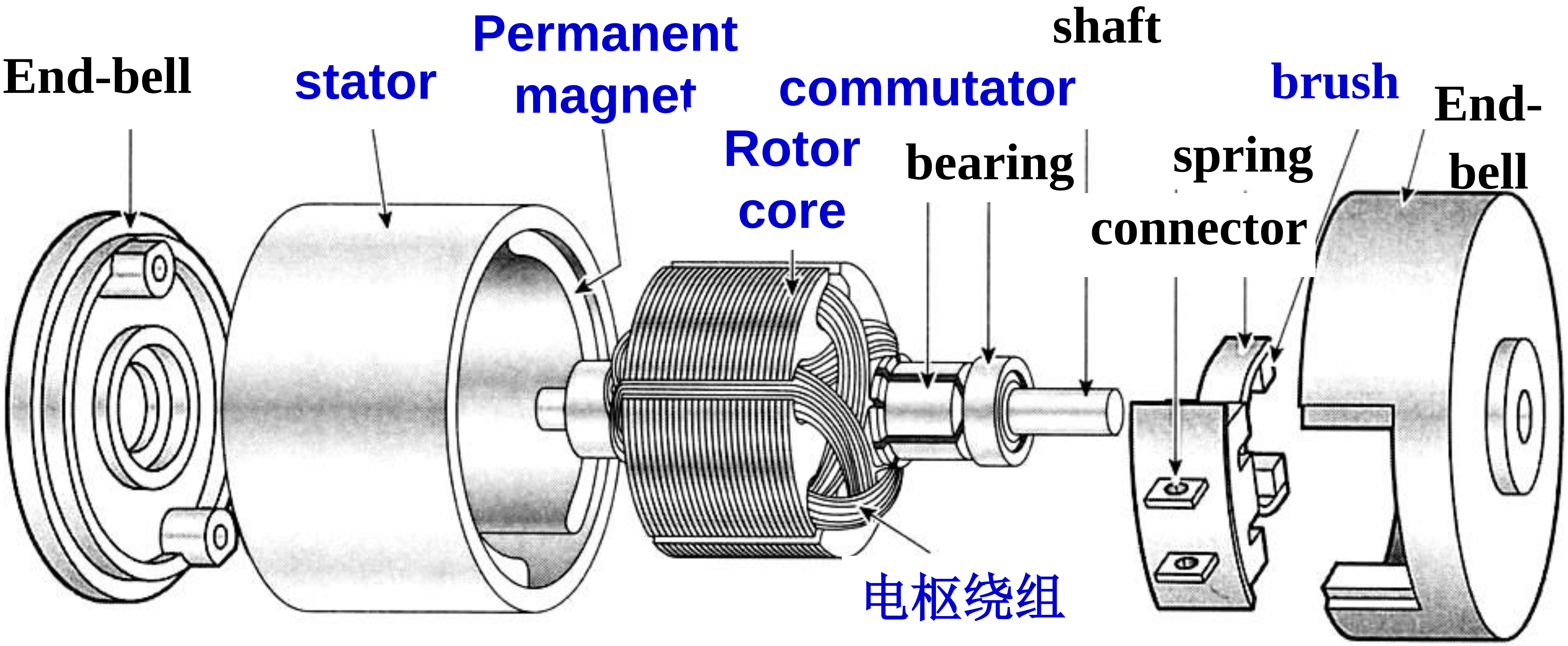


Rotor of DC machines



Commutator

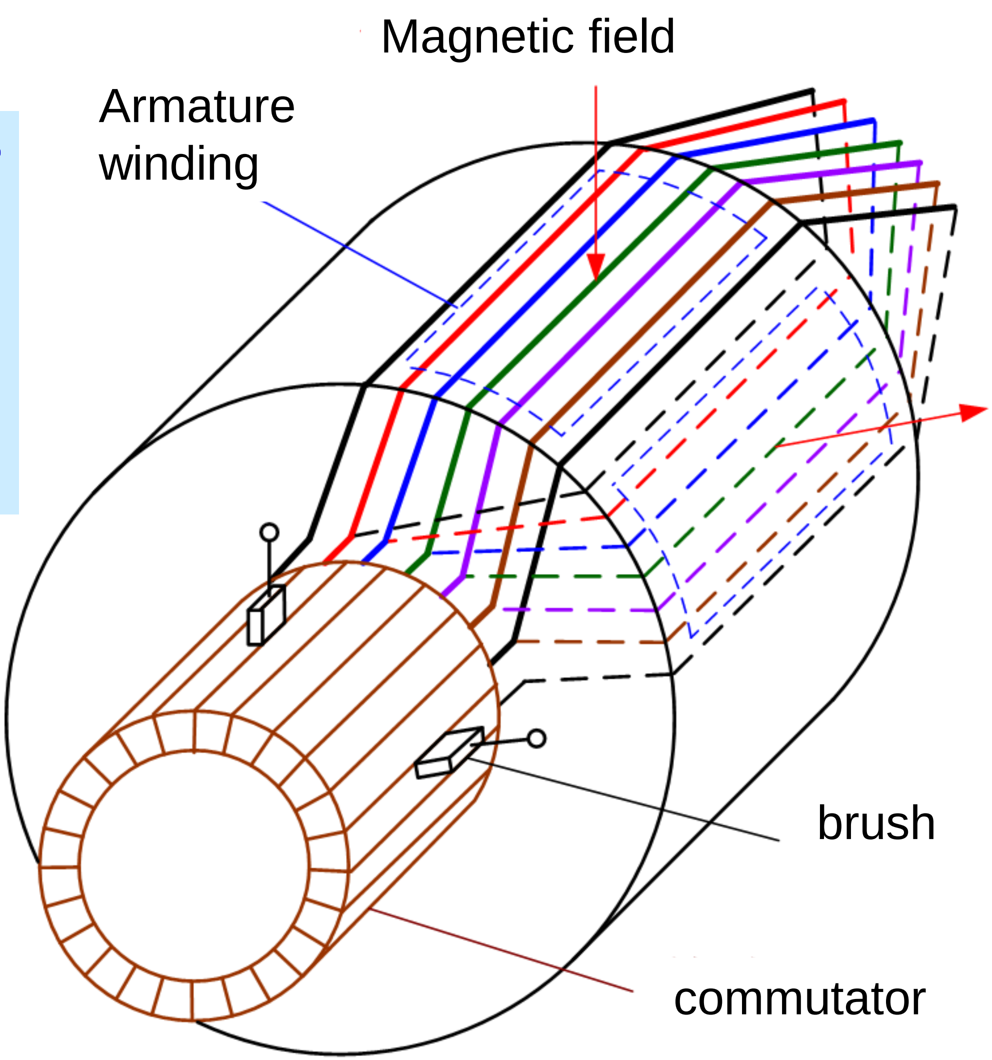
Structure of DC machines



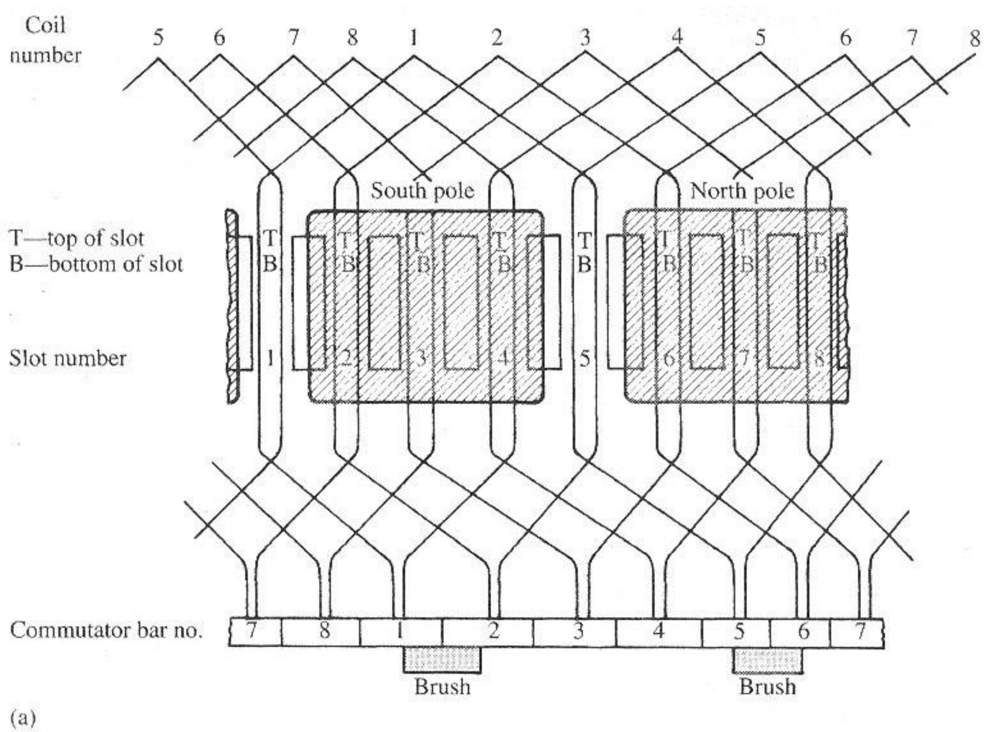
Armature winding of DC machines

Interlacing of armature wiring

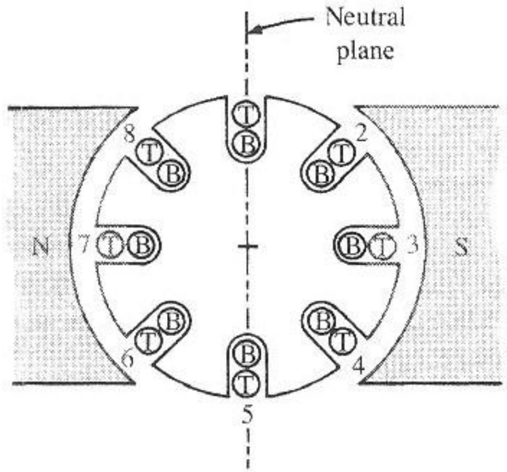
The two terminals of a winding loop are connected to adjacent commutators



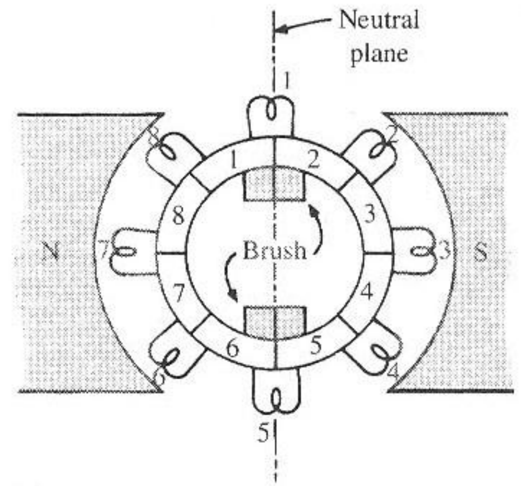
Interlacing of armature wiring



Physical layout of winding



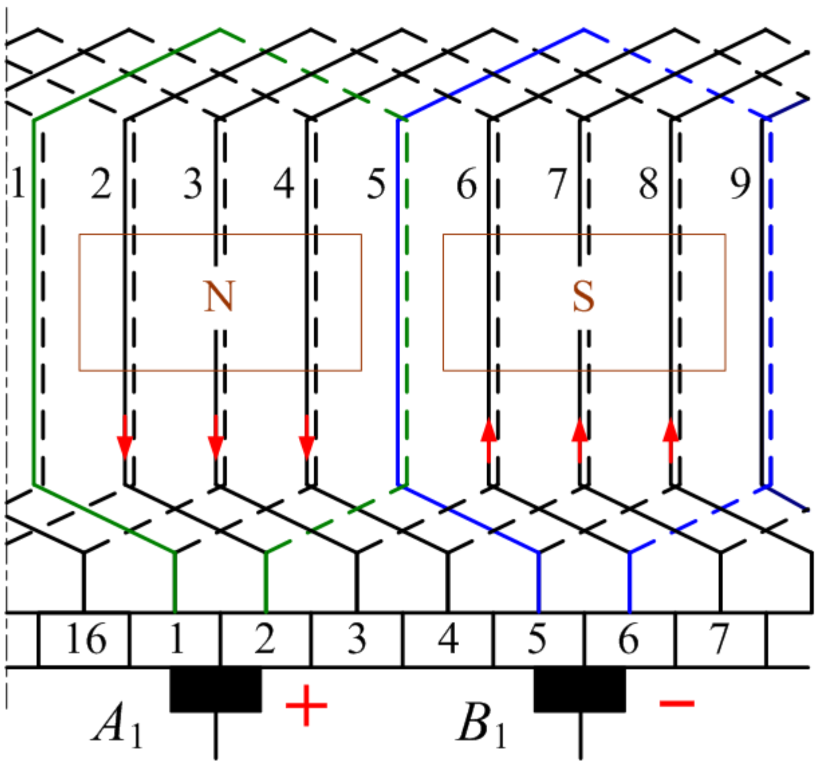
(b)

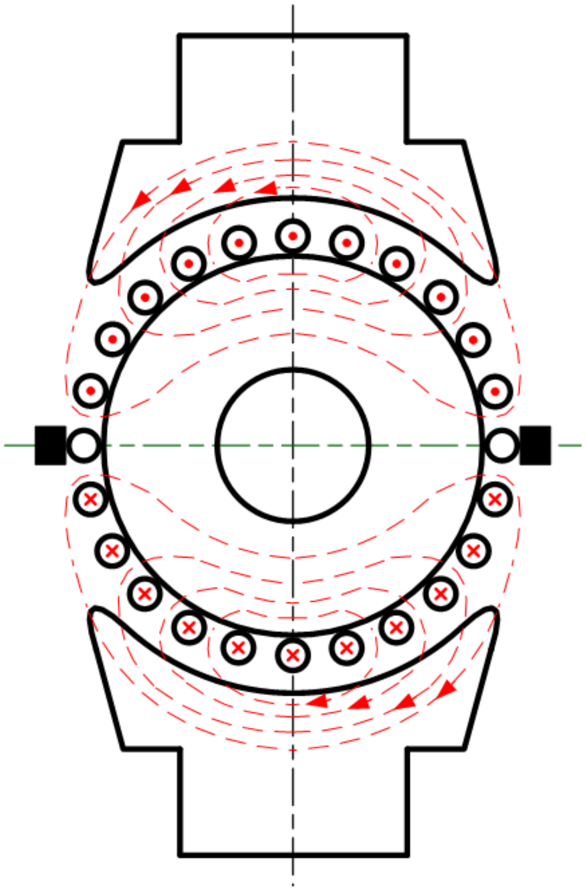


(c)

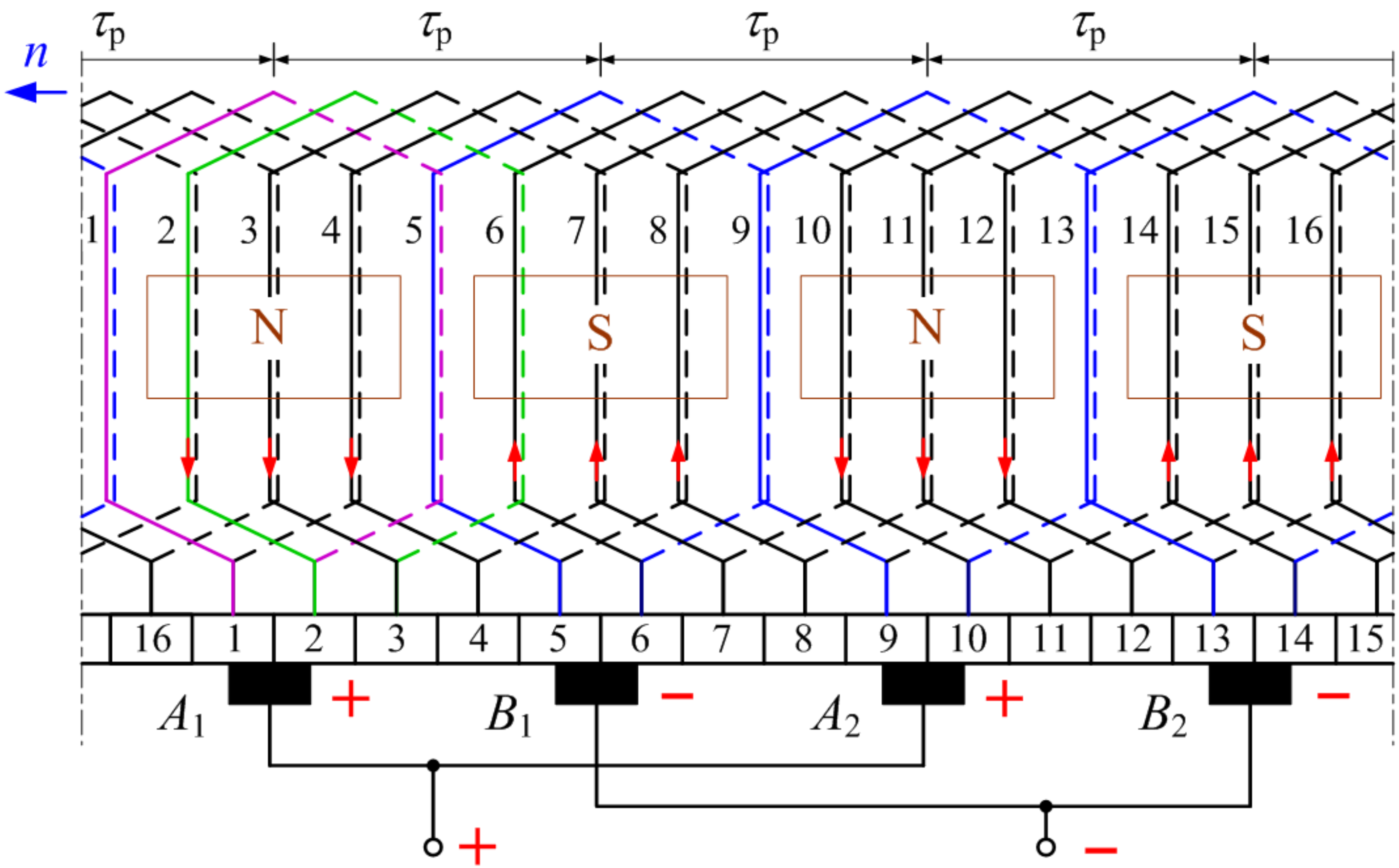
Here the windings are shown straddling different commutation bars.

Armature winding of DC machines





Armature winding of DC machines



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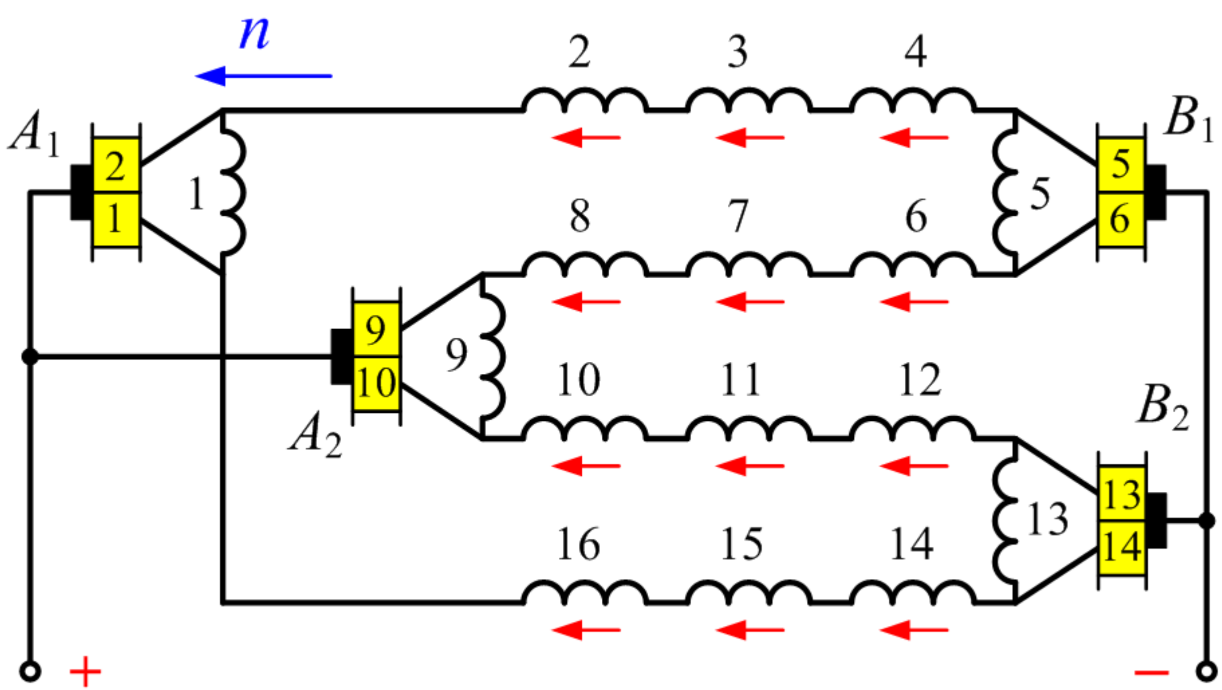
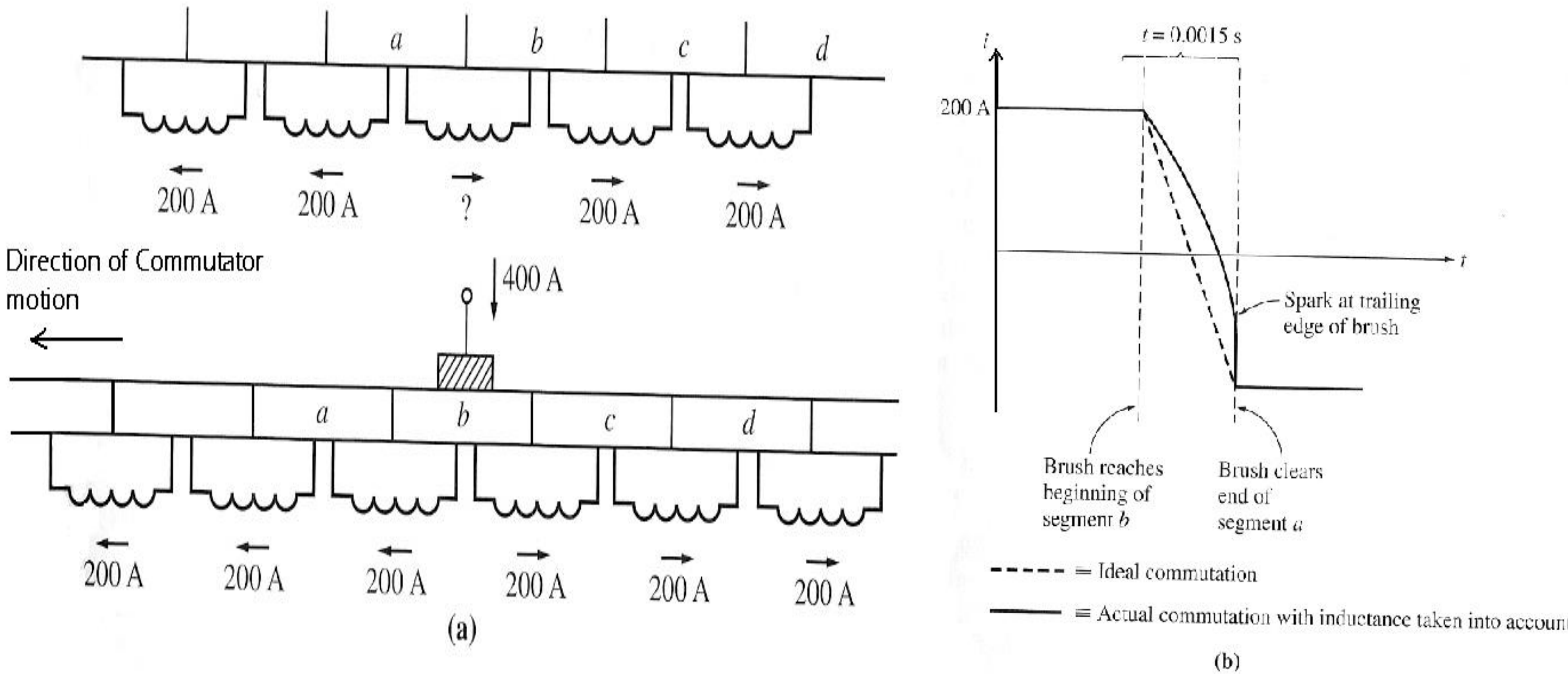
Armature winding of DC machines



Problem with Commutation



Problem with Commutation

- The previous figure, represents a series of commutator segments and conductors connected between them
- Assuming the current in brush is 400 A, current in each path 200 A
- Note: when commutator segment is shorted out, current flow through that commutator segment must reverse
- How fast must this reversal occur? Assuming machine is turning at 800 r/min & there are 50 commutator segments (a reasonable number for a typical motor)➔ each segment moves under a brush & clears it again in $t = 0.0015\text{s}$

➔ rate of change in current, of shorted loop would be:

$$\mathrm{d}i / \mathrm{d}t = 400 / 0.0015 = 266667\,\text{A/s}$$

- With even a very small inductance in loop, a very significant inductive voltage v= Ldi/dt will be induced in the shorted commutator segment
- This high voltage naturally causes sparking at brushes of machine, resulting in same arcing problems that neutral plane shift causes

Interpoles

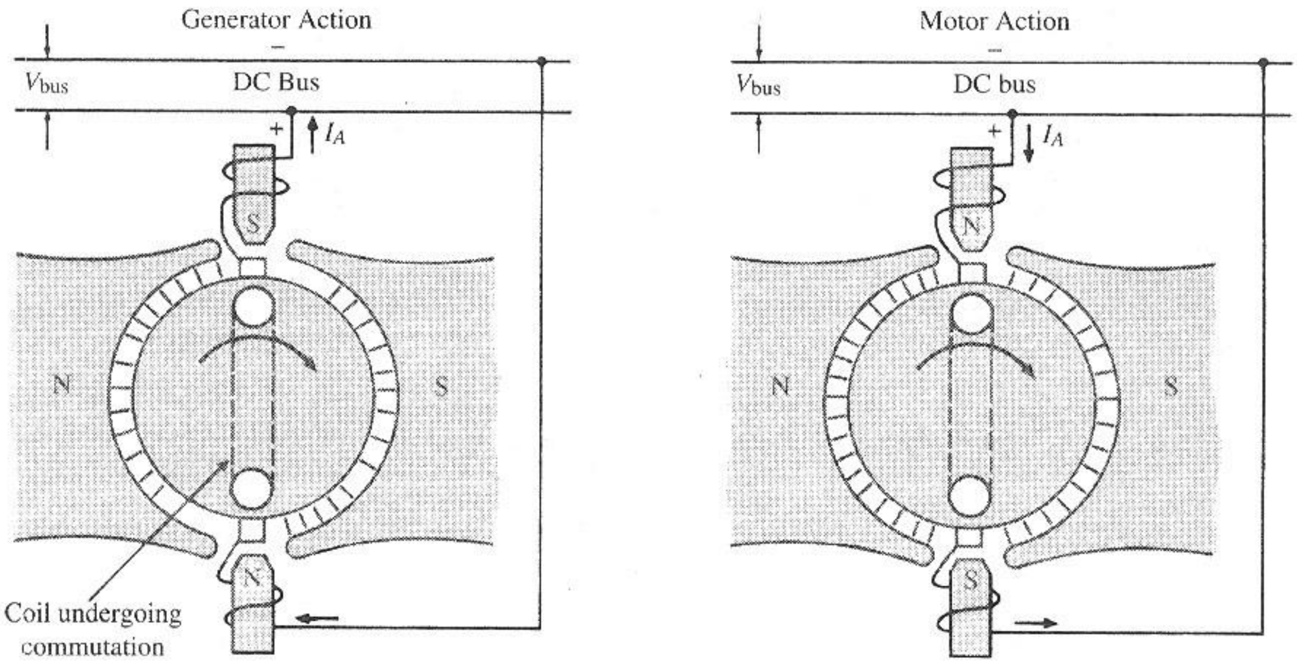


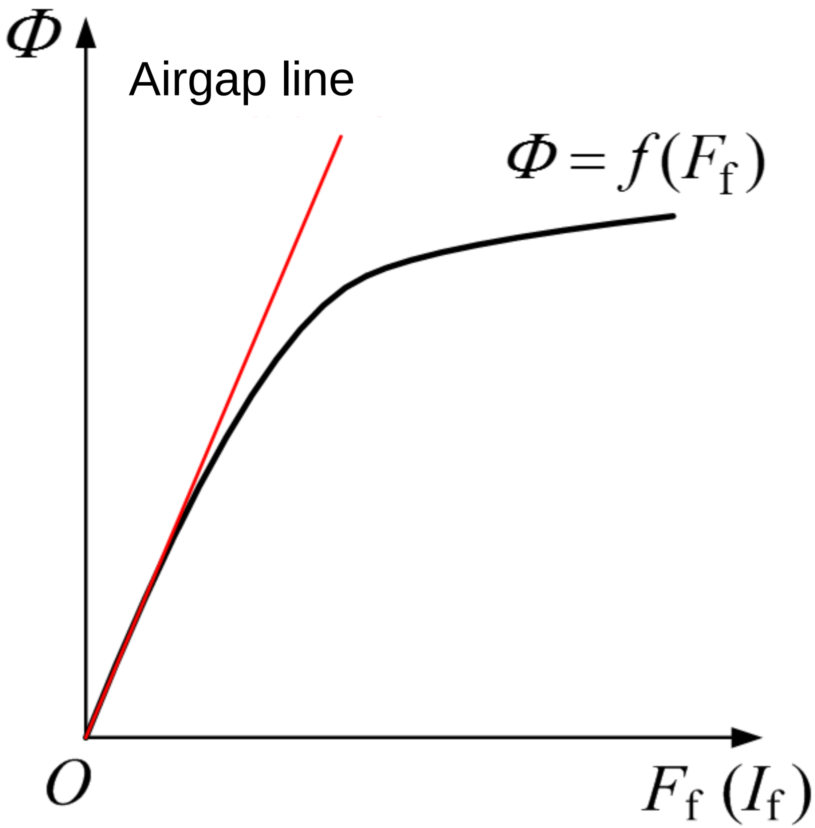
FIGURE 10.16
Location of interpoles, their connections, and their polarity for generators and motors.

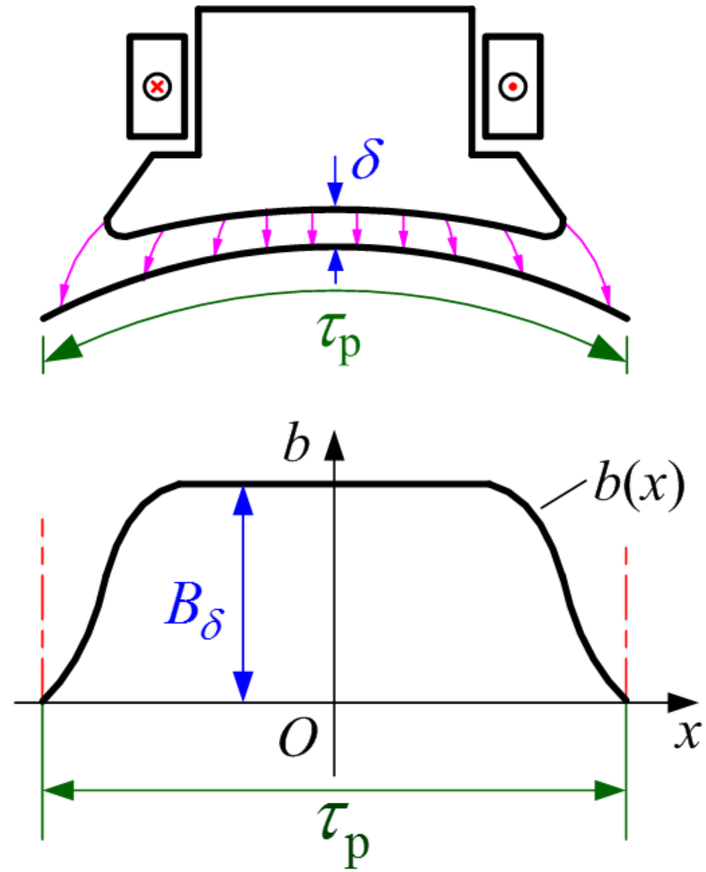
An interpole is a small inductor called a choke used to dampen sparking in the brushes. They sit right over the brushes and are basically an inductor used as a low pass filter to lessen high frequency voltage changes on the DC bus.

Armature Reaction

Magnetic field caused by field current

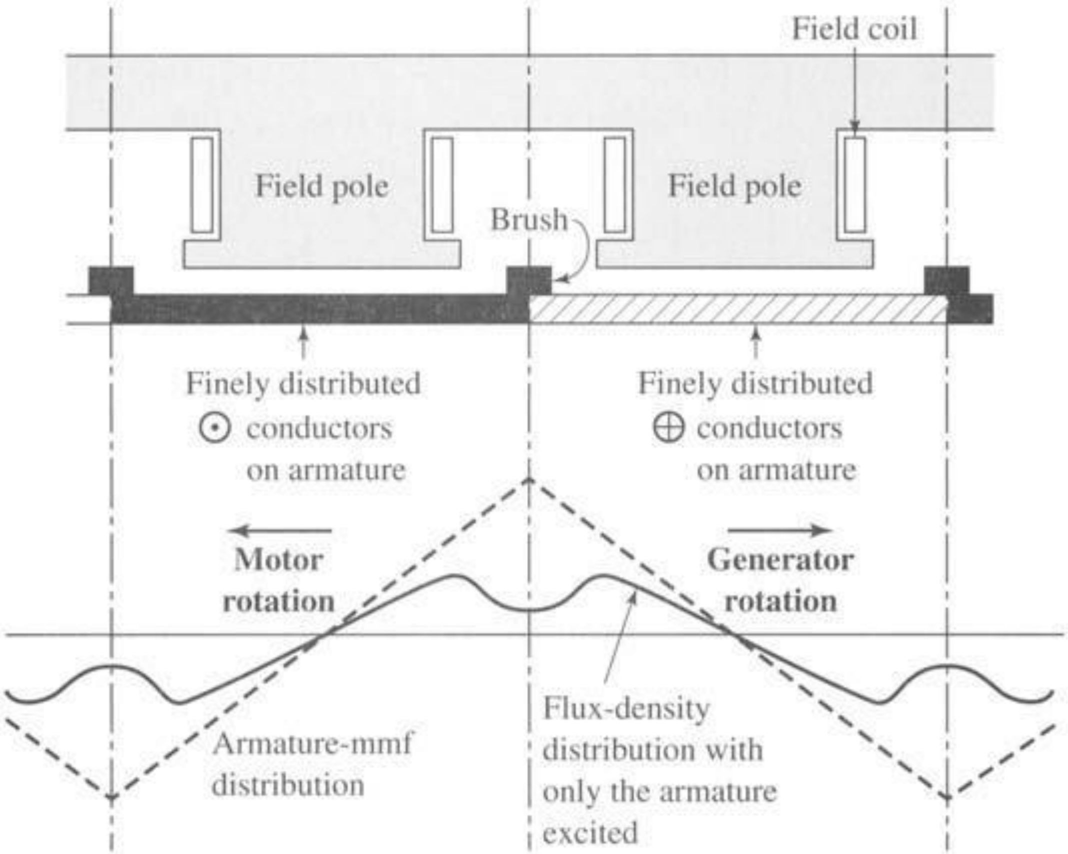
$$\Phi = B_{\mathrm{av}} \tau_p l_e$$

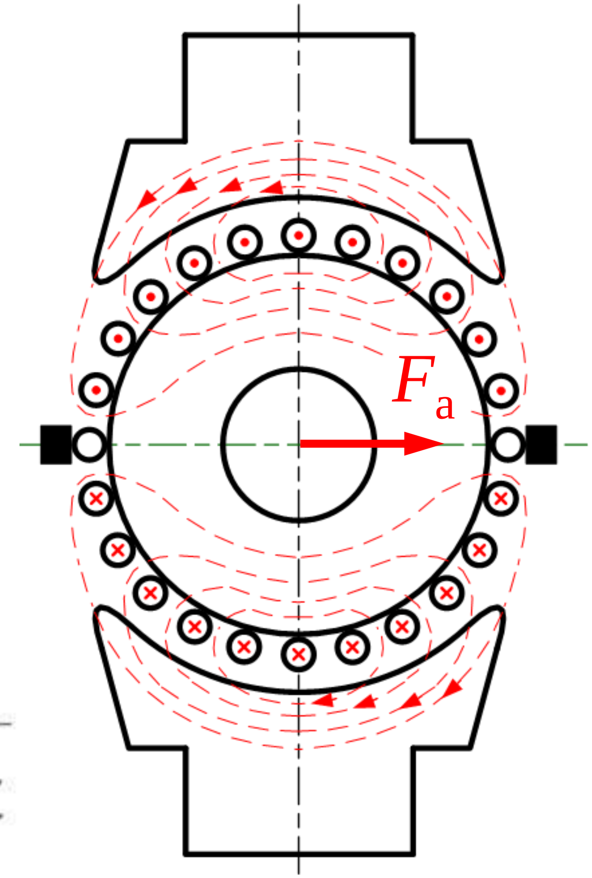




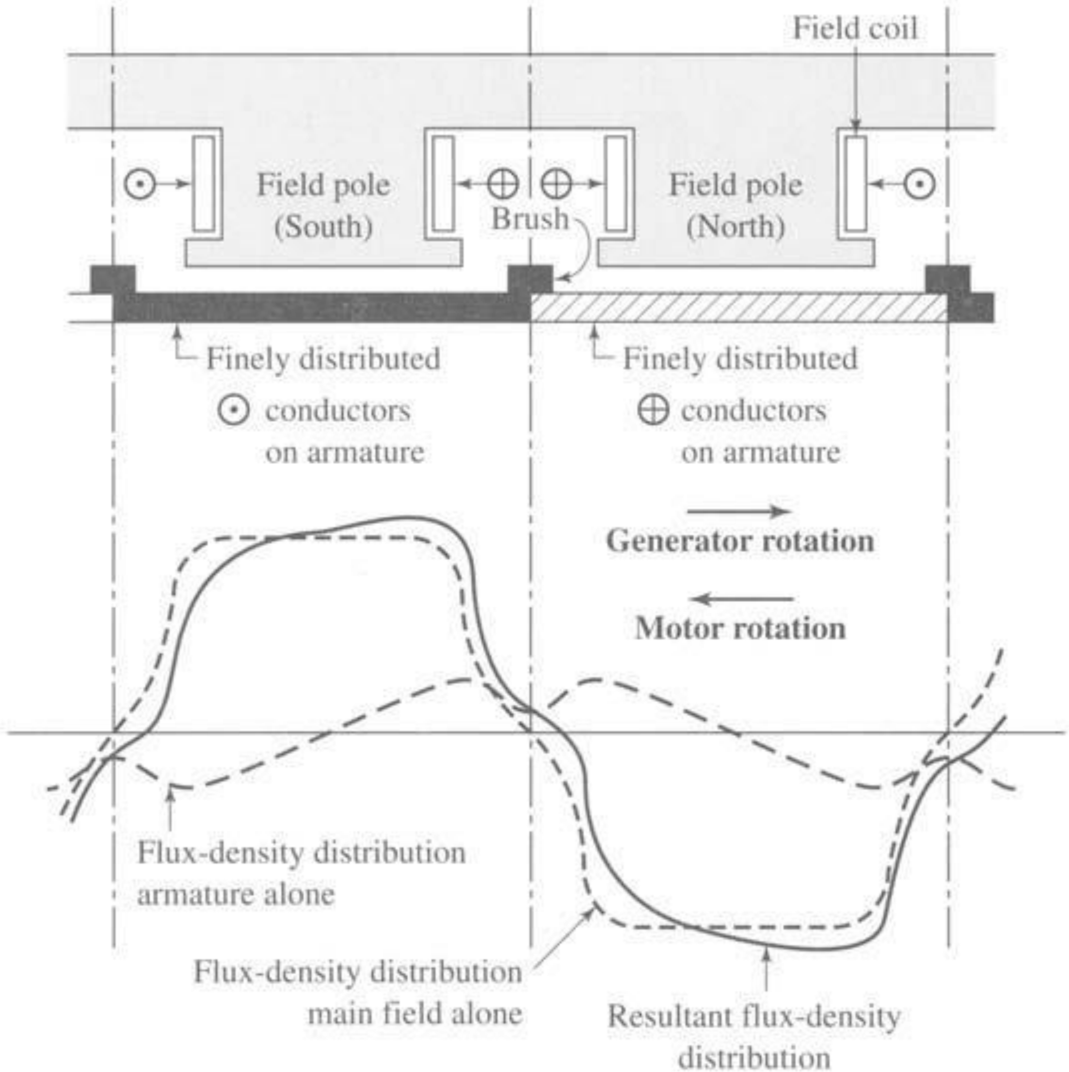
Armature Reaction

- F_a **is on q-axis**





Armature Reaction



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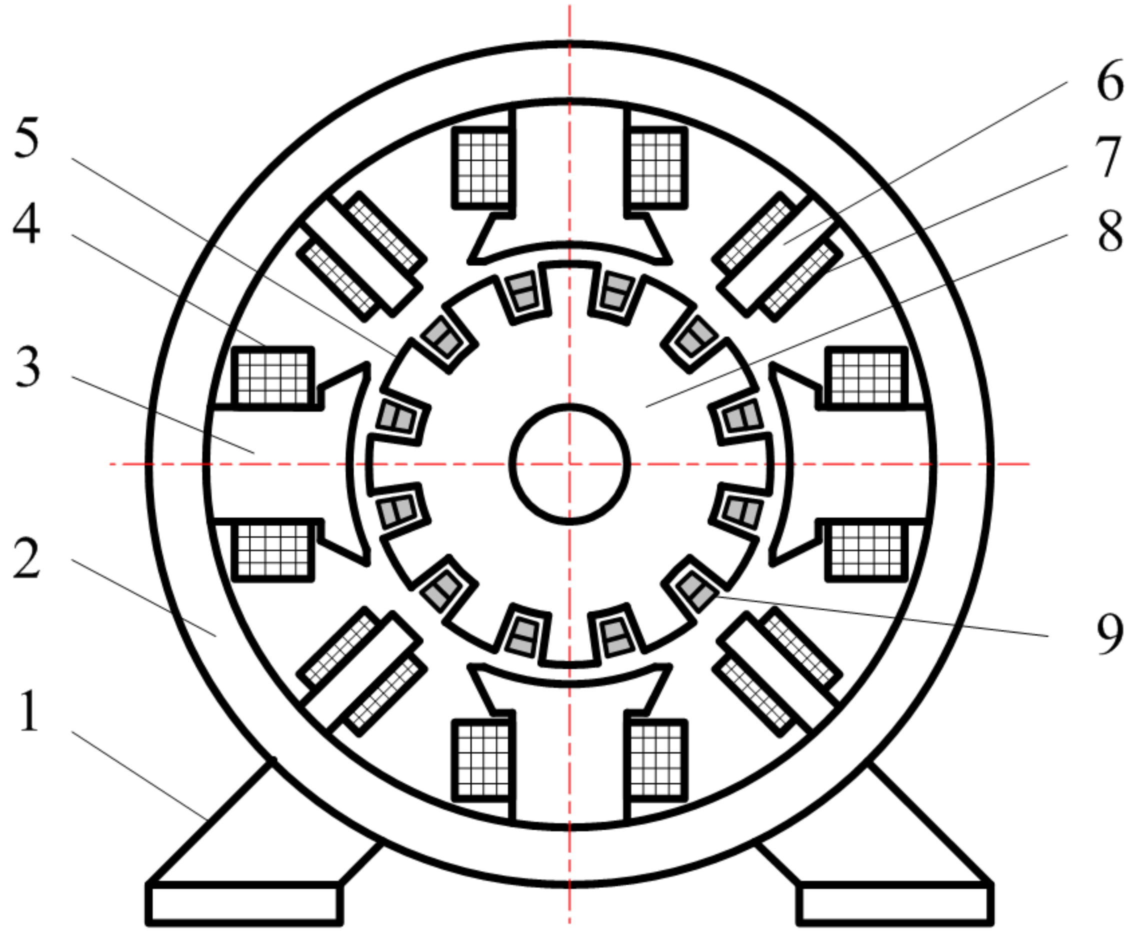
Problems with Commutation in Real Machine
Armature Reaction:field weakening

- Flux weakening causes problems in both generators & motors
- In generators effect of flux weakening is simply to reduce voltage supplied by generator for any given load
- In motors effect can be more serious
- As shown when flux in motor decreased, its speed increases
- But increasing speed of motor can increase its load, resulting in more flux weakening
- It is possible for some shunt dc motors to reach runway condition as a result where speed of motor just keeps increasing until machine is disconnected, or been destroyed

Compensation winding



Equivalent Circuit

Induced voltage & torque

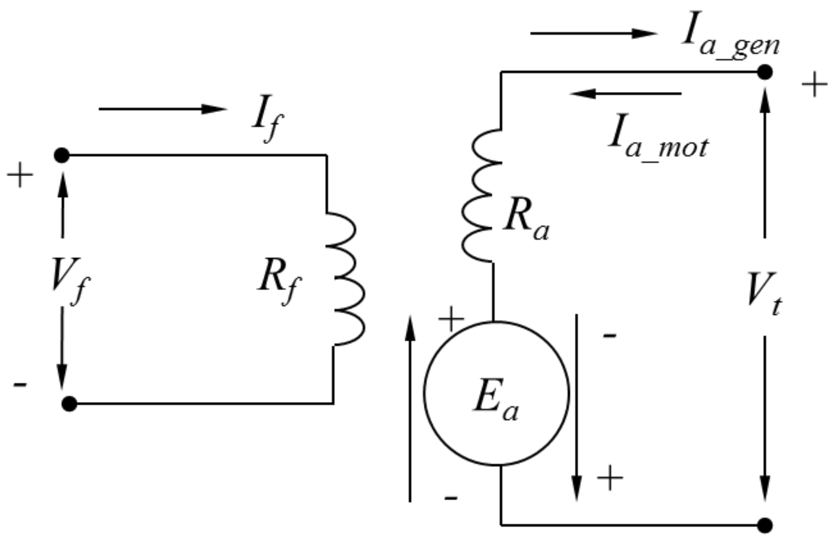
- The internal generated voltage is given by:

$$E_A = K\phi\omega$$

and the torque induced is

$$\tau_{\text{ind}} = K\phi I_A$$

Equivalent circuit

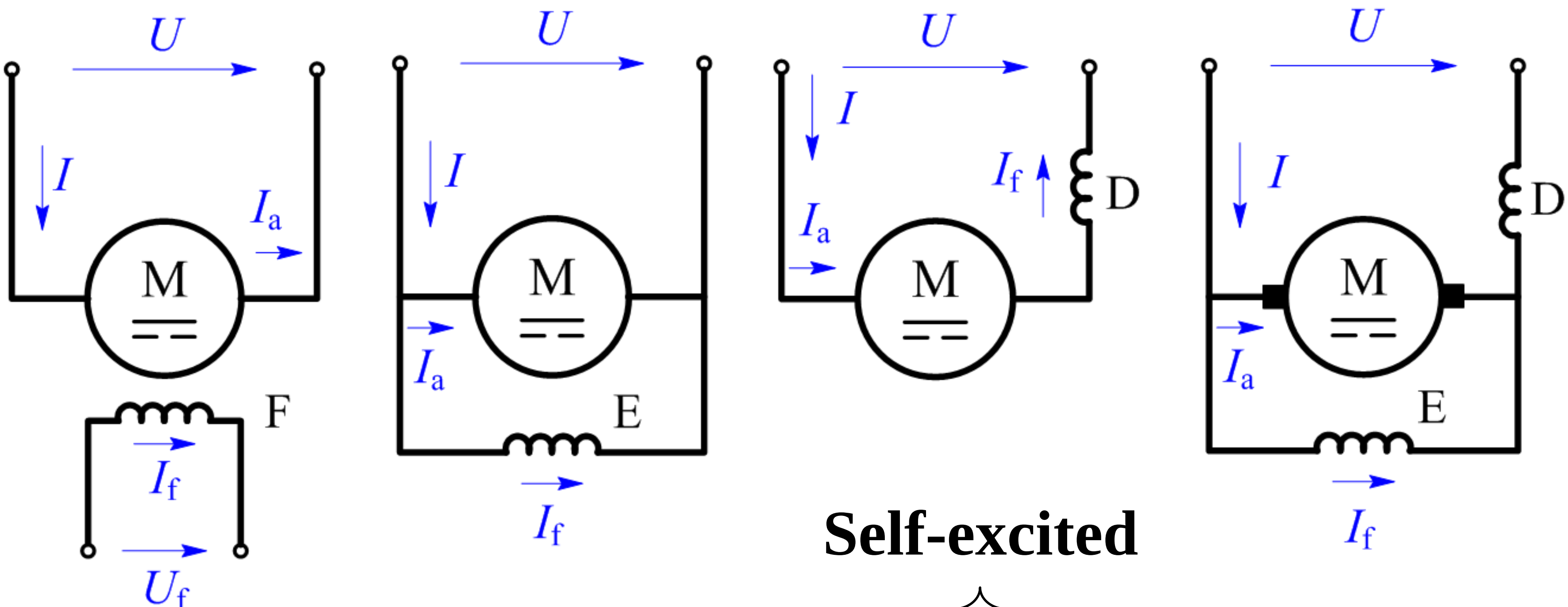


$$\boxed{\begin{aligned} V_f &= I_f R_f \\ V_t &= E_a \pm I_a R_a \end{aligned}}$$

$$\boxed{E_a = K_a \phi_d \omega_m}$$

$$\boxed{T_e = K_a \phi_d I_a}$$

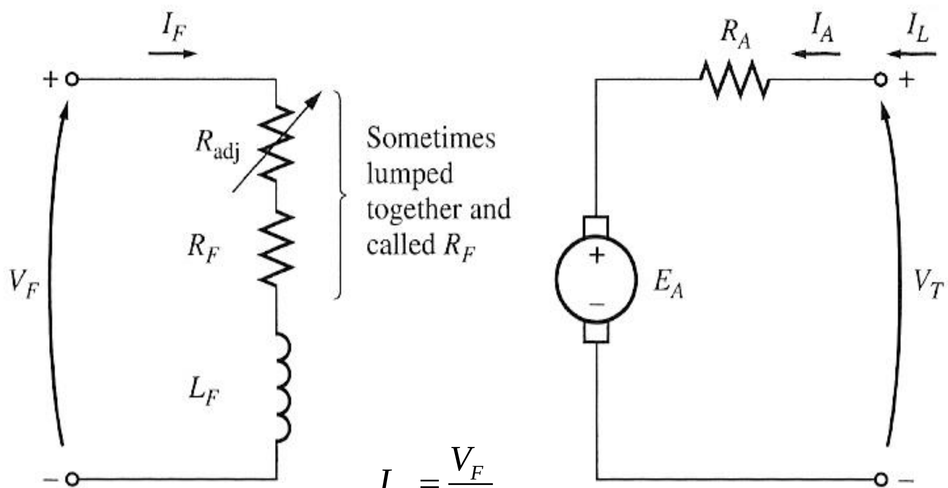
Excitation Type



Self-excited

Separately-excited	**shunt**	**Series**	**compound**
$I = I_a$	$I = I_a + I_f$	$I = I_a = I_f$	$I = I_a + I_f$

Excitation types

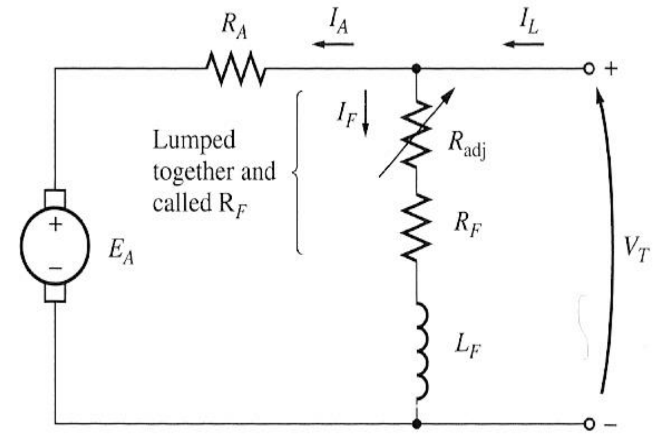


$$I_F = \frac{V_F}{R_F}$$

$$V_T = E_A + I_A R_A$$

$$I_L = I_A$$

(a)



$$I_F = \frac{V_T}{R_F}$$

$$V_T = E_A + I_A R_A$$

$$I_L = I_A + I_F$$

Example 1

A 100-kW, 250-V DC shunt generator has an armature resistance of 0.05 Ω and field circuit resistance of 60 Ω. With the generator operating at rated voltage, determine the induced voltage at

(a) full load,

(b) half-full load.

Solution to Example 1

(a) At full load,

$$V_t = E_a - I_a R_a$$

$$I_f = 250/60 = 4.17\text{A}$$

$$I_{L\_\text{FL}} = 100,000/250 = 400\text{A}$$

$$I_a = I_{L\_\text{FL}} + I_f = 400 + 4.17 = 404.17\text{A}$$

$$E_a = V_t + I_a R_a = 250 + 404.17 \times 0.05 = 270.2\text{V}$$

(b) At half load,

$$I_f = 250/60 = 4.17\text{A}$$

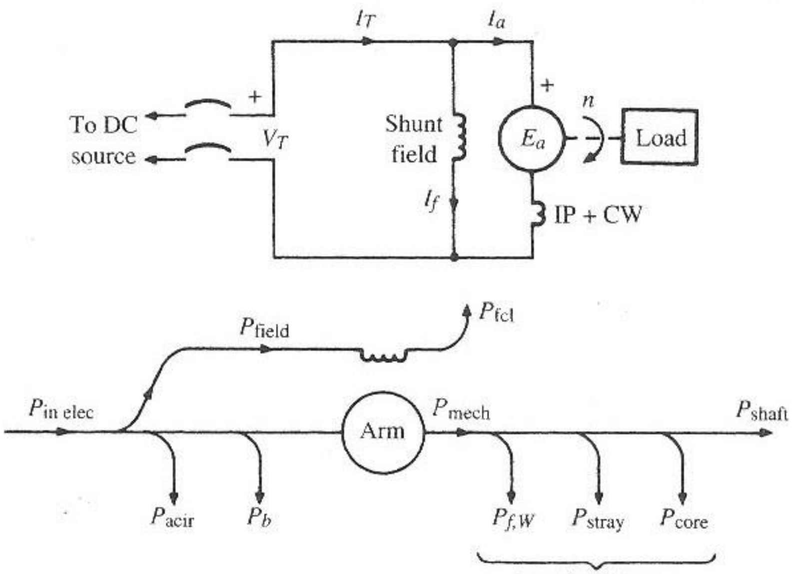
$$I_{L\_\text{HL}} = 50,000/250 = 200\text{A}$$

$$I_a = I_{L\_\text{FL}} + I_f = 200 + 4.17 = 204.17\text{A}$$

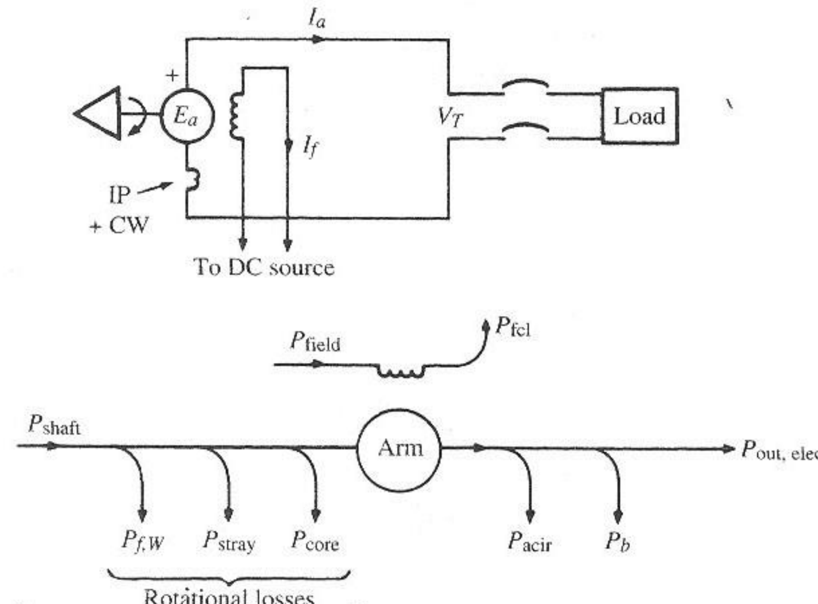
$$E_a = V_t + I_a R_a = 250 + 204.17 \times 0.05 = 260.2\text{V}$$

Power Flow

Power Flow

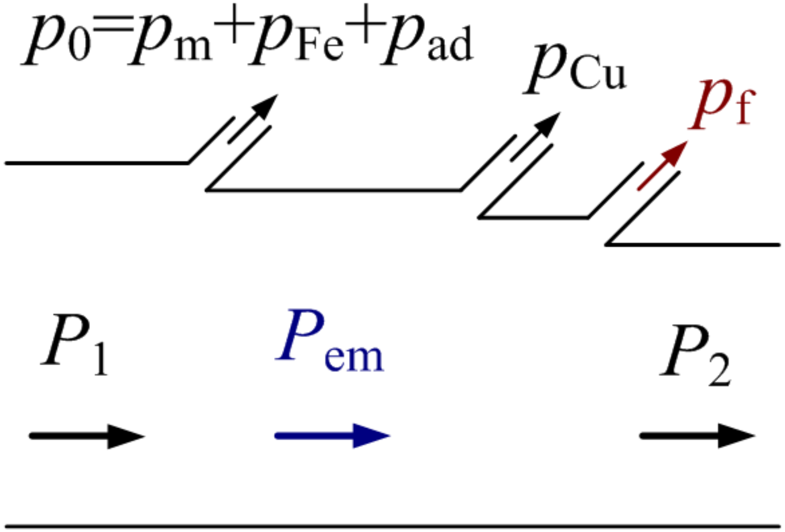


(a) Motor



(b) Generator

Power flow of DC generators



$$P_1 = P_{em} + p_0$$

$$P_1 = T_1 \Omega$$

$$P_{em} = T \Omega$$

$$p_0 = T_0 \Omega = p_m + p_{Fe} + p_{ad}$$

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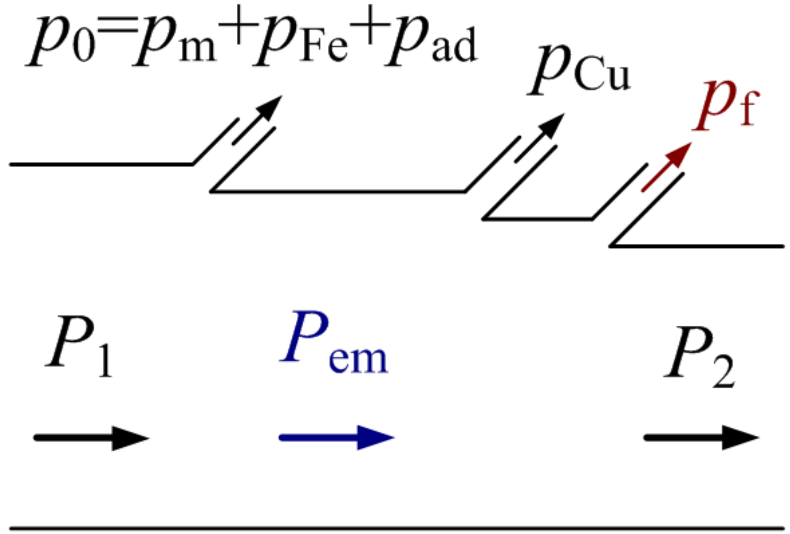
Power flow of DC generators

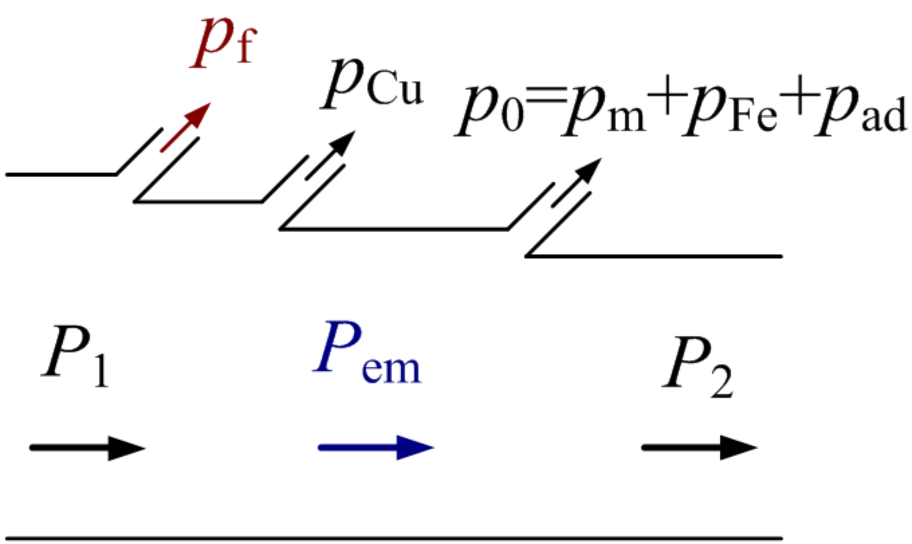


$$P_{em} = E_a I_a = \left(U + I_a R_a\right) I_a$$

$$\boxed{P_{em} = P_2 + p_{Cu} + p_f}$$

$$P_2 = UI \qquad p_{Cu} = I_a^2 R_a \qquad p_f = U_f I_f = U I_f = I_f^2 R_f$$

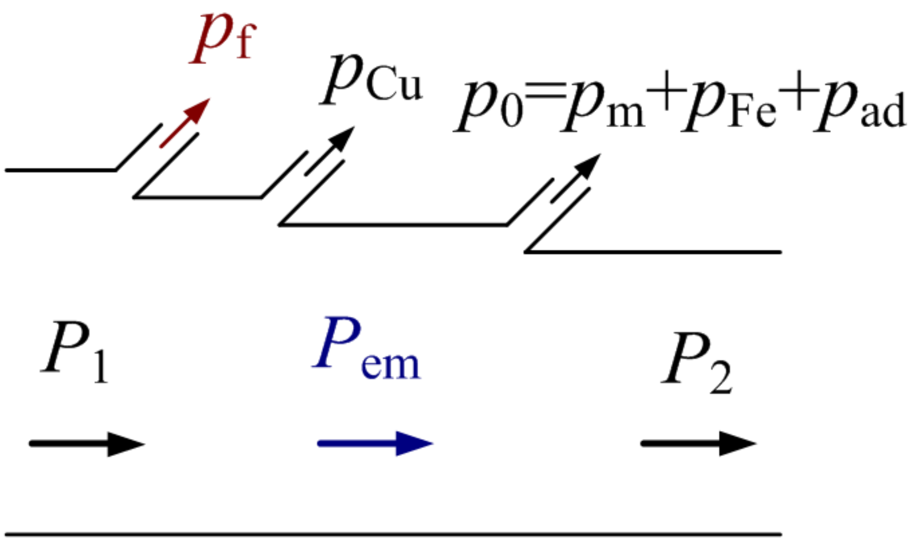
Power flow of DC motors



$$\boxed{P_1 = P_{em} + p_{Cu} + p_f}$$

$$P_1 = UI \quad P_{em} = E_a I_a \quad p_{Cu} = I_a^2 R_a \quad p_f = UI_f = I_f^2 R_f$$

Power flow of DC motors



$$P_{em} = P_2 + p_0$$

$$P_{em} = T\Omega$$

$$P_2 = T_2\Omega = T_L\Omega$$

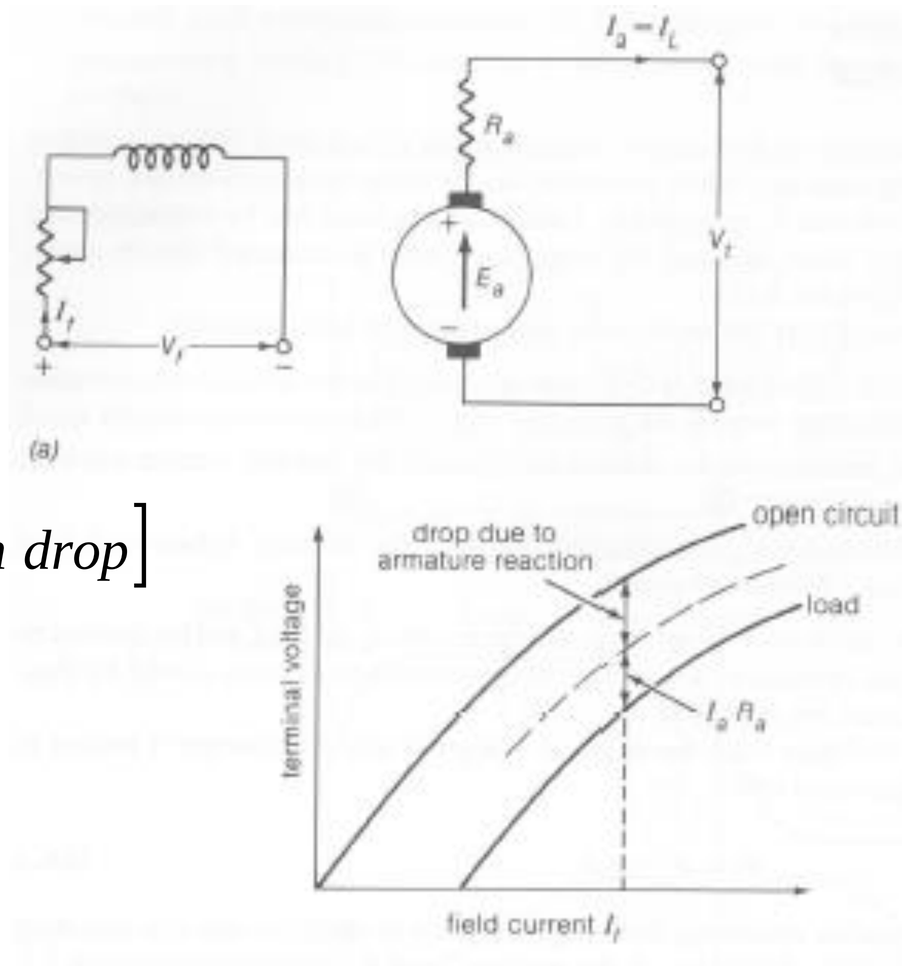
$$p_0 = T_0\Omega = p_m + p_{Fe} + p_{ad}$$

Operation characteristics of DC generators

DC Generator Characteristics

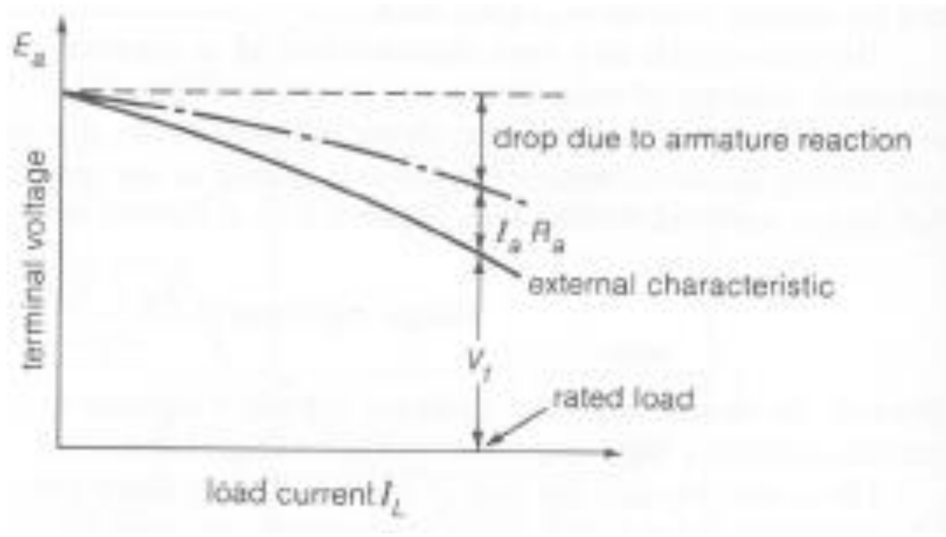
The terminal voltage of a dc generator is given by

$$
\begin{aligned}
V_t &= E_a - I_a R_a \\
&= \left[f\left(I_f, \omega_m\right) - Armature\ reaction\ drop \right] \\
&\quad - I_a R_a
\end{aligned}
$$



DC Generator Characteristics

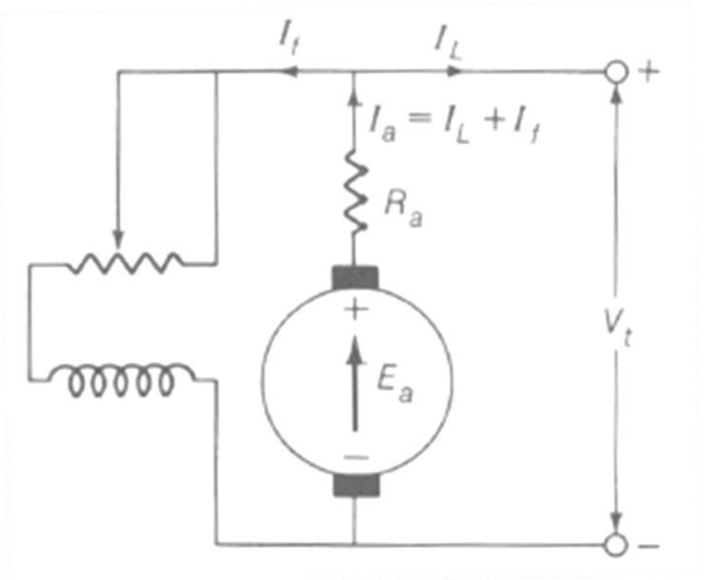
It can be seen from the external characteristics that the terminal voltage falls slightly as the load current increases. *Voltage regulation* is defined as the percentage change in terminal voltage when full load is removed, so that from the external characteristics,



External characteristics

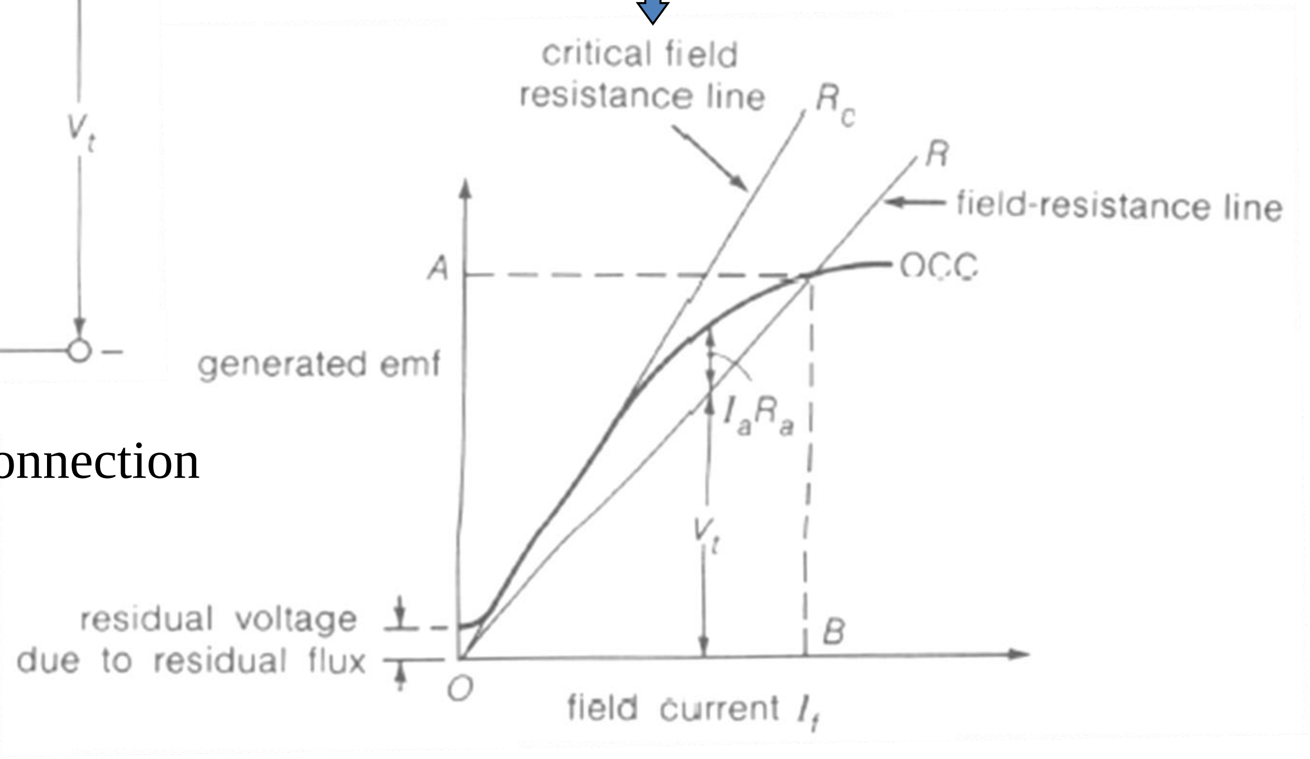
$$Voltage\ regulation = \frac{E_a - V_t}{V_t} \times 100$$

Self-Excited DC Shunt Generator

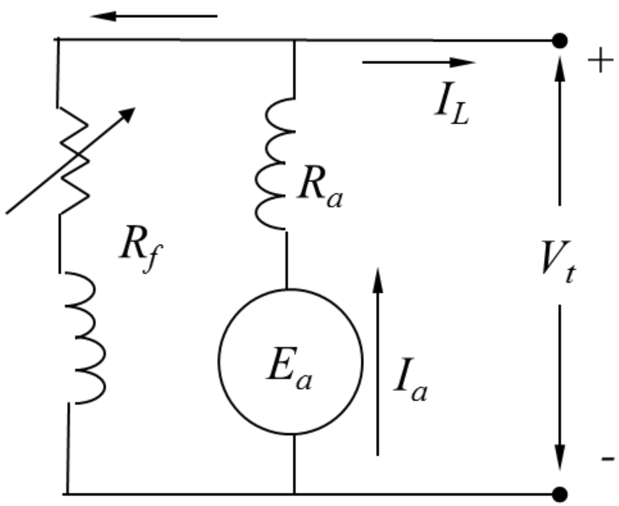


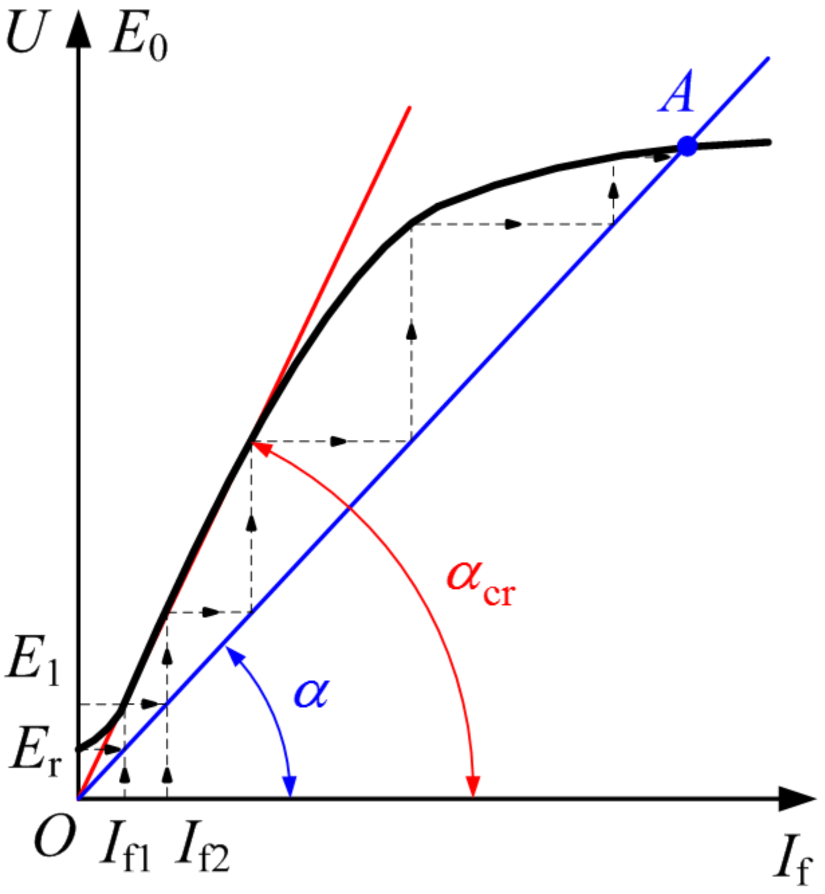
Schematic diagram of connection

Maximum permissible value of the field resistance if the terminal voltage has to build up.



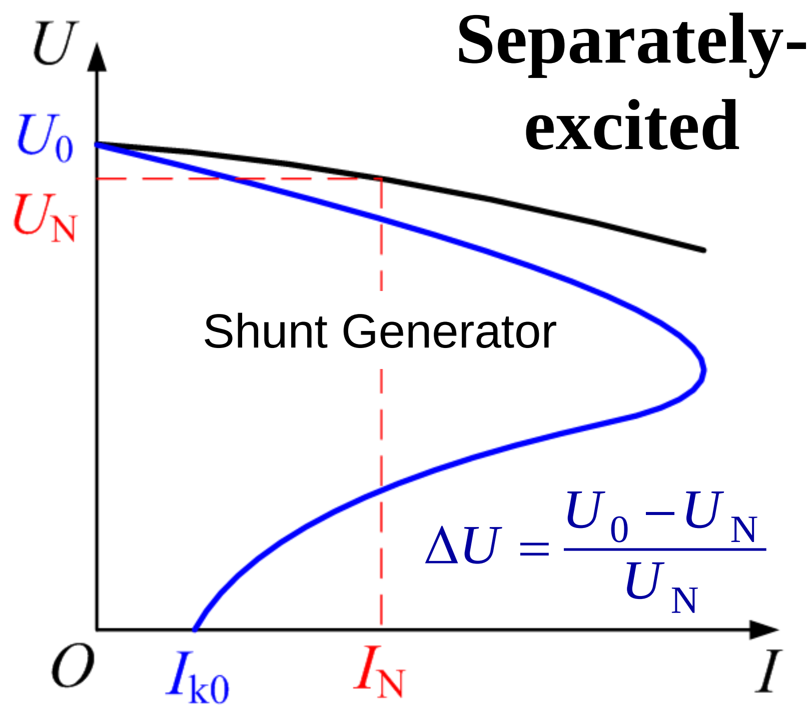
Self-Excited DC Shunt Generator





Voltage regulation

- reasons for voltage regulation difference:
  - Armature reaction
  - Voltage drop on Ra
  - $U \downarrow \Rightarrow I_f \downarrow$



Operation characteristics and Speed control of DC motors

Speed Control in DC Motors

Shunt motor:

Electromagnetic torque is $T_e = K_a \phi_d I_a$, and the conductor emf is $E_a = V_t - R_a I_a$.

$$K_a \phi_d \omega_m = V_t - \left(\frac{T_e}{K_a \phi_d} \right) R_a$$

$$\omega_m = \frac{V_t}{K_a \phi_d} - \frac{T_e R_a}{(K_a \phi_d)^2} \qquad (1)$$

For armature voltage control: R_a and I_f are constant

$$\omega_m = K_1 V_t - K_2 T_e \qquad (2)$$

For field control: R_a and V_t are constant

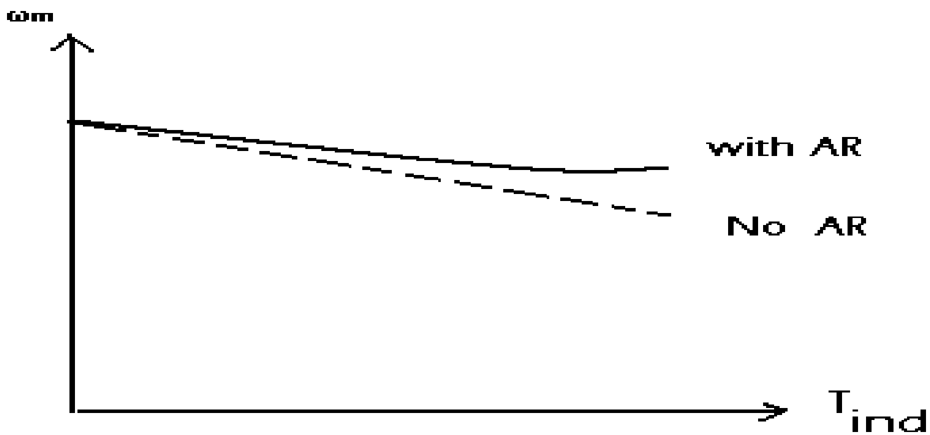
$$\omega_m = \frac{V_t}{K_f I_f} - \frac{R_a}{(K_f I_f)^2} T_e \qquad (3)$$

For armature resistance control: V_t and I_f are constant

$$\omega_m = \frac{V_t}{K_a \phi_d} - \frac{R_a + R_{adj}}{(K_a \phi_d)^2} T_e \qquad (4)$$

TERMINAL CHARACTERISTIC of a SHUNT DC MOTOR

- Torque – speed characteristic of a shunt or separately excited dc motor



Speed of motor with armature reaction is higher than speed of motor with no armature reaction. This relative increase in speed is due to flux weakening in machine with armature reaction.

Speed Control in Shunt DC Motors

Armature Voltage Control:

R_a and I_f are kept constant and the armature terminal voltage is varied to change the motor speed.

$$\omega_m = K_1 V_t - K_2 T_e$$

$$K_1 = \frac{1}{K_a \phi_d}; \quad K_2 = \frac{1}{(K_a \phi_d)^2} \quad ;\phi_d \text{ is const.}$$

For constant load torque, such as applied by an elevator or hoist crane load, the speed will change linearly with V_t. In an actual application, when the speed is changed by varying the terminal voltage, the armature current is kept constant. This method can also be applied to series motor.

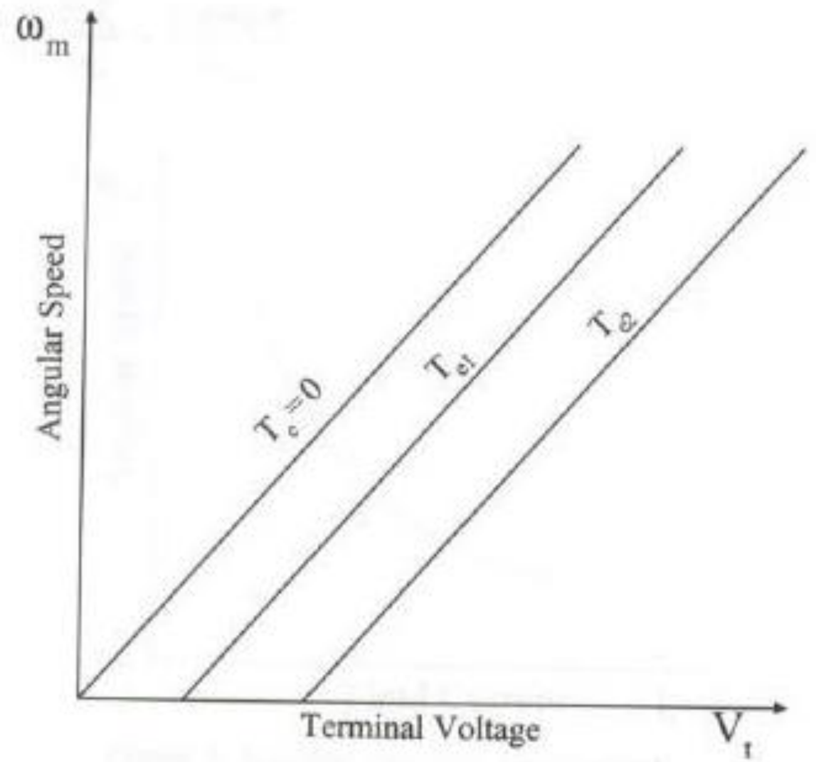


Figure 1: Speed vs. terminal voltage

Speed Control in Shunt DC Motors

Field Control:

R_a and V_t are kept constant, field rheostat is varied to change the field current.

$$\omega_m = \frac{V_t}{K_f I_f} - \frac{R_a}{(K_f I_f)^2} T_e$$

For no-load condition, T_e=0. So, no-load speed varies inversely with the field current.

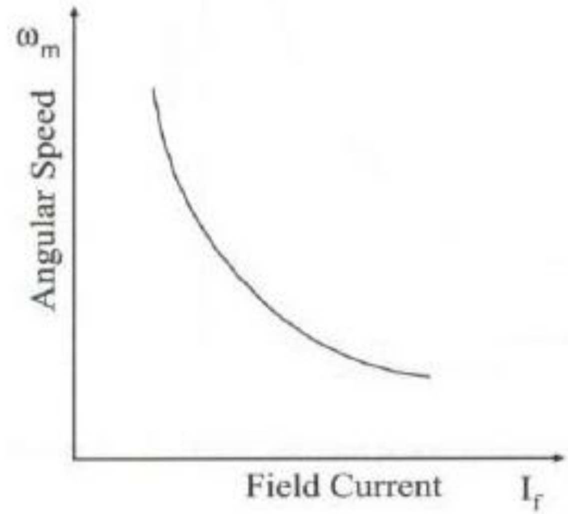


Figure 2: No-load speed vs. field current

Speed control from zero to base speed is usually obtained by armature voltage control. Speed control beyond the base speed is obtained by decreasing the field current. If armature current is not to exceed its rated value (heating limit), speed control beyond the base speed is restricted to constant power, known as constant power application.

$$P = V_t I_a = const = E_a I_a = T_e \omega_m$$

$$T_e = \frac{E_a I_a}{\omega_m} = \frac{const.}{\omega_m}$$

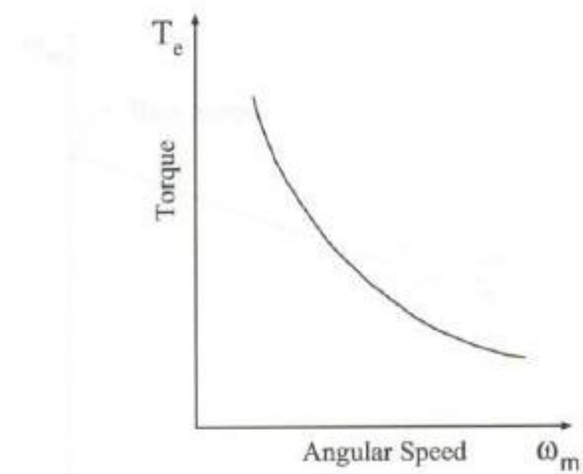


Figure 3a: I_f control, constant power operation

Speed Control in Shunt DC Motors

Armature Resistance Control:

V_t *and* I_f are kept constant at their rated value, armature resistance is varied.

$$\omega_m = \frac{V_t}{K_a\phi_d} - \frac{R_a + R_{adj}}{(K_a\phi_d)^2} T_e = K_5 - K_6 T_e$$

The value of R_{adj} can be adjusted to obtain various speed such that the armature current I_a (hence torque, $T_e = K_a \phi_d I_a$) remains constant.

Armature resistance control is simple to implement. However, this method is less efficient because of loss in R_{adj}. This resistance should also been designed to carry armature current. It is therefore more expensive than the rheostat used in the field control method.

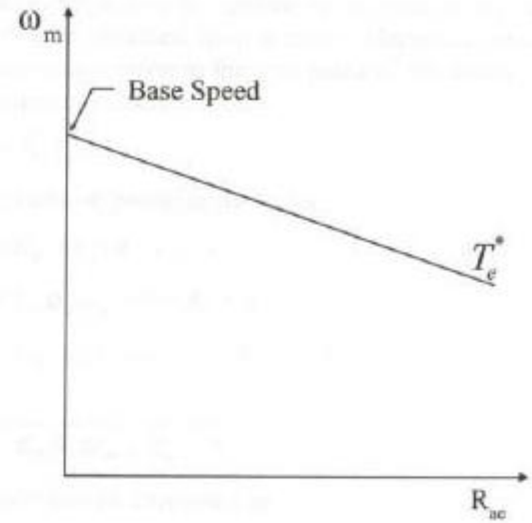


Figure 4: Angular speed vs. armature resistance for a torque of T_e^*

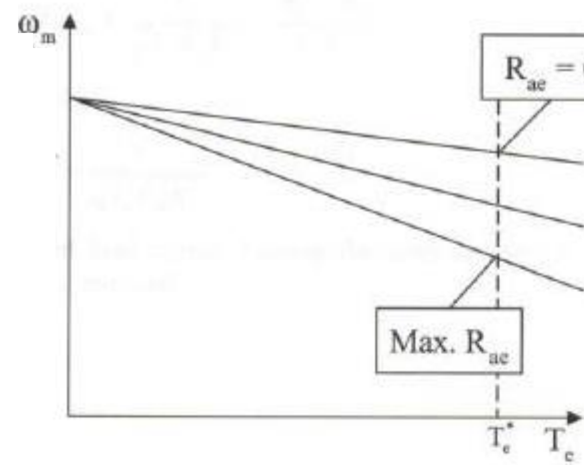
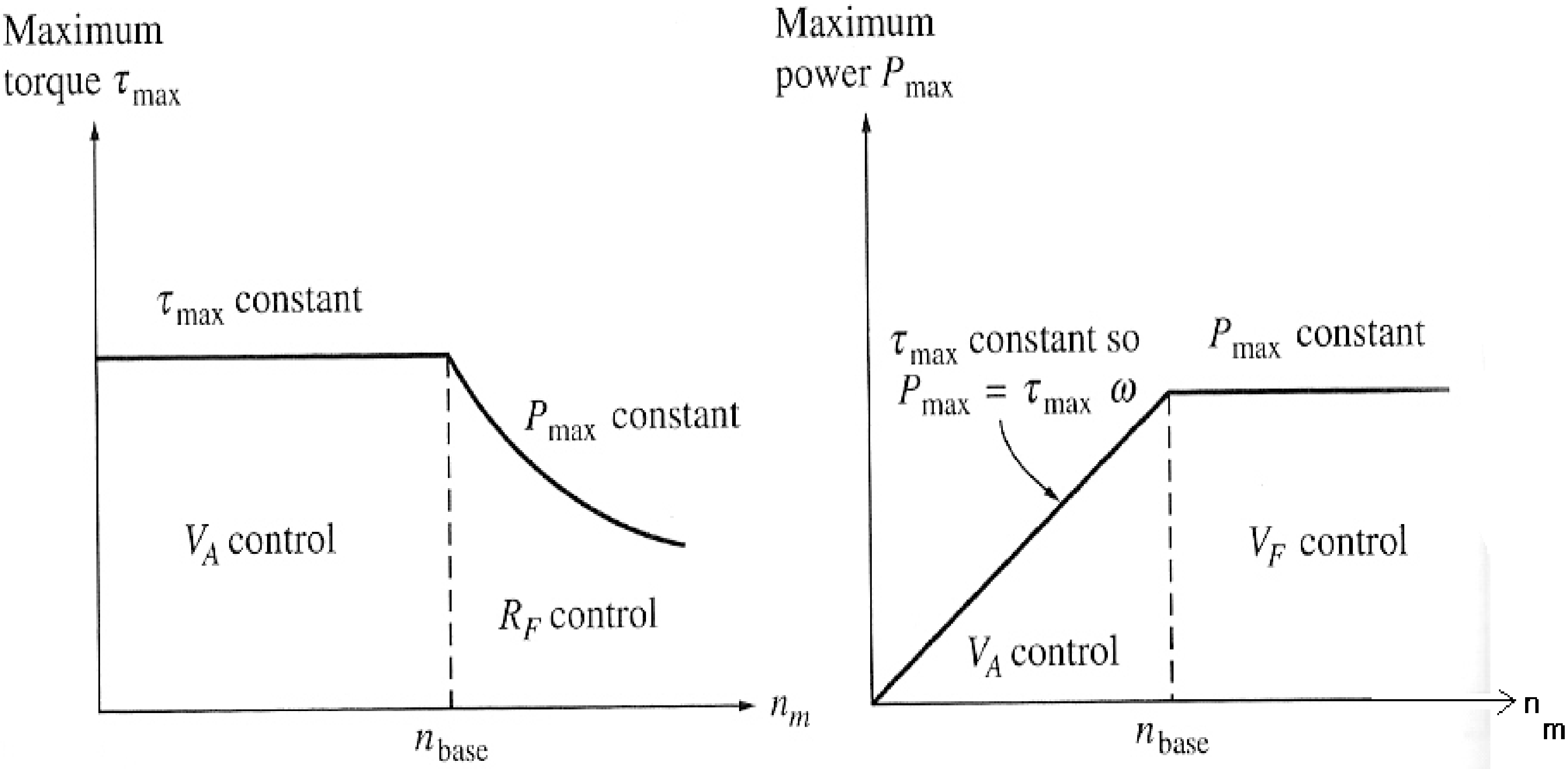


Figure 5: Speed-torque characteristics at different armature resistance

SPEED CONTROL of SHUNT DC MOTOR

- Power & Torque limits as a function of speed for a shunt motor under V_A & R_F control



<u>Speed Control in Series DC Motors</u>

<u>Field Control</u>:

Control of field flux in a sries motor is achieved by using a diverter resistance.
The developed torque can be expressed as.

$$T_e = K_a \phi_d I_a = K_a K_s \left(\frac{R_d}{R_s + R_d} \right) I_a^2 = K \rho I_a^2$$

$$where,\ K = K_a K_s\ and\ \rho = \frac{R_d}{R_s + R_d}$$

$$V_t = E_a + \left(\frac{R_s R_d}{R_s + R_d} \right) I_a + I_a R_a$$

$$= K_a \phi_d \omega_m + \rho I_a R_s + I_a R_a$$

$$= K_a (K_s \rho I_a) \omega_m + (\rho R_s + R_a) I_a$$

$$= (K \rho \omega_m + \rho R_s + R_a) I_a$$

$$or,\ I_a = \frac{V_t}{K \rho \omega_m + \rho R_s + R_a}$$

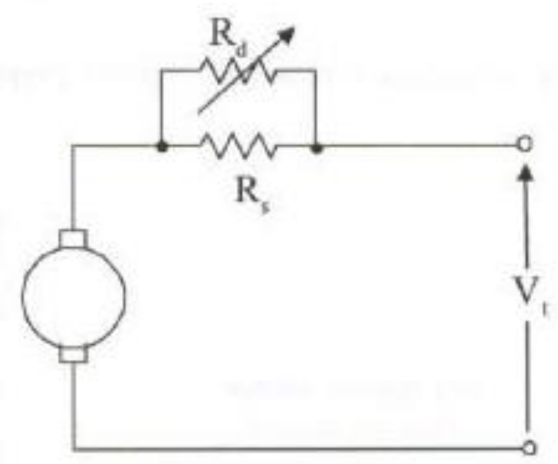


Figure 7: A series motor with a field diverter resistance

Speed Control in Series DC Motors

$$T_e = K\rho\left(\frac{V_t}{K\rho\omega_m + \rho R_s + R_a}\right)^2$$

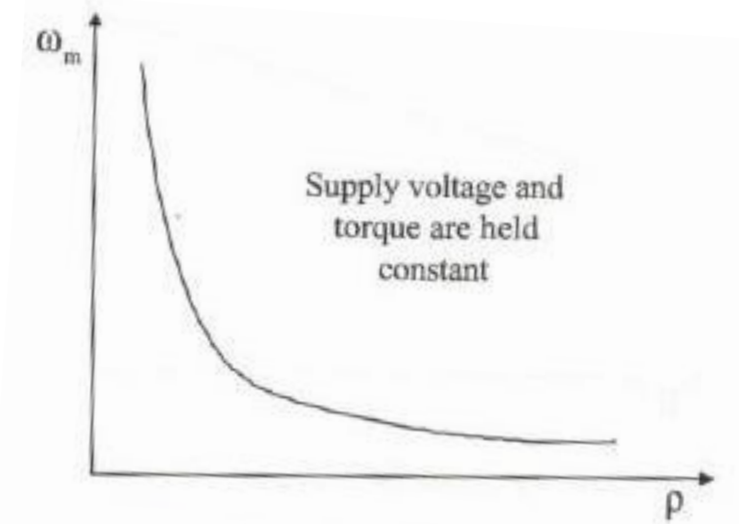


Figure 8: Speed vs. ?

Speed Control in Series DC Motors

Armature Resistance Control:

Torque in this case can be expressed as

$$T_e = \frac{KV_t^2}{\left(R_a + R_{adj} + R_s + K\omega_m\right)^2}$$

R_{ae} is an external resistance connected in series with the armature.

For a given supply voltage and a constant developed torque, the term ($R_a + R_{ae} + R_s + K\omega_m$) should remain constant. Therefore, an increase in R_{ae} must be accompanied by a corresponding decrease in ω_m.

$$\left(R_a + R_{adj} + R_s + K\omega_m\right)^2 = \frac{KV_t^2}{T_e}$$

$$\text{or,}\quad R_a + R_{adj} + R_s + K\omega_m = \sqrt{\frac{K}{T_e}}V_t$$

$$\text{or,}\quad \omega_m = \frac{V_t}{\sqrt{KT_e}} - \frac{R_a + R_{adj} + R_s}{K}$$

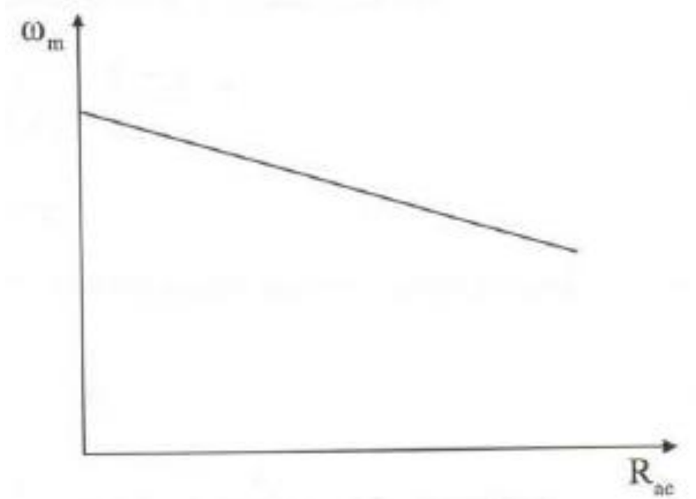


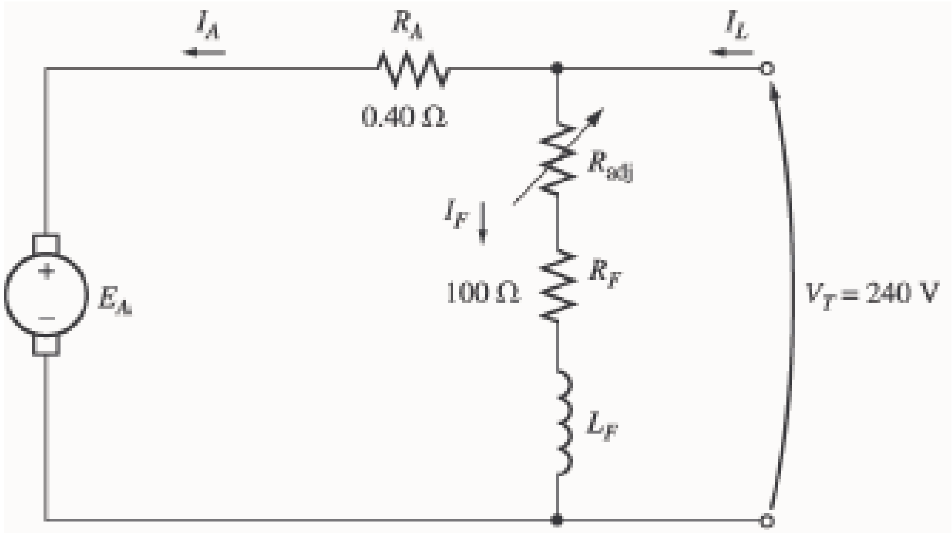
Figure 9: Speed vs. armature resistance

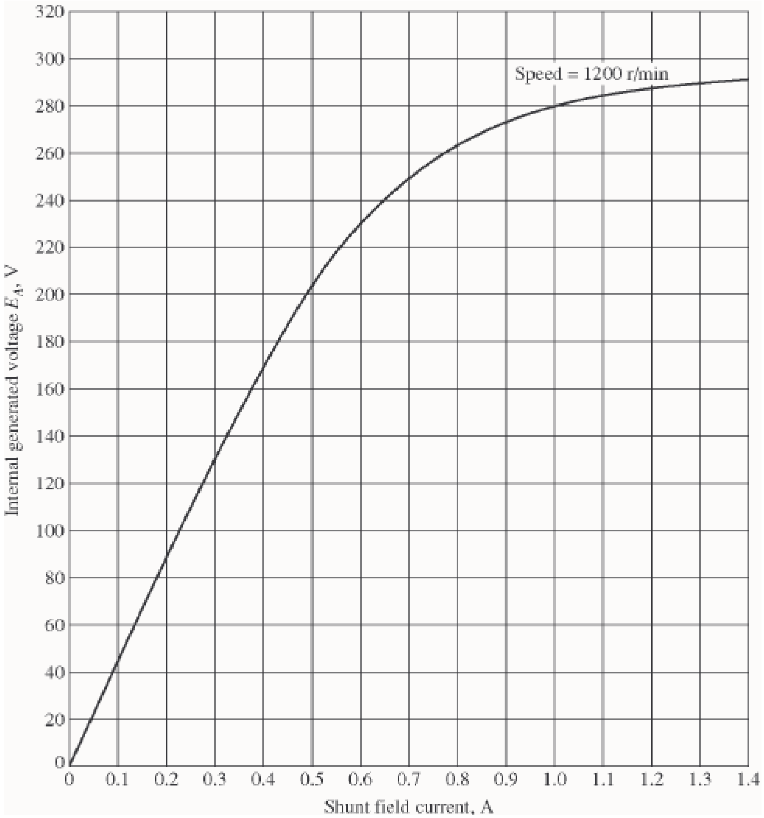
Problem

Problems 9-1 to 9-12 refer to the following dc motor:

$$P_{\text{rated}} = 15\text{hp} \qquad I_{L,\text{rated}} = 55\text{A}$$
$$V_T = 240\text{V} \qquad N_F = 2700 \text{ turns per pole}$$
$$n_{\text{rated}} = 1200\text{r/ min} \qquad N_{\text{SE}} = 27 \text{ turns per pole}$$
$$R_A = 0.40\Omega \qquad R_F = 100\Omega$$
$$R_S = 0.04\Omega \qquad R_{\text{adj}} = 100 \text{ to } 400\Omega$$

Rotational losses=1800W at full load.
Magnetization curve as shown in Figure P9-1.





In Problems 9-1 through 9-7, assume that the motor described above can be connected in shunt. The equivalent circuit of the shunt motor is shown in Figure P9-2.

Solution

$9-1$ If the resistor R_{adj} is adjusted to 175Ω what is the rotational speed of the motor at no-load conditions?

Solution At no-load conditions, $E_A = V_T = 240\text{V}$. The field current is given by

$$I_F = \frac{V_T}{R_{\text{adj}} + R_F} = \frac{240\text{V}}{175\Omega + 100\Omega} = \frac{240\text{V}}{275\Omega} = 0.873\text{A}$$

From Figure P9-1, this field current would produce an internal generated voltage E_{Ao} of 271V at a speed n_o of 1200r/min. Therefore, the speed n with a voltage E_A of 240V would be

$$\frac{E_A}{E_{Ao}} = \frac{n}{n_o}$$

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{240\text{V}}{271\text{V}} \left(1200\text{r/ min}\right) = 1063\text{r/ min}$$

Solution

9 – 1 Assuming no armature reaction, what is the speed of the motor at full load? What is the speed regulation of the motor?

Solution At full load, the armature current is

$$I_A = I_L - I_F = I_L - \frac{V_T}{R_{\text{adj}} + R_F} = 55\text{A} - 0.87\text{A} = 54.13\text{A}$$

The internal generated voltage E_A is

$$E_A = V_T - I_A R_A = 240\text{V} - (54.13\text{A})(0.40\Omega) = 218.3\text{V}$$

The field current is the same as before, and there is no armature reaction, so E_{Ao} is still 271V at a speed n_o of 1200r/min. Therefore,

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{218.3\text{V}}{271\text{V}}(1200\text{r/min}) = 967\text{r/min}$$

The speed regulation is

$$\text{SR} = \frac{n_{\text{nl}} - n_{\text{fl}}}{n_{\text{fl}}} \times 100\% = \frac{1063\text{r/min} - 967\text{r/min}}{967\text{r/min}} \times 100\% = 9.9\%$$

9−1 If R_{adj} can be adjusted from 100Ω to 400Ω, what are the maximum minimum no-load speeds possible with this motor?

Solution The minimum speed will occur when $R_{\text{adj}} = 100\Omega,$ and the maximum speed will occur when $R_{\text{adj}} = 400\Omega.$

The field current when $R_{\text{adj}} = 100\Omega$ is:

$$I_F = \frac{V_T}{R_{\text{adj}} + R_F} = \frac{240\text{V}}{100\Omega + 100\Omega} = \frac{240\text{V}}{200\Omega} = 1.20\text{A}$$

From Figure P9-1, this field current would produce an internal generarted voltage E_{Ao} of 287V at a speed n_o of 1200r/min. Therefore, the speed n with a voltage of 240V would be

$$\frac{E_A}{E_{Ao}} = \frac{n}{n_o}$$

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{240\text{V}}{287\text{V}} (1200\text{r/ min}) = 1004\text{r/min}$$

The field current when $R_{\text{adj}} = 400\Omega$ is:

$$I_F = \frac{V_T}{R_{\text{adj}} + R_F} = \frac{240\text{V}}{400\Omega + 100\Omega} = \frac{240\text{V}}{500\Omega} = 0.480\text{A}$$

From Figure P9-1, this field current would produce an internal generated voltage E_{Ao} of 199V at a speed n_o of 1200r/min. Therefore, the speed n with a voltage of 240V would be

$$\frac{E_A}{E_{Ao}} = \frac{n}{n_o}$$

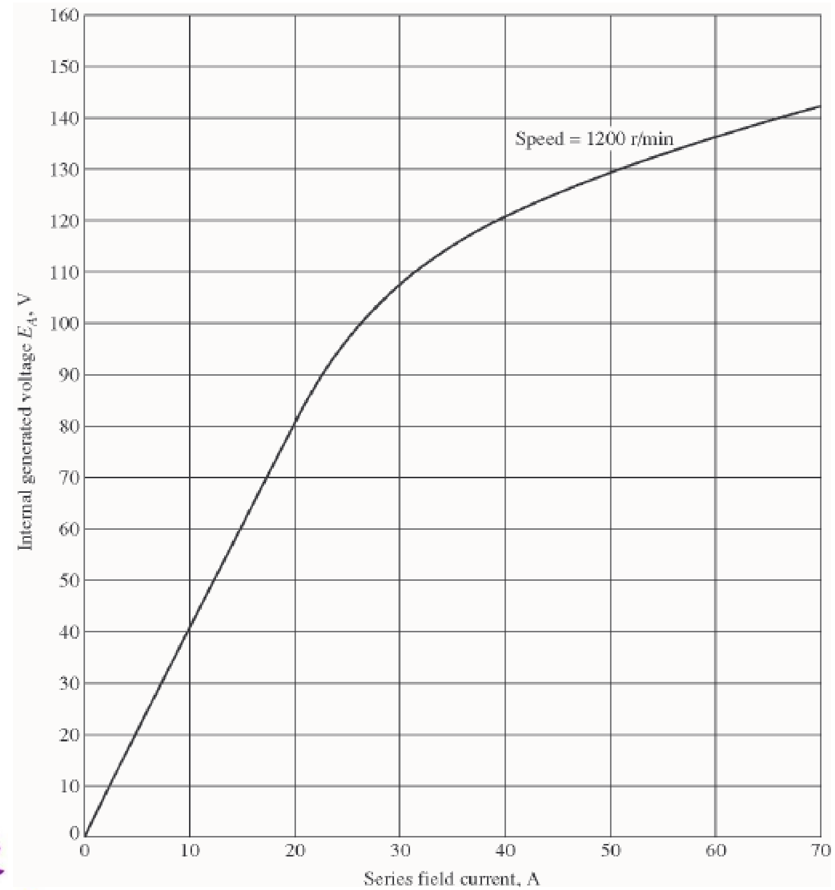
$$n = \frac{E_A}{E_{Ao}} n_o = \frac{240\text{V}}{199\text{V}} (1200\text{r/ min}) = 1447\text{r/min}$$

Problem

A 7.5-hp 120-V series dc motor has an armature resistance of 0.2 Ω and a series field resistance of 0.16 Ω. At full load, the current input is 58 A, and the rated speed is 1050 r/min. Its magnetization curve is shown in Figure P9-5. The core losses are 200 W. and the mechanical losses are 240 W at full load. Assume that the mechanical losses vary as the cube of the speed of the motor and that the core losses are constant.

(a) What is the efficiency of the motor at full load?

(a) What are the speed and efficiency of the motor if it is operating at an armature current of 35 A?



Solution

(a) The output power of this motor at full load is

$$P_{\text{OUT}} = (7.5\text{hp})(746\text{W/hp}) = 5595\text{W}$$

The input power is

$$P_{\text{IN}} = V_T I_L = (120\text{V})(58\text{A}) = 6960\text{W}$$

Therefore the efficiency is

$$\eta = \frac{P_{\text{OUT}}}{P_{\text{IN}}} \times 100\% = \frac{5595\text{W}}{6960\text{W}} \times 100\% = 80.4\%$$

(b) If the armature current is 35A, then the input power to the motor will be

$$P_{\text{IN}} = V_T I_L = (120\text{V})(35\text{A}) = 4200\text{W}$$

The internal generated voltage at this condition is

$$E_{A2} = V_T - I_A(R_A + R_S) = 120\text{V} - (35\text{A})(0.20\Omega + 0.16\Omega) = 107.4\text{V}$$

and the internal generated voltage at rated conditions is

$$E_{A2} = V_T - I_A(R_A + R_S) = 120\text{V} - (58\text{A})(0.20\Omega + 0.16\Omega) = 99.1\text{V}$$

The final speed is given by the equation

$$\frac{E_{A2}}{E_{A1}} = \frac{K\phi_2\omega_2}{K\phi_1\omega_1} = \frac{E_{Ao,2}n_2}{E_{Ao,1}n_1}$$

Solution

since the ratio $E_{Ao,2} / E_{Ao,1}$ is the same as the ratio ϕ_2 / ϕ_1. Therefore, the final speed is

$$n_2 = \frac{E_{A2}}{E_{A1}} \frac{E_{Ao,1}}{E_{Ao,2}} n_1$$

From Figure P9-5, the internal generated voltage $E_{Ao,2}$ for a current of 35A and a speed of $n_o = 1200$ r/min is $E_{Ao,2} = 115\text{V}$, and the internal generated voltage $E_{Ao,1}$ for a current of 58A and a speed of $n_o = 1200\text{r/min}$ is $E_{Ao,1} = 134\text{V}$.

$$n_2 = \frac{E_{A2}}{E_{A1}} \frac{E_{Ao,1}}{E_{Ao,2}} n_1 = \frac{107.4\text{V}}{99.1\text{V}} \frac{134\text{V}}{115\text{V}} \left(1050\text{r/min}\right) = 1326\text{r/min}$$

The power converted from electrical to mechanical form is

$$P_{\text{conv}} = E_A I_A = \left(107.4\text{V}\right)\left(35\text{A}\right) = 3759\text{W}$$

The core losses in the motor are 200W, and the mechanical losses in the motor are 240W at a speed of 1050r/min. The mechanical losses in the motor scale proportionally to the cube of the rotational speedm so the mechanical losses at 1326 r/min are

$$P_{\text{mech}} = \left(\frac{n_2}{n_1}\right)^3 \left(240\text{W}\right) = \left(\frac{1326\text{ r/min}}{1050\text{ r/min}}\right)^3 \left(240\text{W}\right) = 483\text{W}$$

Therefore, the output power is

$$P_{\text{OUT}} = P_{\text{conv}} - P_{\text{mech}} - P_{\text{core}} = 3759\text{W} - 483\text{W} - 200\text{W} = 3076\text{W}$$

and the efficiency is

$$\eta = \frac{P_{\text{OUT}}}{P_{\text{IN}}} \times 100\% = \frac{3076\text{W}}{4200\text{W}} \times 100\% = 73.2\%$$

Permanent Magnet DC machines

PERMANENT-MAGNET DC MOTOR

- A permanent magnet dc motor (PMDC) is a dc motor whose poles are made of permanent magnets.
- PMDC motor offer a number of benefits compared with shunt dc motors in some applications
- ***Advantage*:** Since these motors do not require an external field circuit, they do not have the field circuit copper losses. Because no field windings are required, they can be smaller than corresponding shunt dc motors

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PERMANENT-MAGNET DC MOTOR

- *Disadvantages*:

(a) Permanent magnets cannot produce as high flux density as an externally supplied shunt field

so a PMDC motor will have a lower induced torque per ampere of armature current than a shunt motor of the same size.

(b) **PMDC motors run risk of demagnetization**

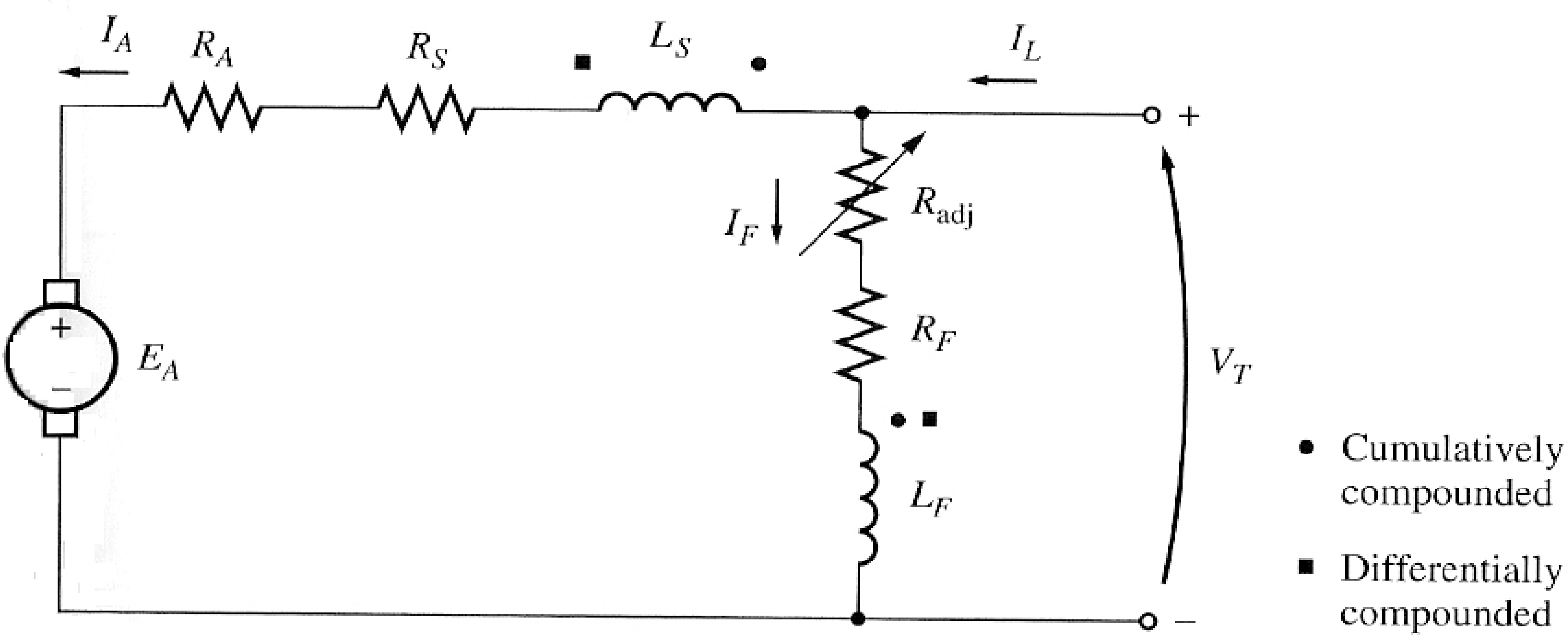
due to A.R. effect which reduces overall net flux, also if I_A become very large there is a risk that its mmf demagnetize poles, permanently reducing & reorienting residual flux

(c) A PMDC motor is basically the same machine as a shunt dc motor, except that flux of a PMDC motor is fixed. Therefore, it is not possible to control the speed of the PMDC motor by varying the field current or flux. The only methods of speed control available for a PMDC motor are armature voltage control and armature resistance control.

COMPOUND DC MOTOR

- A compound dc motor is a motor with both a shunt & a series field
- Such a motor shown below:

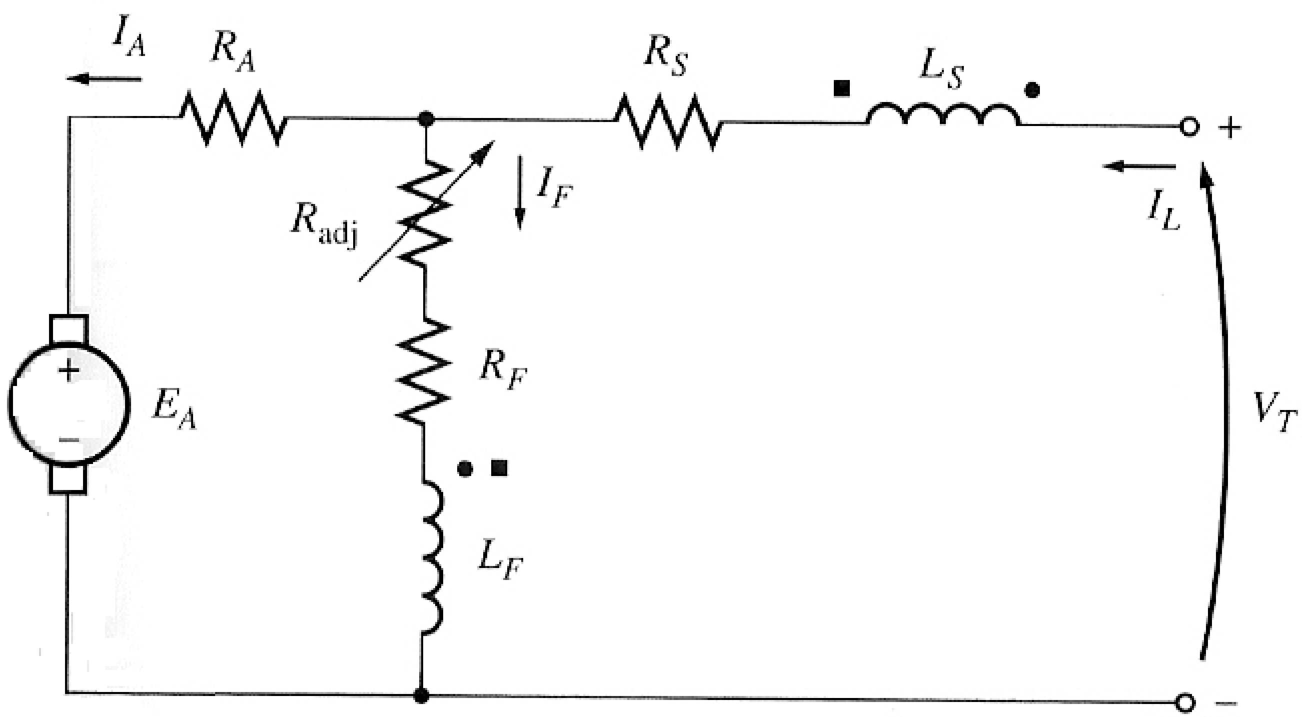
(a) long-shunt connection



(a)

COMPOUND DC MOTOR

(b) Compound dc motor with short-shunt connection



(b)

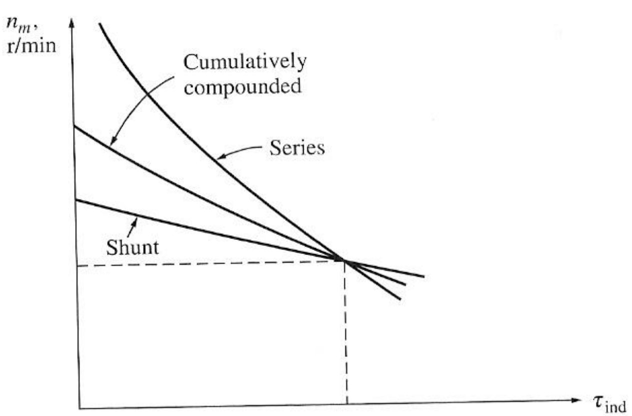
COMPOUND DC MOTOR

- Current flowing into dot produces a positive mmf (same as in transformer)
- If current flows into dots on both field coils, resulting mmfs add to produce a larger total mmf
- This situation is known as cumulative compounding
- If current flows into dot on one field coil & out of dot on other field coil resulting mmfs subtract
- In previous (a)&(b) figures round dots correspond to cumulative compounding & squares corresponds to differential compounding

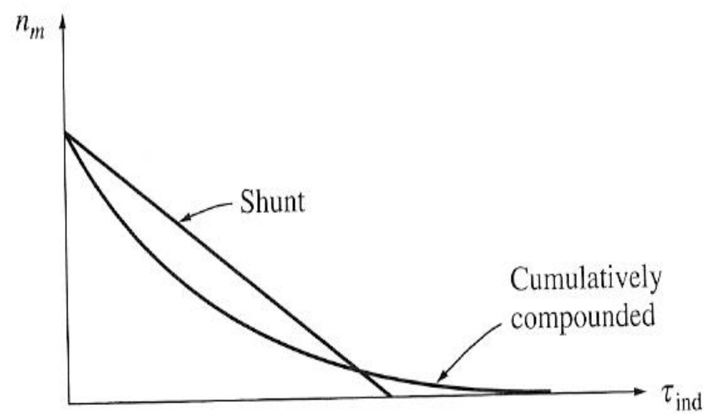
COMPOUND DC MOTOR
Torque-Speed Characteristic

(a) $T-\omega$ curve of cumulatively compound, compared to series & shunt motors with same full-load rating

(b) $T-\omega$ curve of cumulatively compound, compared to shunt motor with same no-load speed



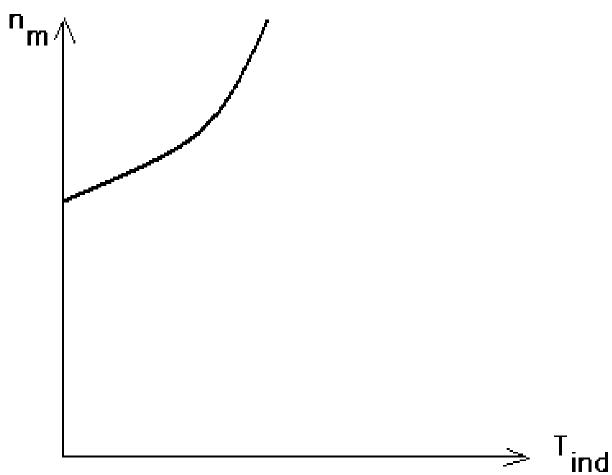
(a)



(b)

COMPOUND DC MOTOR
Torque-Speed Characteristic

- The result is that a differentially compounded motor is unstable and tends to runaway
- This instability is much worse than that of a shunt motor with armature reaction. It is so bad that a differentially compounded motor is unsuitable for any application.



Characteristics of motor types

This graph is actually two graphs that share the x-axis in common.   Speed and torque characteristics of the three DC motor types are compared.   A Series motor is the most non-linear but are capable of extremely high torque at low speeds (with high current). Whatever a shunt motor can do…a compound motor can do better (slightly). In common are the crossing points for Series, Compound, and Shunt motors at 100% speed and 100% torque. These crossings occur at 100% armature current. At these two points all three motors are essentially the same.

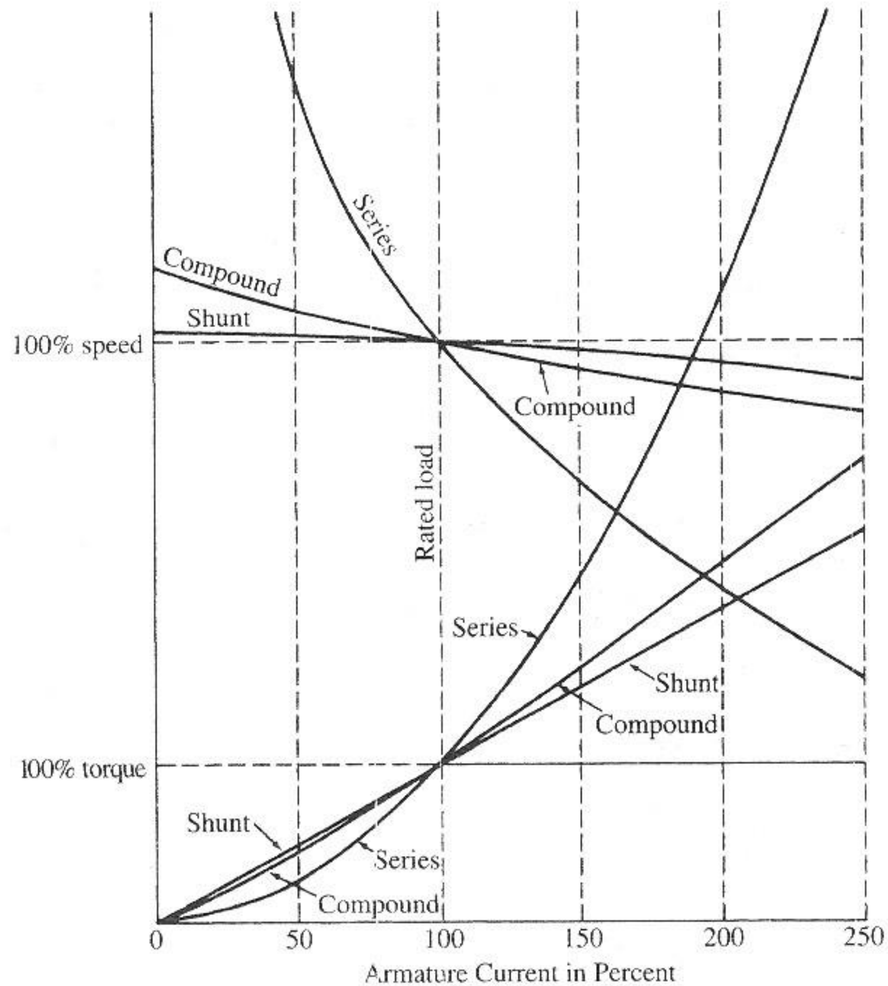


FIGURE 11.9
Steady-state speed and torque characteristics of typical shunt, series, and compound motors.

How to change direction of rotation for a Compound motor

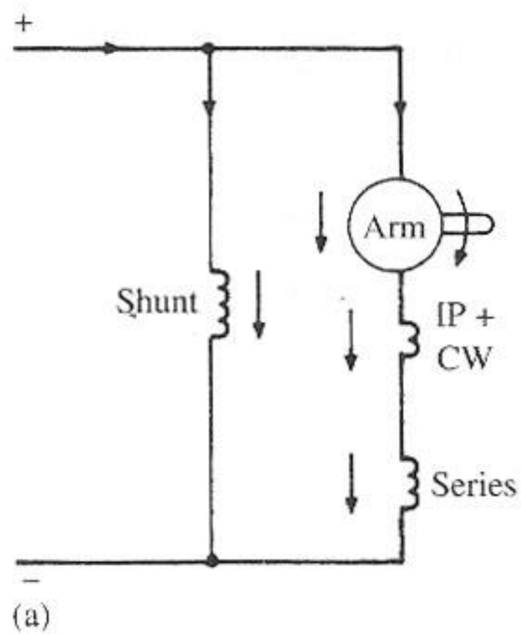


FIGURE 11.3
Reversing the direction of rotation of a compound motor by reversing the current in tl
armature, interpoles, and compensating winding.

How to change direction of rotation for a Series motor

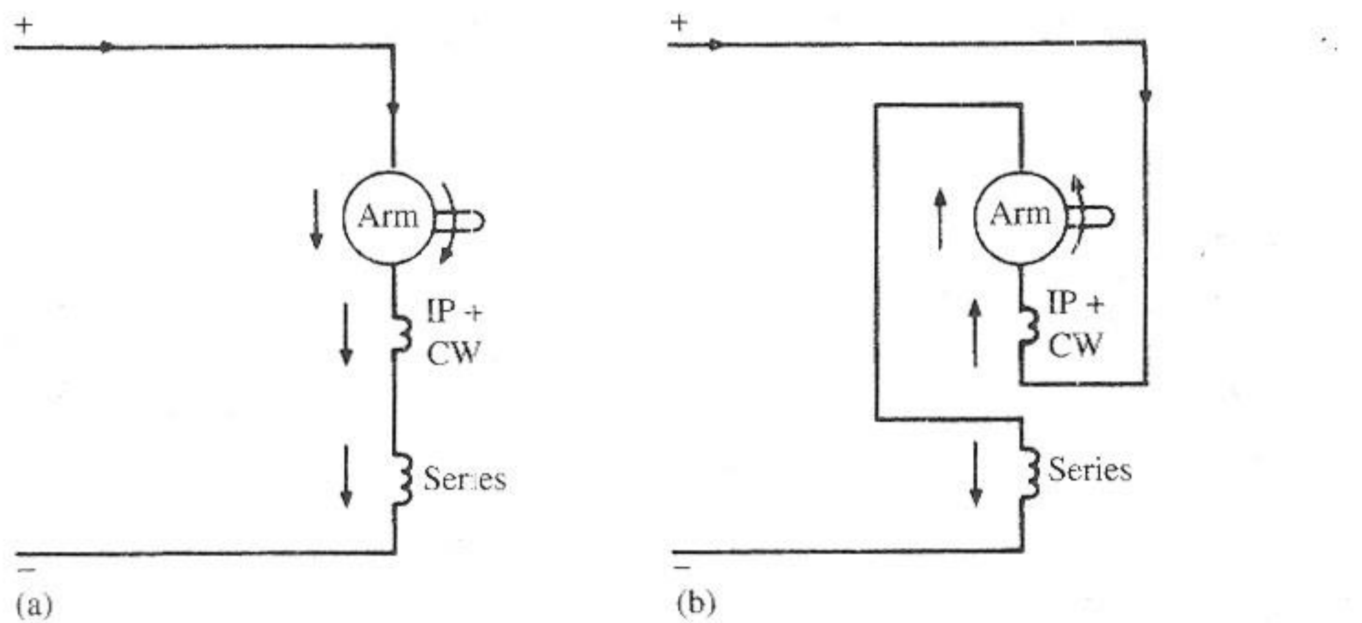


FIGURE 11.4
Reversing the direction of rotation of a series motor by reversing the current in the armature, interpoles, and compensating winding.

Starting of DC machines

DC MOTOR PROBLEMS on STARTING

- In order for a dc motor to function properly, it must be protected from physical damage during starting period
- At starting conditions, motor is not turning & so $E_A = 0\text{V}$
- since internal resistance of a normal dc motor is very low compared to its size (3 to 6 percent per unit for Medium size motors) a very high current flows
- Consider for example, 50 hp, 250 V motor of EXAMPLE 1, R_A is 0.06 Ω, & full-load current less than 200 A, but current on starting is:

$$I_A = \left(V_T - E_A\right) / R_A = \left(250 - 0\right) / 0.06 = 4167\text{A}$$

This current is over 20 times motor's rated full-load current

It is possible a motor severely damaged by such current

DC MOTOR STARTERS

- Equipments used for protection of dc motors, for the following reasons:

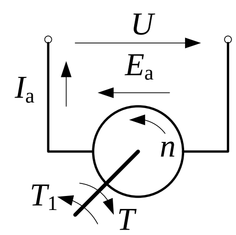
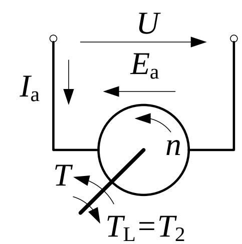
1- protect motor against damage due to short circuits in equipment

2- protect motor against damage from long-term overloads

3-protect motor against damage from excessive starting currents

4- provide a convenient manner in which to control the operating speed of motor

Basic equations for dc machines

		generator	motor
			
excitation	Separately-excited	$I = I_a$	
	shunt	$I = I_a - I_f$	$I = I_a + I_f$
electrical		$E_a = U + I_a R_a$	$U = E_a + I_a R_a$
torque		$T_1 = T + T_0$	$T = T_L + T_0 = T_2 + T_0$
power		$P_1 = P_{\text{em}} + p_0$ $P_{\text{em}} = P_2 + p_{\text{Cu}} \left(+p_f\right)$	$P_1 = P_{\text{em}} + p_{\text{Cu}} \left(+p_f\right)$ $P_{\text{em}} = P_2 + p_0$
		$p_0 = p_m + p_{\text{Fe}} + p_{\text{ad}}$	
Power-torque		$P_{\text{em}} = T\Omega = E_a I_a$ $\quad p_0 = T_0 \Omega$ $p_{\text{Cu}} = I_a^2 R_a$ $\quad p_f = U_f I_f = I_f^2 R_f$	
		$P_1 = T_1 \Omega \quad P_2 = UI$	$P_1 = UI \quad P_2 = T_2 \Omega$

DC Machines

- DC Machine Construction
- Basic Principles
- Armature winding of DC machines
- Armature Reaction
- Equivalent Circuit
- Power & Torque
- Operation characteristics of DC generators
- Speed control of DC machines
- Starting of DC machines