UNIVERSITY OF TECHNOLOGY, SYDNEY
FACULTY OF ENGINEERING

48550 Electrical Energy Technology

DC Machines

Topics to cover:

1. Introduction

2. EMF & Torque

3. Equivalent Circuit

4. Performance

I. Introduction

- **Principle of DC machines**

A DC motor is a device for converting DC electrical energy into rotary (or linear) mechanical energy. This process can be reversed, as in a DC generator, to convert mechanical to electrical power. The working principle of the DC (and AC as well) generator is Faraday's Law, which states that *emf* and electric current if the circuit is closed, is produced when a conductor cuts through magnetic force lines. The opposite of the law applies for the DC (and AC) motor. Motion is produced when a current carrying wire is put in a magnetic field.

Introduction - commutation

- In DC machines the current in each wire of the armature is actually alternating, and hence a device is required to convert the alternating current generated in the DC generator by electromagnetic induction into direct current, or at the armature of a DC motor to convert the input direct current into alternating current at appropriate times, as illustrated in Fig.1.
- Fig.1(a): DC generator: induced AC *emf* is converted to DC voltage; (b) DC motor: input direct current is converted to alternating current in the armature at appropriate times to produce a unidirectional torque.

Commutation

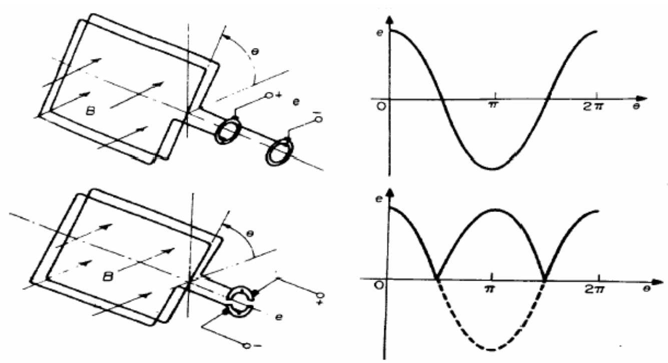


Fig.1 (a) DC generator

Commutation

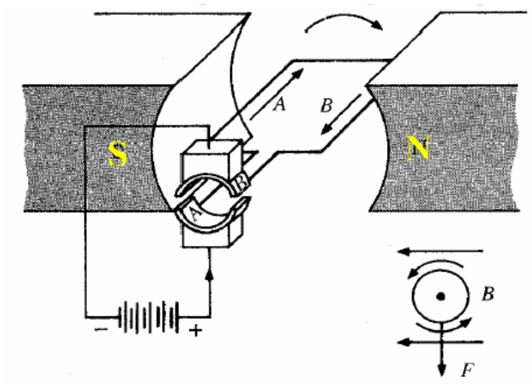


Fig.1 (b) DC motor

DC Machine Construction

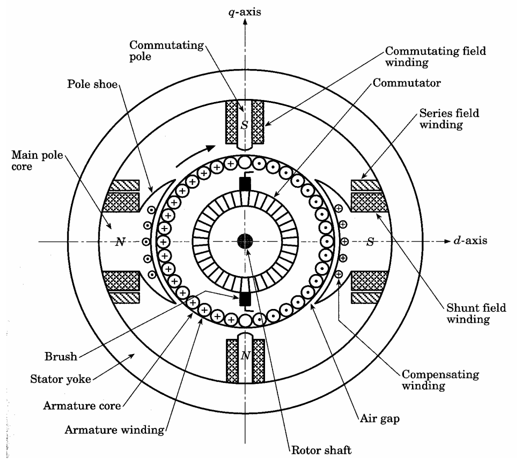
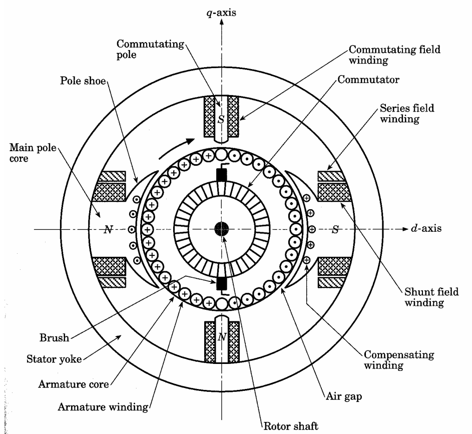


Fig.2 DC machine construction.

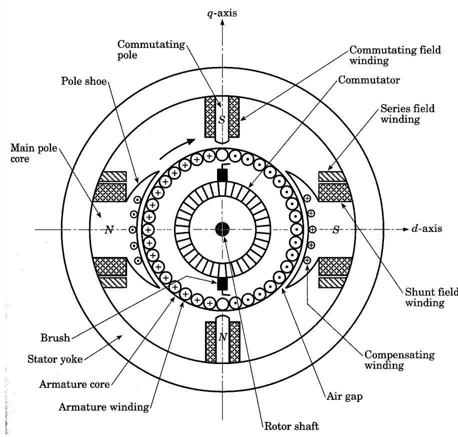
DC Machine: Major Components

- **The stator of the dc machine has poles, which are excited by dc current to produce magnetic fields.**
- **In the neutral zone, in the middle between the poles, commutating poles are placed to reduce sparking of the commutator. The commutating poles are supplied by dc current.**
- **Compensating windings are mounted on the main poles. These short-circuited windings damp rotor oscillations.**



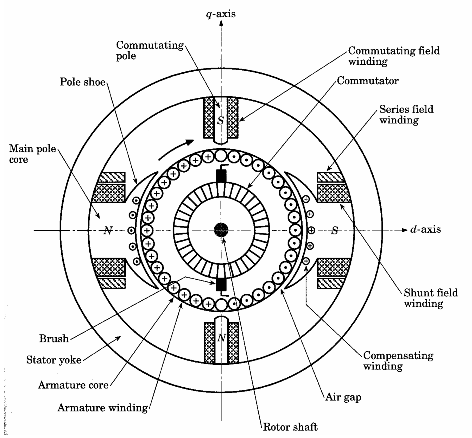
DC Machine: Major Components

- **The poles are mounted on an iron core that provides a closed magnetic circuit.**
- **The motor housing supports the iron core, the brushes and the bearings.**
- **The rotor has a ring-shaped laminated iron core with slots.**
- **Coils with several turns are placed in the slots. The distance between the two legs of the coil is about 180 electric degrees.**
- **The coils are connected in series through the commutator segments.**



DC Machine: Major Components

- The ends of each coil are connected to a commutator segment.
- The commutator consists of insulated copper segments mounted on an insulated tube.
- Two brushes are pressed to the commutator to permit current flow.
- The brushes are placed in the neutral zone, where the magnetic field is close to zero, to reduce arcing.



DC Machine: Commutator

- The rotor has a ring-shaped laminated iron core with slots.
- The commutator consists of insulated copper segments mounted on an insulated tube.
- Two brushes are pressed to the commutator to permit current flow.
- The brushes are placed in the neutral zone, where the magnetic field is close to zero, to reduce arcing.

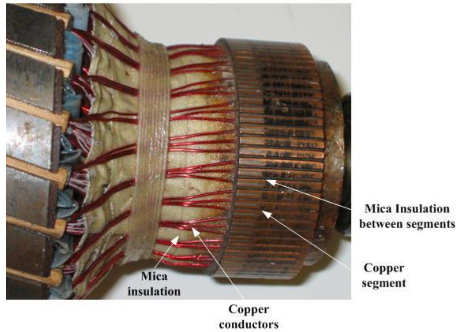
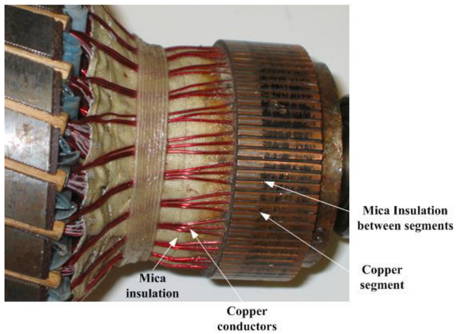


Fig.3 Commutator

DC Machine: Commutator

- The *commutator* switches the current from one rotor coil to the adjacent coil.
- The switching requires the interruption of the coil current.
- The sudden interruption of an inductive current generates high voltages .
- The high voltage produces flashover and arcing between the commutator segment and the brush.



DC Machine: Commutator

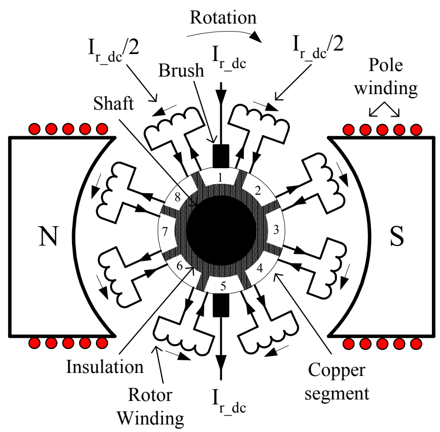


Fig.3 Commutator with the rotor coils connections.

DC Machine Construction

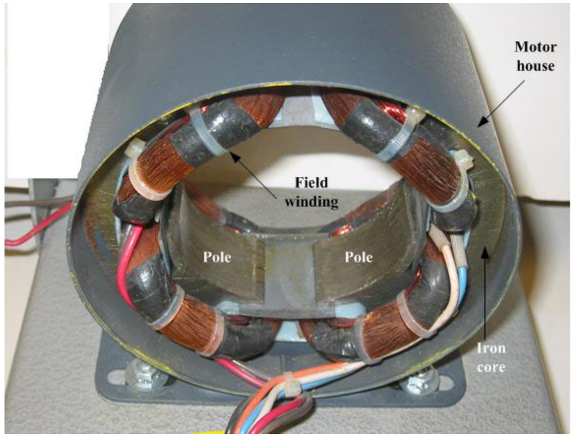


Fig.4 DC motor stator with poles visible (4 pole machine).

DC Machine Construction

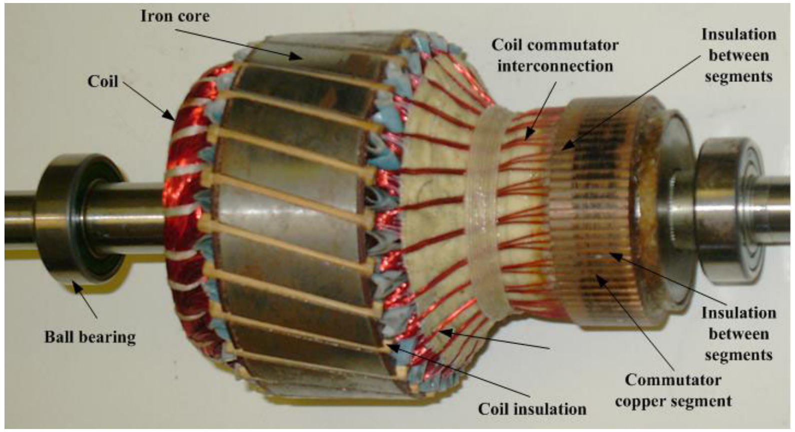


Fig.5 Rotor of a DC motor.

DC Machine Construction

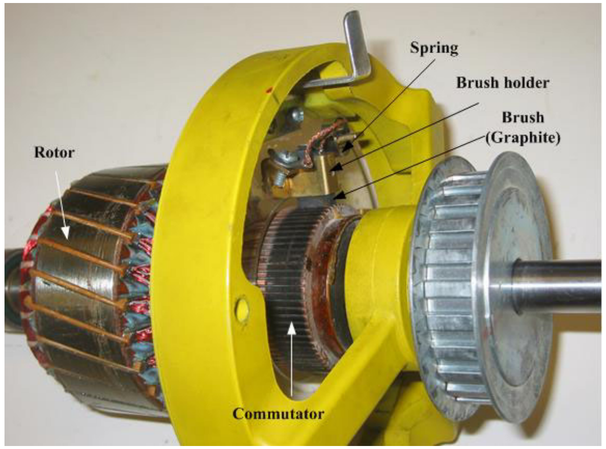


Fig.6 Cutaway view of a DC motor.

II. Emf & Torque

- **The magnetic field produced by the stator poles induces a electromagnetic force (emf) in the rotor (or armature) coils when the machine rotates or is rotated.**
- **The pole flux is produced by the DC excitation/field current, which is magnetically coupled to the rotor.**
- **The flux is proportional to the field current if the iron core is not saturated:**

$$\Phi = K_1 \, I_f$$

- **The rotor conductors cut the field lines that generate emf in the coils**

$$E_a = 2 \, N_r \, B_{ag} \, \ell_g \, v$$

where N_r is the number of coils in series, B_{ag} the average flux density, l_g effective axial length, v the velocity of the conductor.

Emf & Torque

- **The motor speed and flux equations are :**

$$v = \omega_m \frac{D_g}{2} \qquad \Phi = B_{ag}\,\ell_g\,\pi D_g / p$$

where ω_m is the rotor mechanical angular speed, D_g rotor diameter, p the number of poles, and ϕ flux per pole. The combination of the three equations gives the induced emf:

$$E_a = 2N_r B_{ag}\,\ell_g v = 2N_r B_{ag}\,\ell_g \left(\omega_m \frac{D_g}{2}\right) = \frac{p}{\pi} N_r \left(B_{ag}\,\ell_g\,\pi D_g\right)\omega_m$$

$$= \frac{p}{\pi} N_r\,\Phi\,\omega_m = \frac{p}{\pi}\frac{C_a}{2a}\Phi\,\omega_m = k_a \Phi\,\omega_m$$

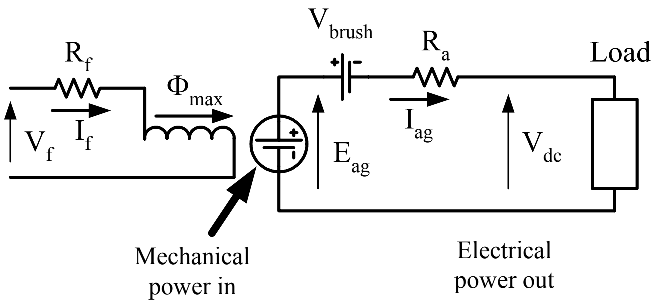
Emf & Torque

$$T = \frac{E_a I_a}{\omega_m} = k_a \Phi\, I_a$$

where k_a is armature constant, C_a is the total number of conductors, a is the number of the parallel paths of the armature winding, p is the number of magnetic poles, a=2 for wave windings, and a=p for lap windings.

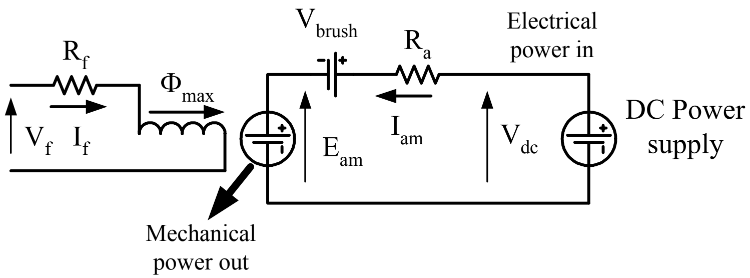
III. Equivalent Circuit

III.(1) A separately excited dc generator



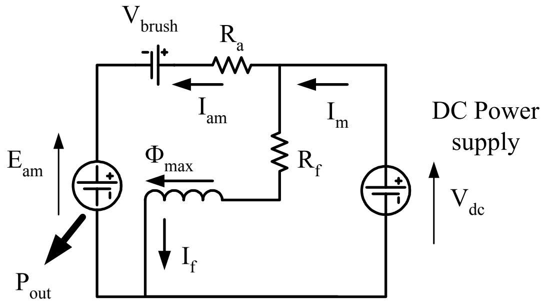
$$V_{dc} = E_a - R_a I_a \qquad V_f = R_f I_f \qquad T = T_{shaft} - T_{loss}$$

III.(2) A separately excited dc motor



$$V_{dc} = E_a + R_a I_a \qquad V_f = R_f I_f \qquad T = T_{load} + T_{loss}$$

III.(3) Shunt dc motor

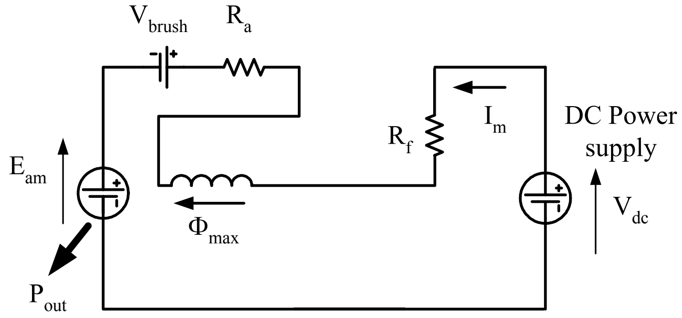


$$V_{dc} = E_a + R_a I_a \qquad V_f = V_{dc} = R_f I_f \qquad I_m = I_a + I_f$$

For shunt dc generator

$$V_{dc} = E_a - R_a I_a \qquad V_f = V_{dc} = R_f I_f \qquad I_a = I_m + I_f$$

III.(4) Series dc motor

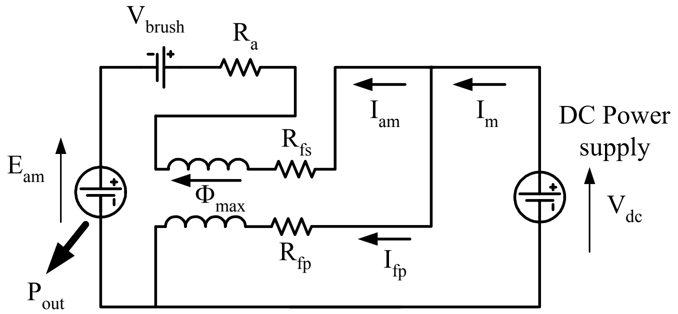


$$V_{dc} = E_a + (R_a + R_f) I_a \qquad I_m = I_a = I_f$$

For series dc generator

$$V_{dc} = E_a - (R_a + R_f) I_a \qquad I_m = I_a = I_f$$

III.(5) Compound dc motor



$$V_{dc} = E_a + (R_a + R_{fs}) I_a \qquad I_m = I_a + I_{fp} = I_{fs} + I_{fp} \qquad V_{fp} = V_{dc} = R_{fp} I_{fp}$$

For series dc generator

$$V_{dc} = E_a - (R_a + R_{fs}) I_a \qquad I_a = I_{fs} = I_m + I_{fp} \qquad V_{fp} = V_{dc} = R_{fp} I_{fp}$$

IV. Performance
(1) Separately excited generator

__Open circuit characteristic__

$I_a = 0 \qquad \omega_m = \omega_{mrated}$

$V_t (i.e. V_{dc}) = E_a = k_f I_f$

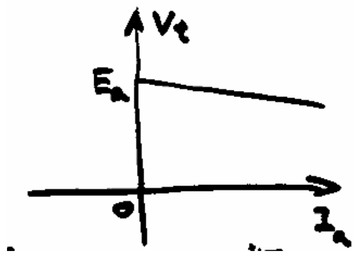
The relation of E_a and I_f is the magnetisation curve.

__External characteristic__: **(V_t vs. I_a)**

$\omega_m = \omega_{mrated}$

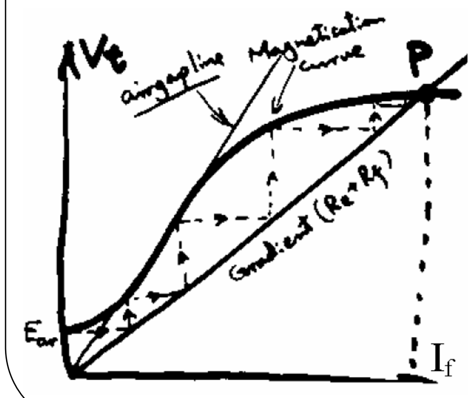
$I_f = I_{frated}$

$V_f = V_{dc} = E_a - R_a I_a$



IV. Performance
(2) Shunt generator

Build up of v_t for self-excitation:



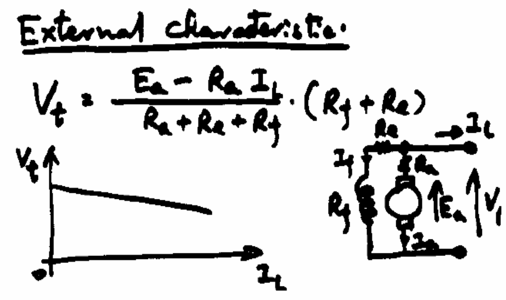
Conditions for building up v_t:

- **Residual magnetism – Initial magnetisation using batteries, etc.**
- **Field winding being connected correctly to armature winding such that the generated flux aids the residual magnetism – swap the terminals.**
- **The slop of the resistance line (Re+Rf) must be smaller than of the airgap line – reduce Re.**

IV. Performance
(2) Shunt generator – cont.

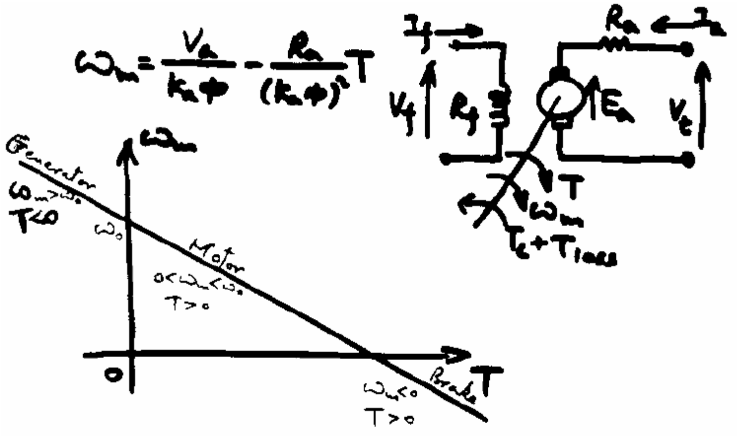
External characteristic:

$$I_a = I_L + I_f$$
$$= I_L + \frac{V_L}{R_f + R_e}$$



$$V_t = E_a - R_a I_a$$
$$= E_a - R_a\left(I_L + \frac{V_L}{R_f + R_e}\right)$$

IV. Performance
(3) Separately excited motor



IV. Performance
(3) Separately excited motor –cont.

Method for speed control:

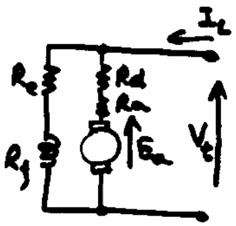
Varying terminal voltage for speed below the base speed, suitable for constant torque load;

Field weakening for speed control above the base speed, suitable for constant power load.

IV. Performance
(4) Shunt motor

④ Shunt motor

$$\omega_m = \frac{V_t}{K_a\Phi} - \frac{R_a + R_d}{(K_a\Phi)^2}T$$

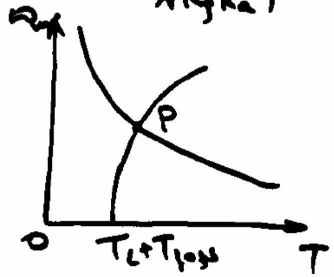


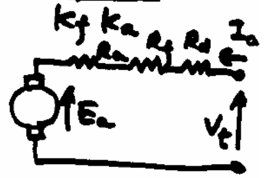
Speed control

* $R_d \uparrow$ suitable for constant torque load;
* $R_e \uparrow$ (field weakening) suitable for constant power load.

IV. Performance
(5) Series motor

$$\omega_m = \frac{V_t}{\sqrt{K_f K_a T}} - \frac{R_a + R_f + R_d}{K_f K_a}$$





Note: * A series motor can not run at no-load;

** $\because T = K_a K_f I_L^2$, $I_L \le I_{rated}$

$\therefore$ a series motor can produce high torque at a low speed.

IV. Performance
(6) Efficiency

$$\eta = \frac{P_{out}}{P_{in}} = 1 - \frac{P_{loss}}{P_{in}}$$

Generators

$P_{in} = T_m\omega_m + V_f I_f$ (separately excited)

or $= T_m\omega_m$ (shunt or series)

$P_{out} = V_t I_L$

$P_{loss} = R_a I_a^2 + R_f I_f^2 + T_{loss}\omega_m$

($T_{loss}\omega_m$ ↑ rotational loss)

IV. Performance
(6) Efficiency – cont.

Motors

$P_{in} = V_t I_L + V_f I_f$ (separately excited)

or $= V_t I_L$ (shunt or series motors)

$P_{out} = T_m\omega_m$

$P_{loss} = R_a I_a^2 + R_f I_f^2 + T_{loss}\omega_m$

($T_{loss}\omega_m$ ↑ rotational loss)

Note:

$T_m = T + T_{loss}$ for generator

$T_m = T - T_{loss}$ for motors

$P_{em} = E_a I_a = T\omega_m$