Dr. Adel Gastli

Electromechanical Systems & Actuators

DC MACHINES

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DC Machines

LEARNING GOALS

- Introduction
  - Application of DC Machine
  - Advantages & Disadvantages of DC Machine
- Construction of DC Machine
  - Field System
  - Armature
  - Commentator
  - Brush
- Principle of Operation
  - Faraday's Law
  - Armature Voltage & Developed Torque
- Classification of DC Machine
  - Permanent Magnet
  - Self-Excited
  - Separately-Excited
- DC Machine Representation
- Magnetization Curve (Saturation)
- DC Motor & Generator Equations
- Power Flow & Efficiency
- Torque-Speed Characteristics
- Starting of DC Machine

Introduction

- Most of the electrical machine in service are AC type.
- DC machine are of considerable industrial importance.
- DC machine mainly used as DC motors and the DC generators are rarely used.
- DC motors provides a fine control of the speed which can not be attained by AC motors.
- DC motors can developed rated torque at all speeds from standstill to rated speed.
- Developed torque at standstill is many times greater than the torque developed by an AC motor of equal power and speed rating.

Application of DC Machines

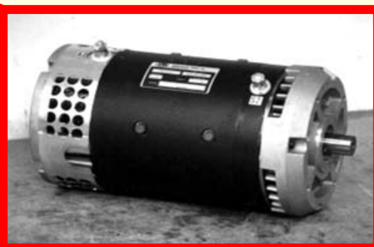
- The d.c. machine can operate as either a motor or a generator, at present its use as a generator is limited because of the widespread use of ac power.

- Large d.c. motors are used in machine tools, printing presses, fans, pumps, cranes, paper mill, traction, textile mills and so forth.

- Small d.c. machines (fractional horsepower rating) are used primarily as control device-such as tachogenerators for speed sensing and servomotors for position and tracking.

Application of DC Machines

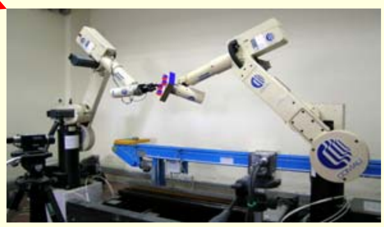
DC Motor




Paper Mills


Oil Rigs


Steel Mills


Robots


Mining


Machine Tools


Petrochemical

Advantages & Disadvantages Of D.C. Motors

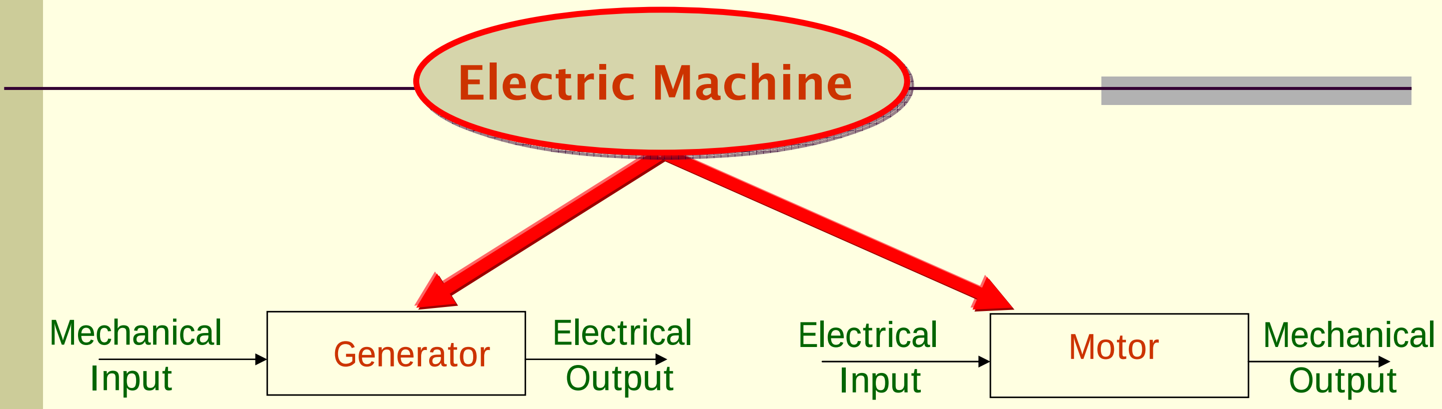
Advantages

- High starting torque
- Rapid acceleration and deceleration.
- Speed can be easily controlled over wide speed range.
- Used in tough gobs (traction motors, electric trains, electric cars,….)
- Built in wide range of sizes.

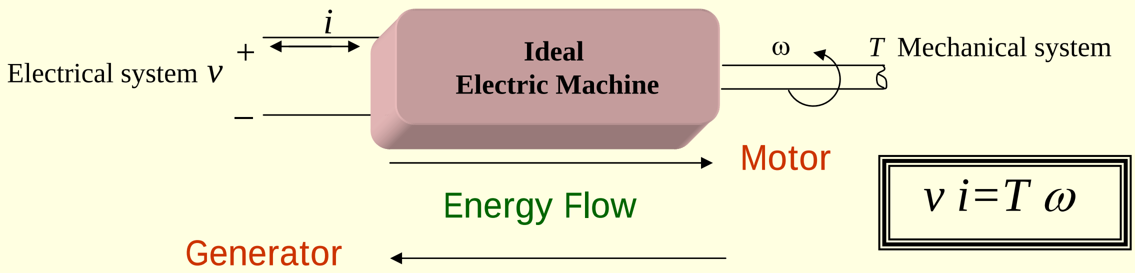
Disadvantages

- Needs regular maintenance
- Cannot be used in explosive area
- High cost

Introduction

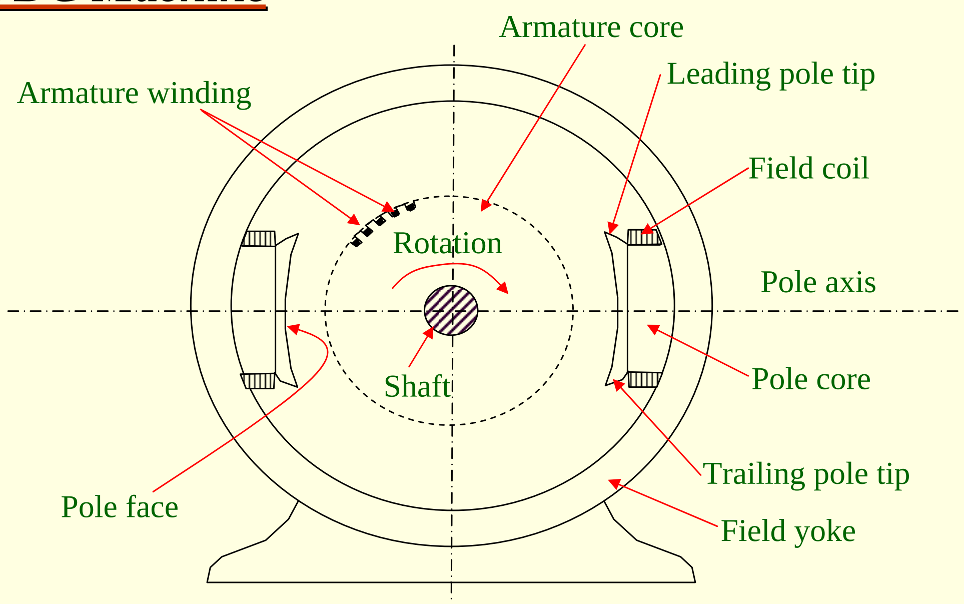


Electromechanical Energy Conversion

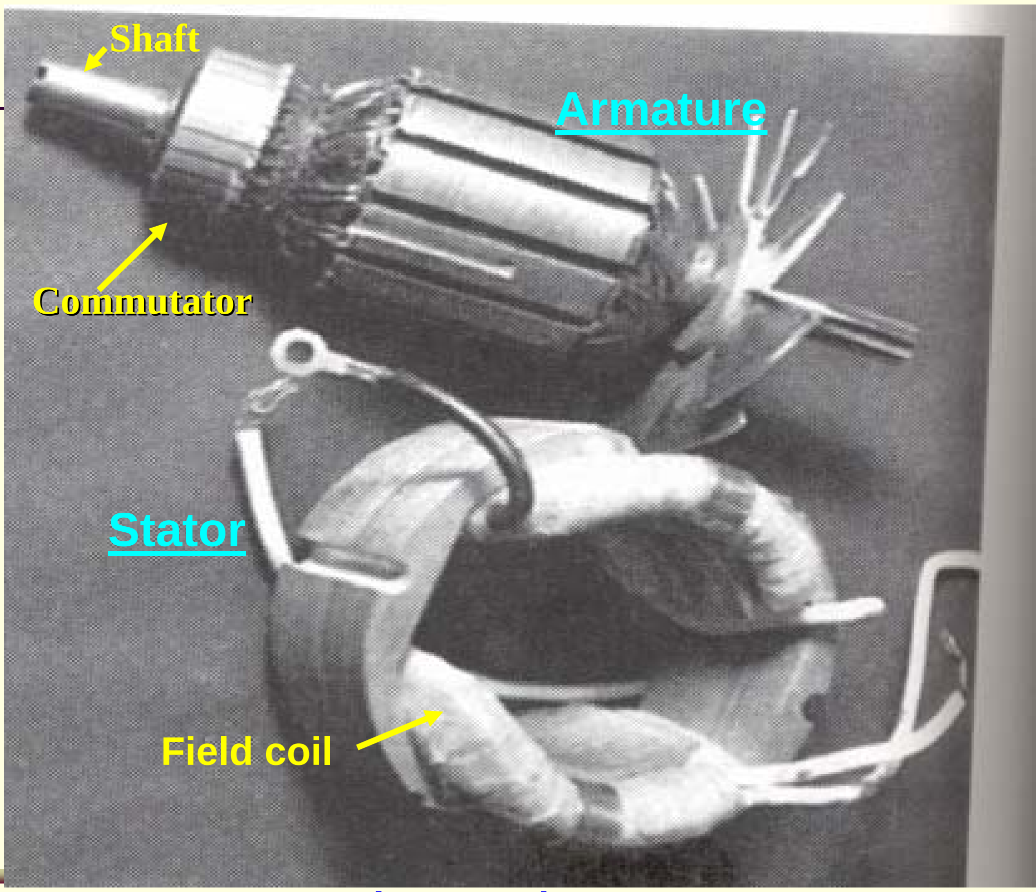


Construction of DC Machine

Parts of a DC Machine



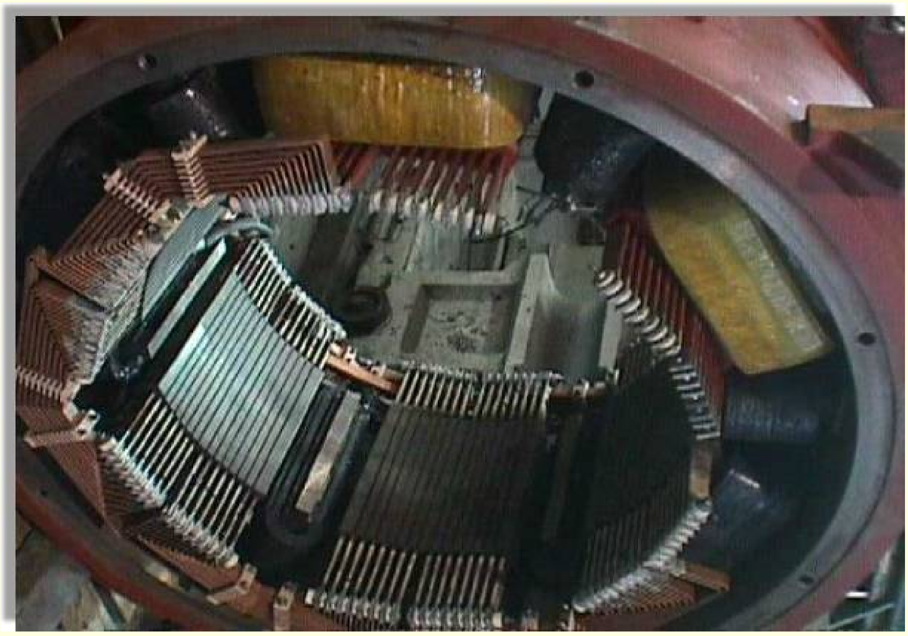
Construction of DC Machine



2 Pole DC Machine

Construction of DC Machine: Field System

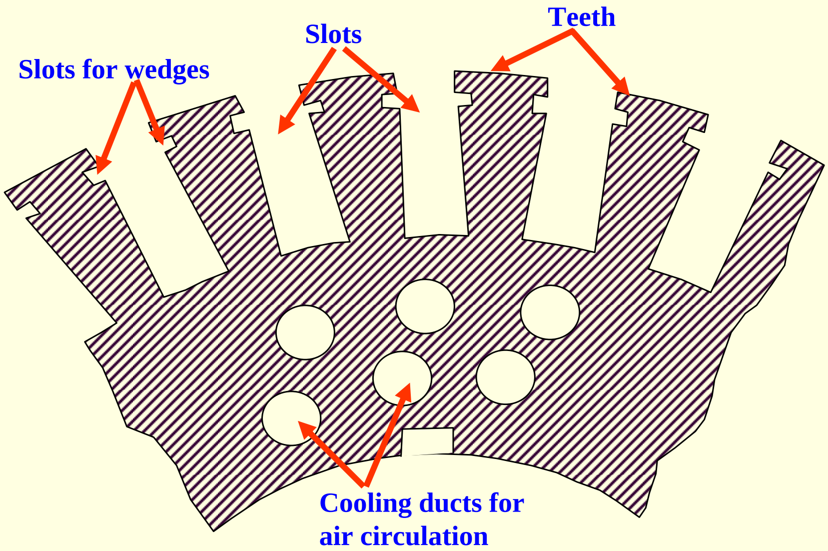
The field system is to produce uniform magnetic field within which the armature rotates. This consists of Yoke or frame: Acts as a mechanical support of the machine



2000HP DC Motor field System

Construction of DC Machine: Armature

The rotor or the armature core, which carries the rotor or armature winding, is made of sheet-steel laminations. The laminations are stacked together to form a cylindrical structure

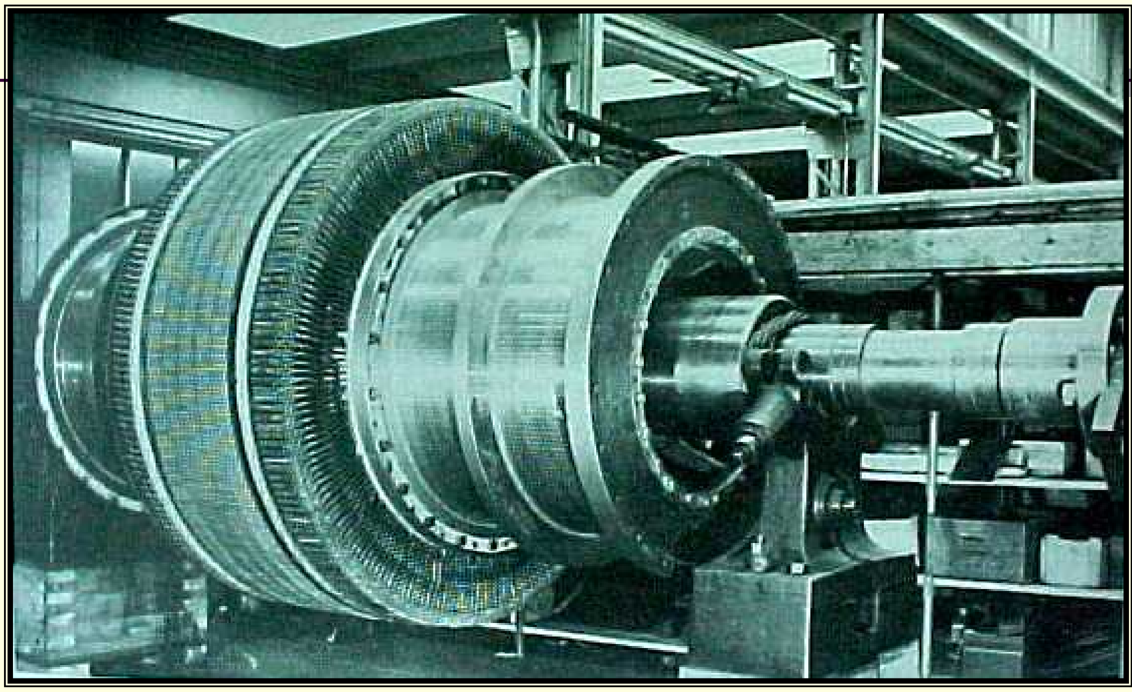


The armature coils that make the armature winding are located in the slots

Non-conducting slot liners are wedged in between the coil and the slot walls for protection from abrasion, electrical insulation and mechanical support

Portion of an armature lamination of a dc machine showing slots and teeth

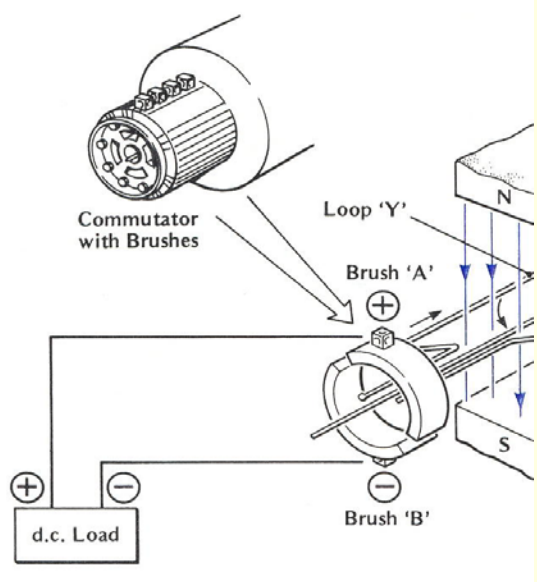
Construction of DC Machine: Armature

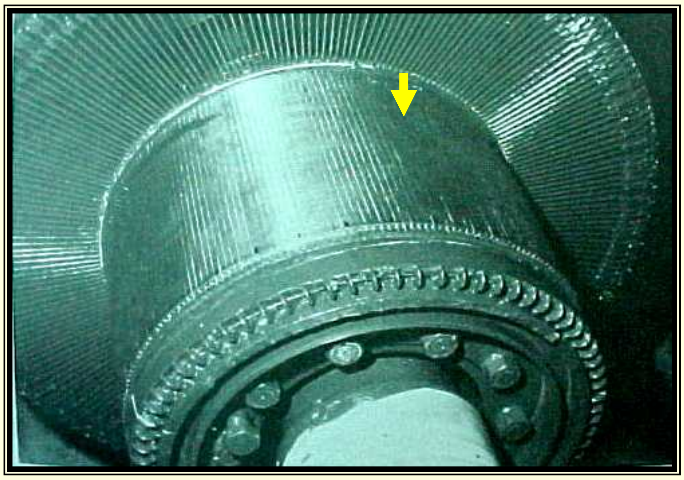


Armature of a DC Machine

Construction of DC Machine: Commutator

Commutator: is a mechanical rectifier, which converts the alternating voltage generated in the armature winding into direct voltage across the brush. It is made of copper segments insulated from each other by mica and mounted on the shaft of the machine. The armature windings are connected to the commutator segments.

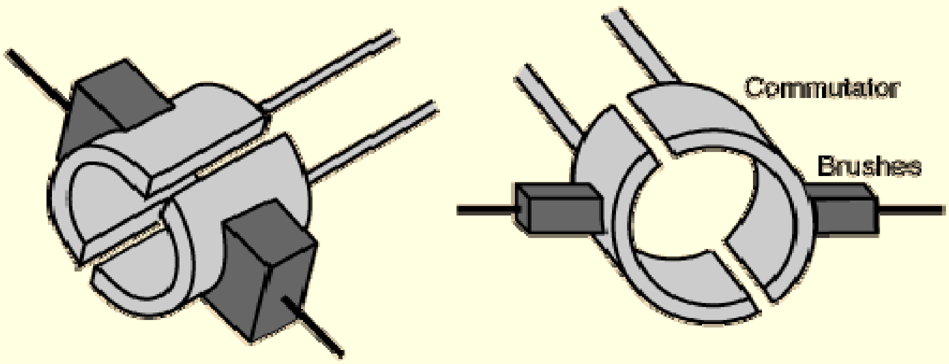




Commutator

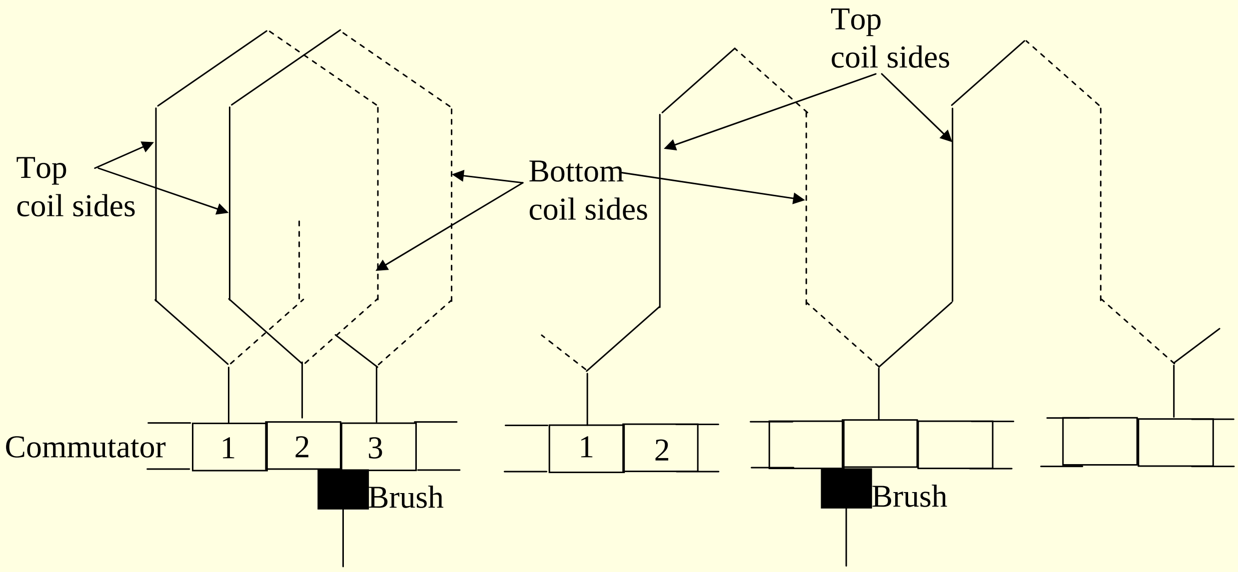
Construction of DC Machine: Brush

The purpose of the brush is to ensure electrical connections between the rotating commutator and stationary external load circuit. It is made of carbon and rest on the commutator.



Commutator and Brushes

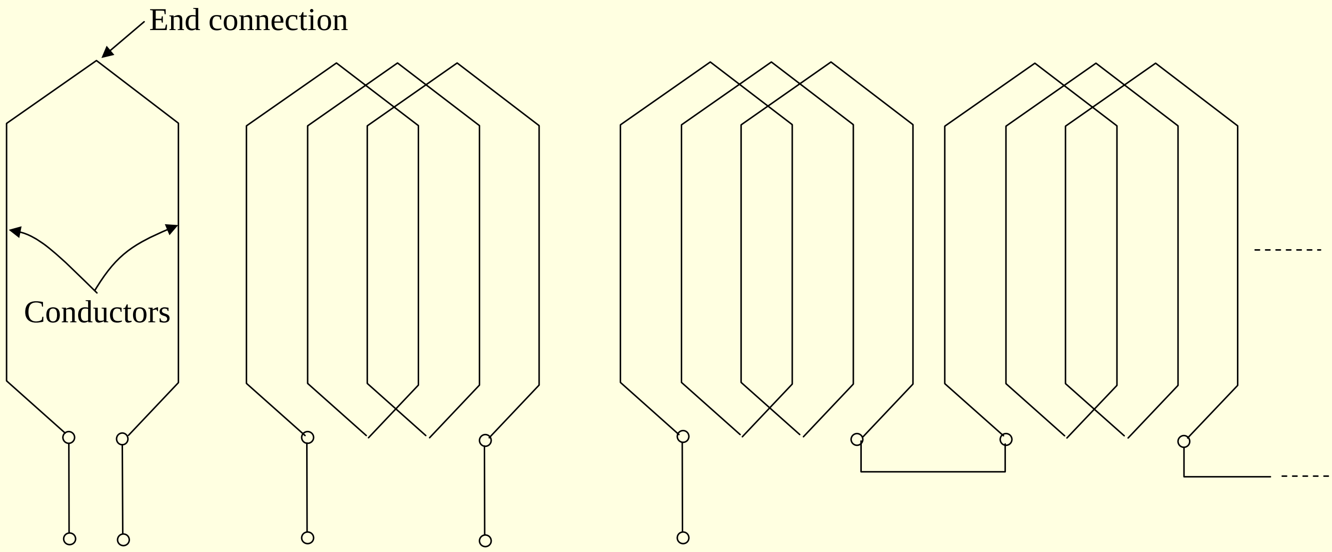
Construction of DC Machine: Armature Winding



Elements of Lap Winding

Elements of Wave Winding

Construction of DC Machine: Armature Winding



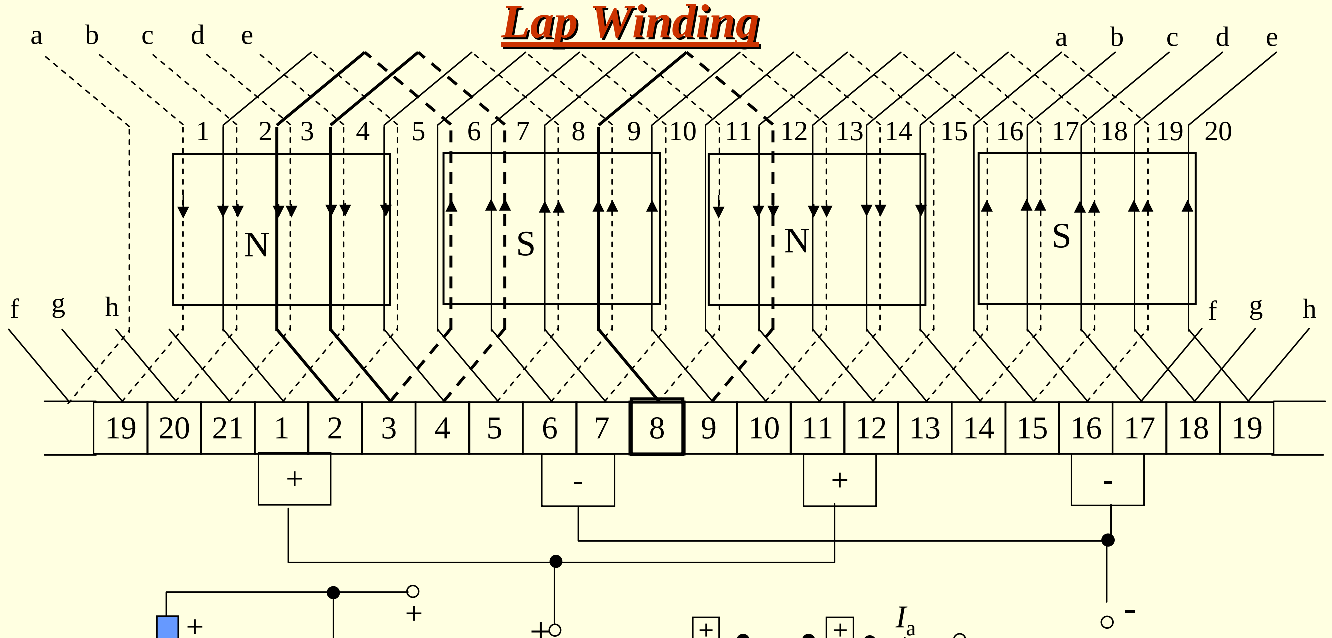
Turn

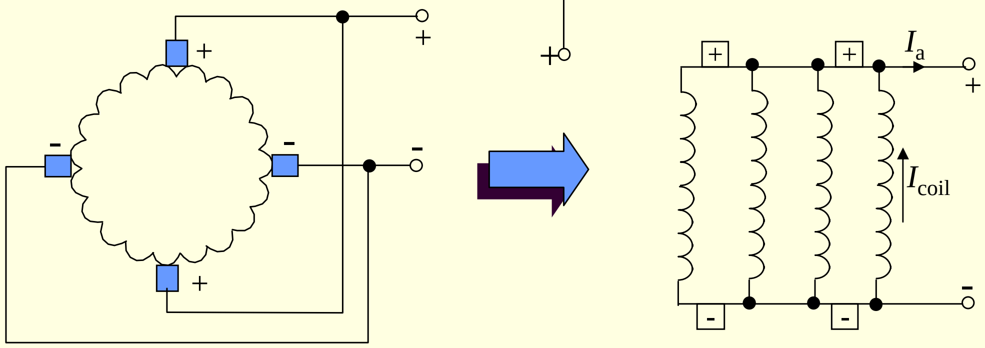
Coil

Winding

Construction of DC Machine: Armature Winding

Lap Winding



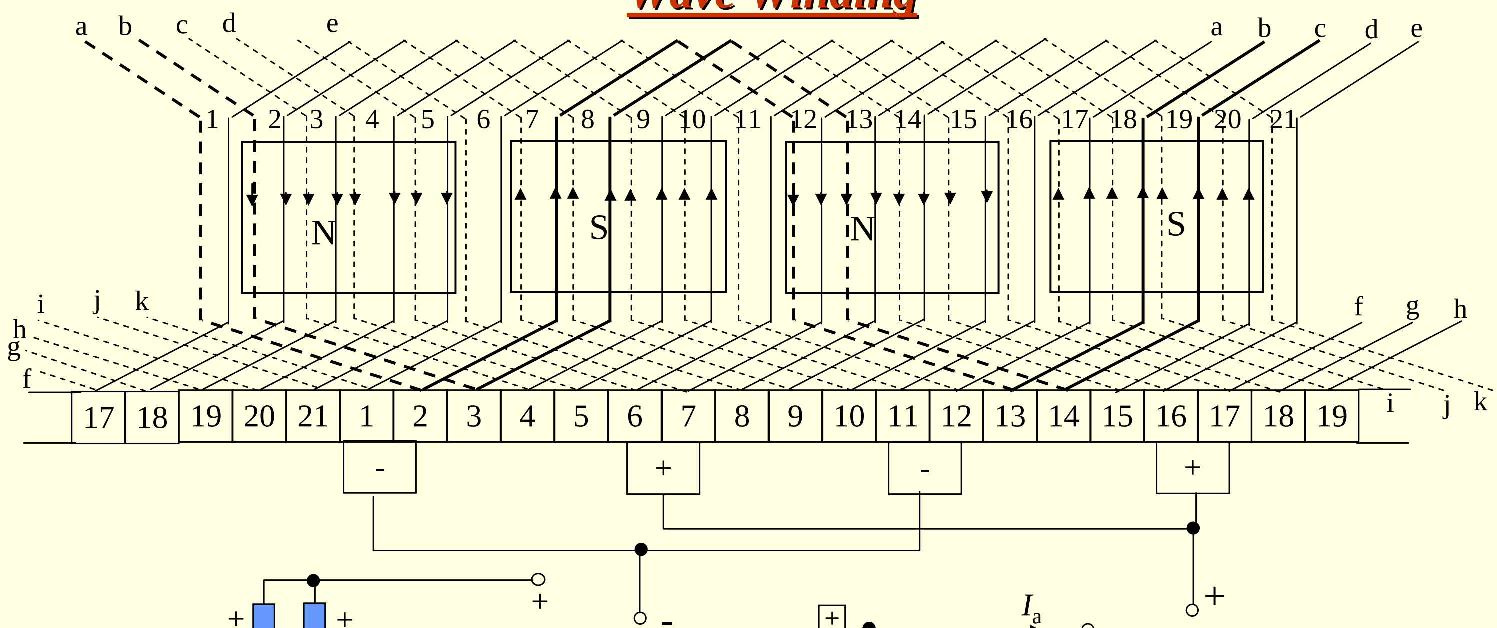


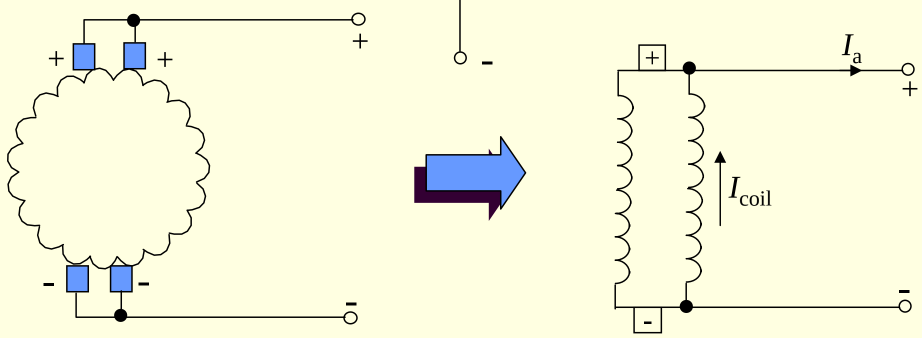
$$a = b = p$$

// paths brushes poles

Construction of DC Machine: Armature Winding

Wave Winding





$$a = 2$$

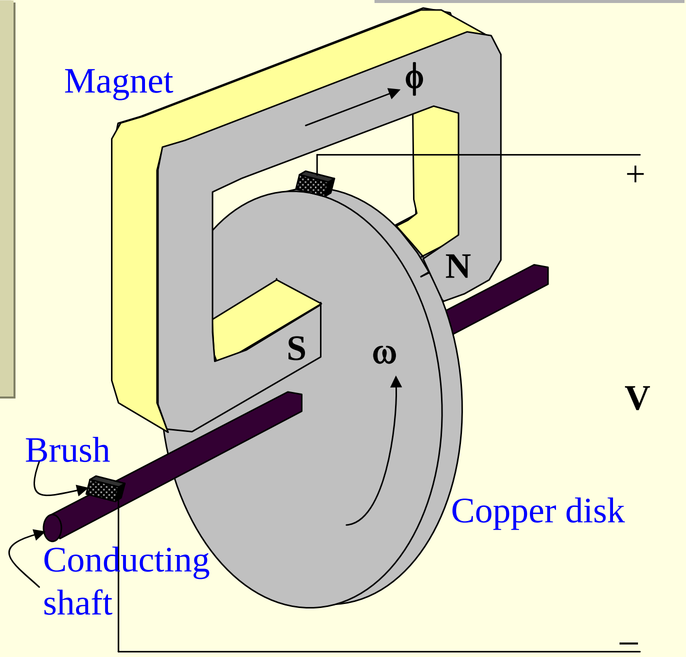
Nb. of // paths

Principle of Operation

The Faraday Disk and Faraday's Law

An emf is induced in a circuit placed in a magnetic field if either:

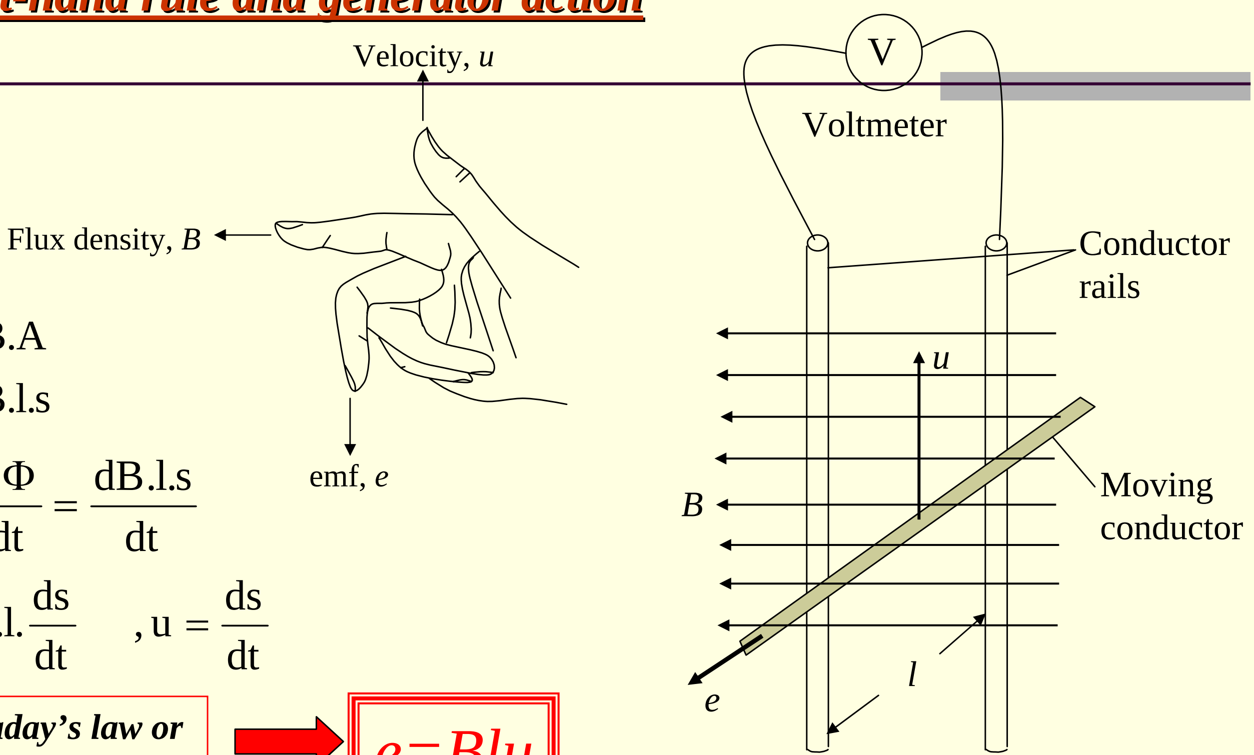
- the magnetic flux linking the circuit is time varying
- or there is a relative motion between the circuit and the magnetic field such that the conductors comprising the circuit cut a cross the magnetic flux lines.



- 1st form of the law is the basis of transformers.
- 2nd form is the basic principle of operation of electric generators.

Principle of Operation

The right-hand rule and generator action



$$\Phi = B.A$$

$$\Phi = B.l.s$$

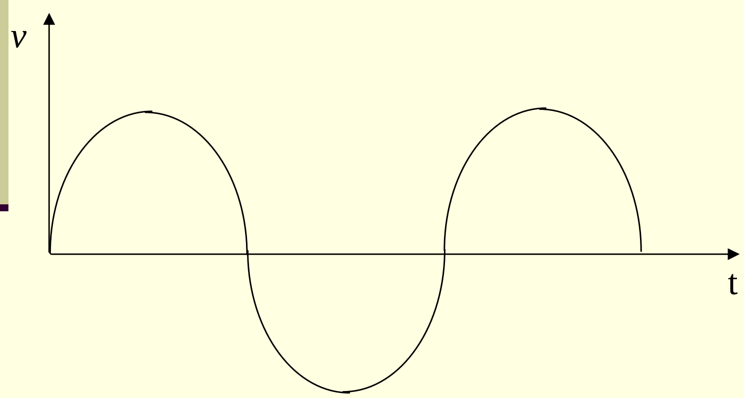
$$e = \frac{d\Phi}{dt} = \frac{dB.l.s}{dt}$$

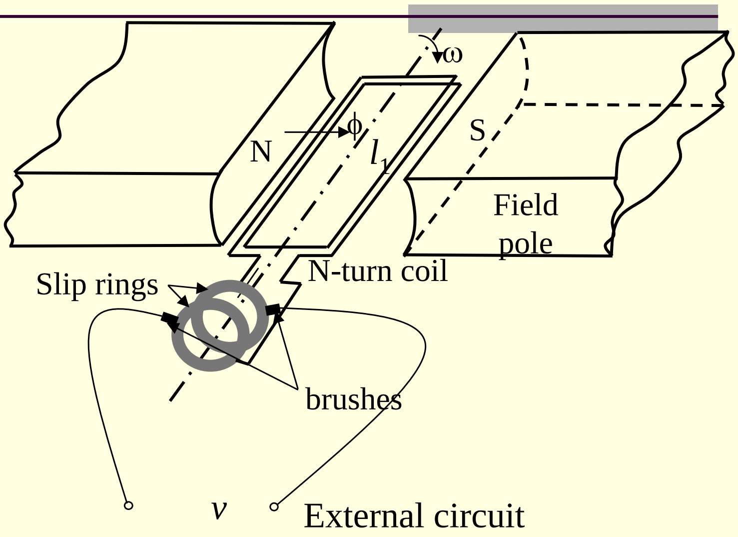
$$e = B.l.\frac{ds}{dt} \quad , u = \frac{ds}{dt}$$

Faraday's law or flux cutting rule → $e = Blu$

Principle of Operation

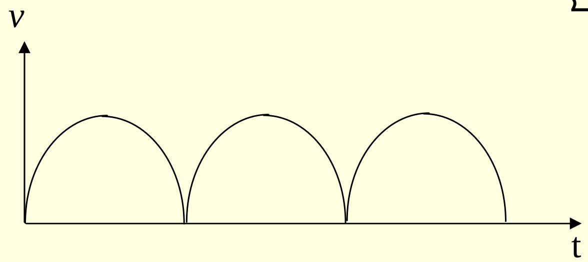
Without Commutator

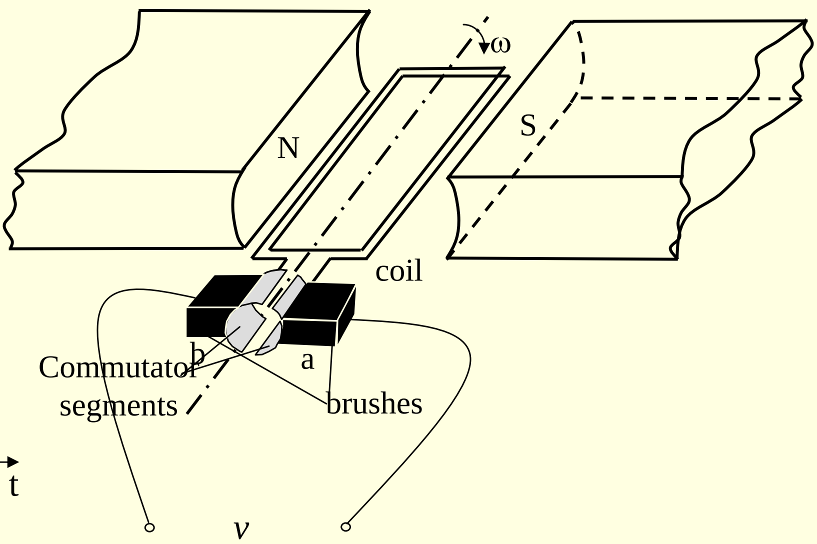




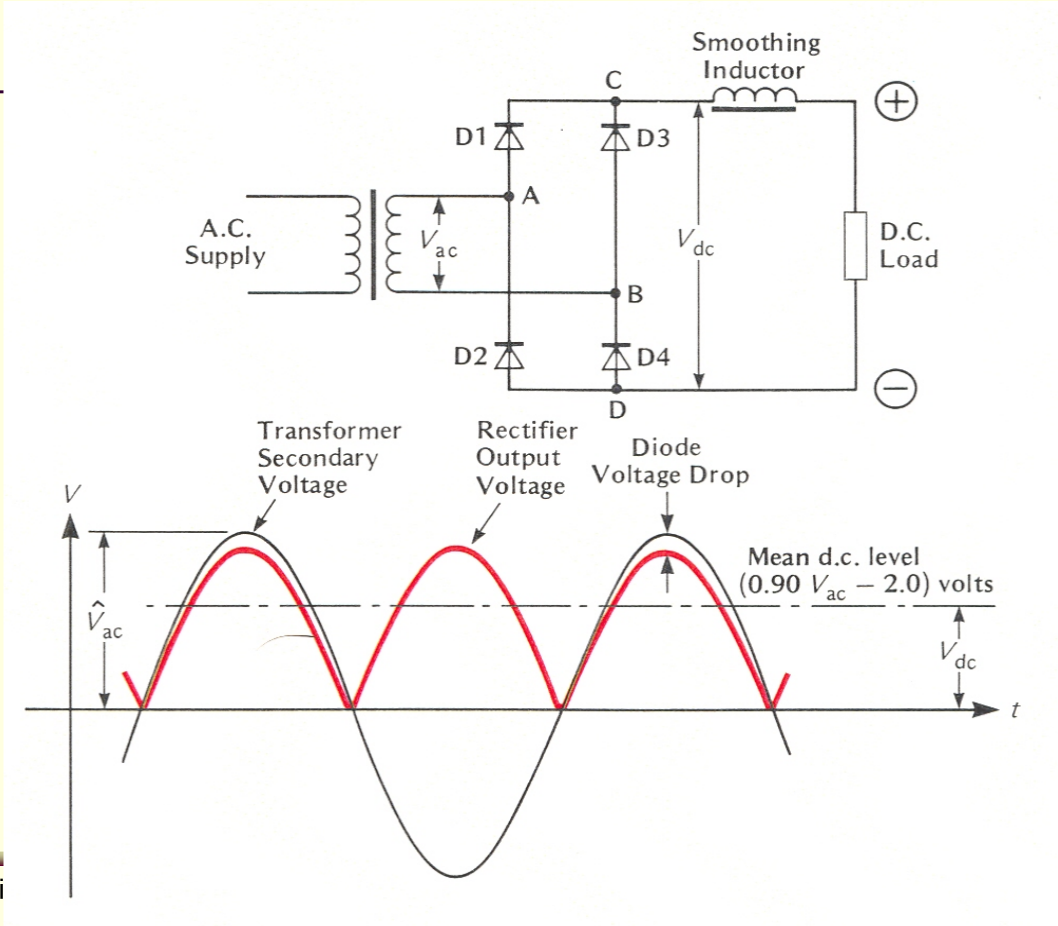
Principle of Operation

With Commutator





Single-Phase Full wave Rectifier

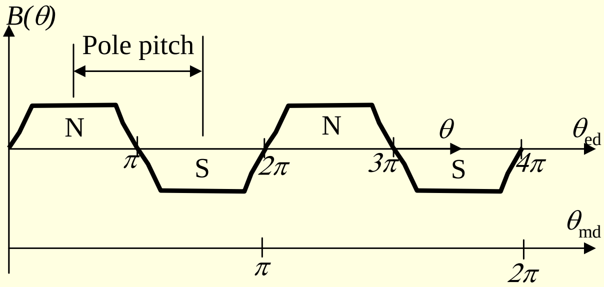


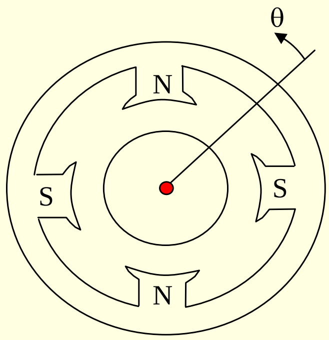
Multi-Pole Machines

If p is the number of poles, then p/2 cycles of variation of the flux are encountered every complete mechanical rotation.

$$\text{One pole pitch} = 180^o\,\text{ed} = \frac{360^o\,\text{md}}{p}$$

$$\theta_{ed} = \frac{p}{2}\theta_{md}$$





θ_{ed} : electrical degrees or angular measure in cycles
θ_{md} : mechanical degrees or angular measure in space

Principle of Operation: Armature Voltage

$$Emf_{conductor} = \frac{Flux / \mathrm{Rev.}}{time / \mathrm{Rev.}} = \frac{p.\Phi}{(60 / N_m)} = \frac{p.\Phi.N_m}{60}$$

$$Emf_{Total} = \frac{Emf_{conductor}}{Number\ \ of\ \ conductor\ \ /\ path}$$

$$\boxed{Emf_{Total} = \left(\frac{p.\Phi.N_m}{60}\right) / \left(\frac{Z}{a}\right) = \frac{p.\Phi.Z.N_m}{60\,a}}$$

where

p = number of poles

Z = total number of armature conductors

a = number of parallel paths, *2 for wave and p for lab*.

Φ = flux per pole (Weber)

N_m = speed of the motor in the revolutions per minute (rpm)

time of 1 revolution = 60/Nm (sec)

Principle of Operation: Armature Voltage

Let $\omega_m = \frac{2.\pi.N_m}{60} \Rightarrow N_m = \frac{\omega_m.60}{2.\pi}$

ω_m= speed of the motor in radians per second

$$Emf_{Total} = \frac{p.\Phi.Z}{60\,a} . \frac{\omega_m.60}{2.\pi} = \frac{p.\Phi.Z.\omega_m}{2.\pi.a}$$

$$\boxed{Emf_{Total} = K_a.\Phi.\omega_m}$$

K_a: armature constant $K_a = \frac{p.Z}{2.\pi.a}$

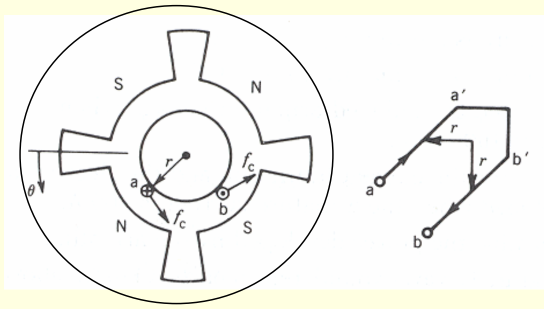
Generated voltage : generator operation

Back emf : motor operation

Developed (or Electromagnetic) Torque

Consider the turn shown in the following Figure.

Area per pole $A = \dfrac{2\pi r l}{p}$



Flux density $B = \dfrac{\Phi}{A} = \dfrac{p\,\Phi}{2\pi\, r\, l}$

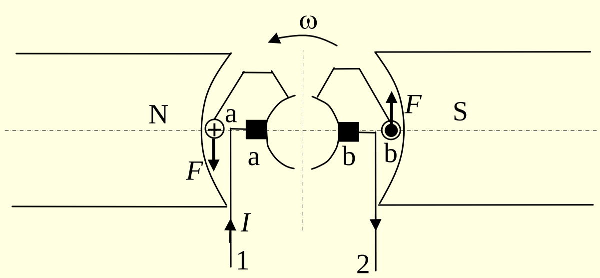
Current / conductor is $I_c = \dfrac{I_a}{a}$

The force on a conductor is $f_c = B\, l\, \dfrac{I_a}{a}$

The torque developed by a conductor is $T_c = f_c\, r = B\, l\, \dfrac{I_a}{a}\, r = \dfrac{\Phi\, p\, I_a}{2\pi\, a}$

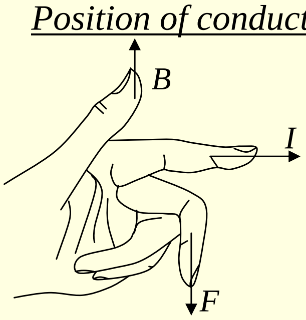
The total torque developed is $\boxed{T_e = \dfrac{Zp\,\Phi\, I_a}{2\pi a} = K_a \Phi I_a = \dfrac{E_a I_a}{\omega_m}}$

Production of Unidirectional Torque and Operation of an Elementary



Position of conductor a under N-pole

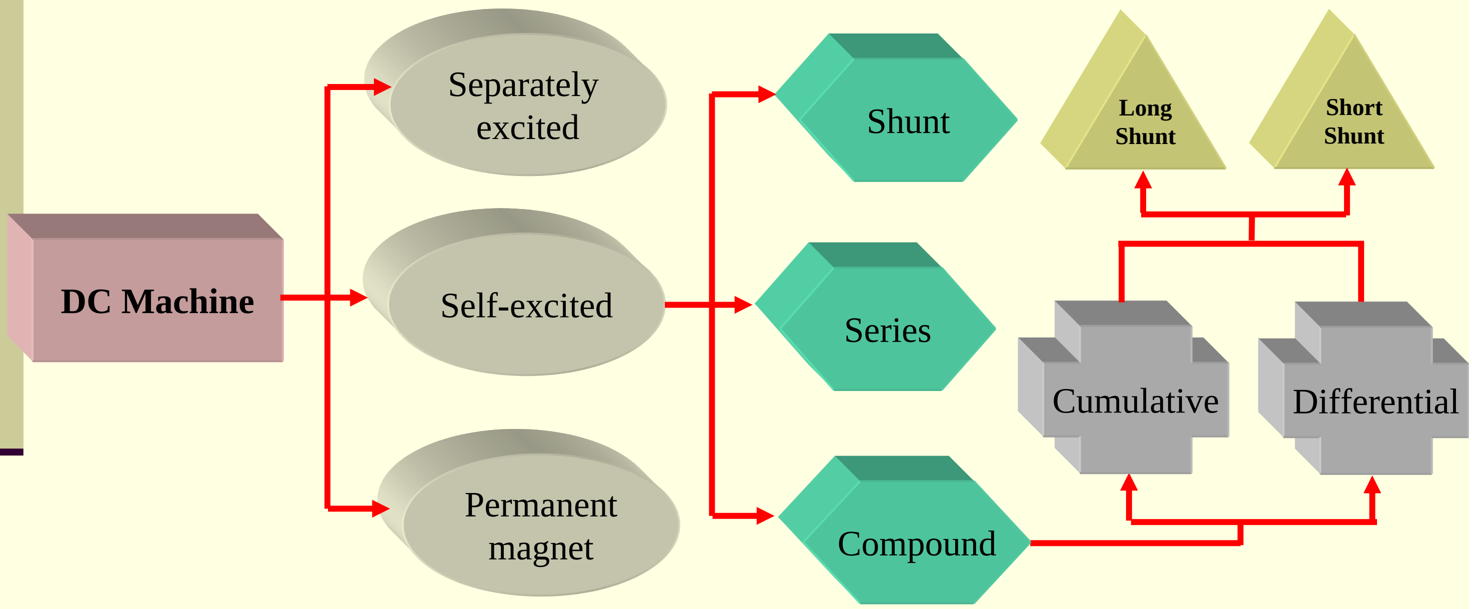
Position of conductor a under S-pole



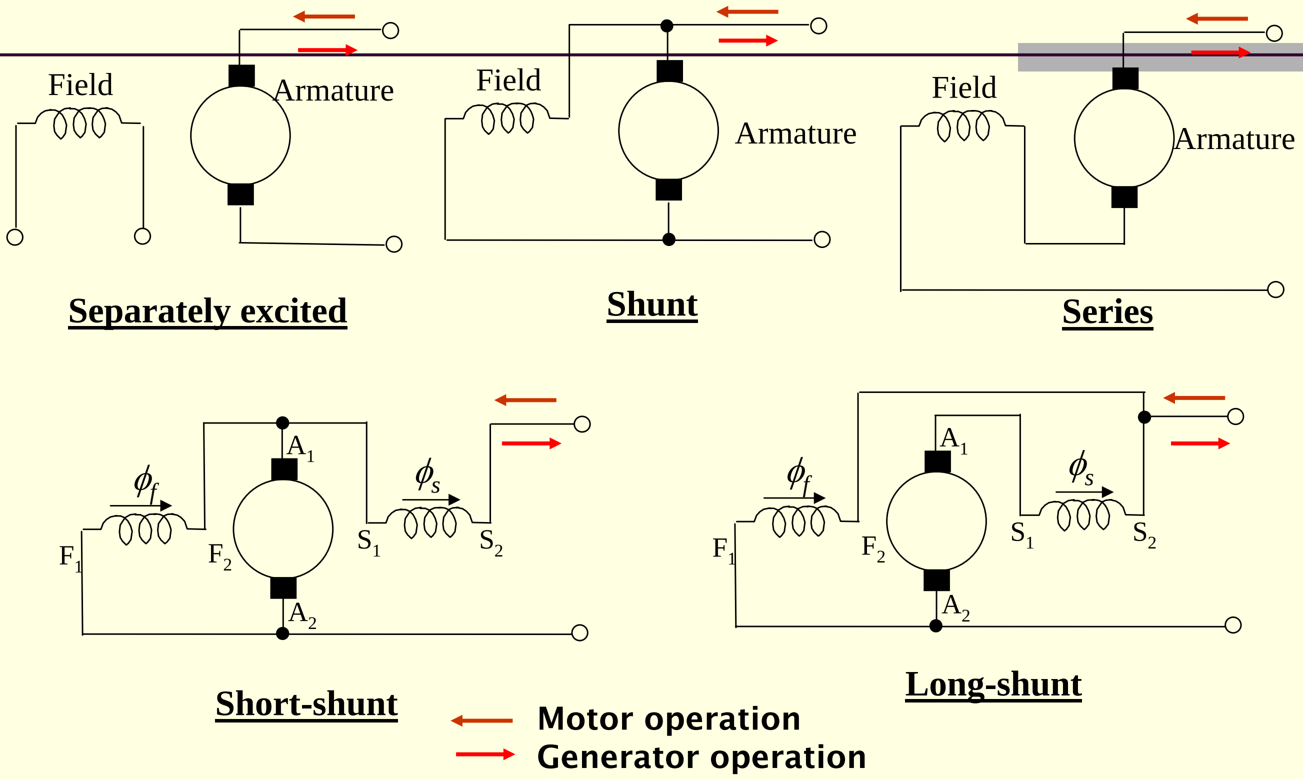
Left-hand rule

With this configuration the torque is unidirectional and independent of conductor position

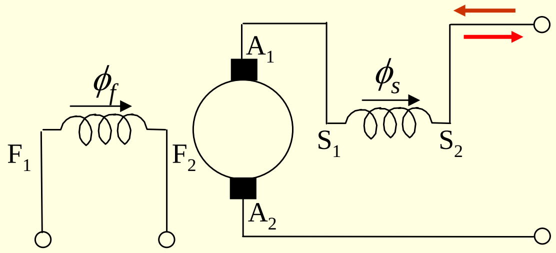
Classification of DC Machine



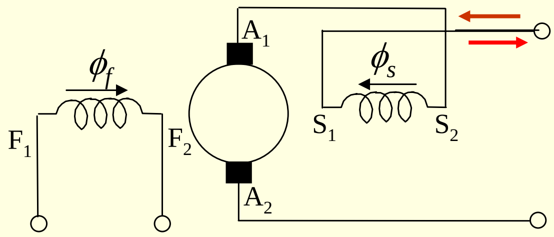
Classification of DC Machine



Classification of DC Machine



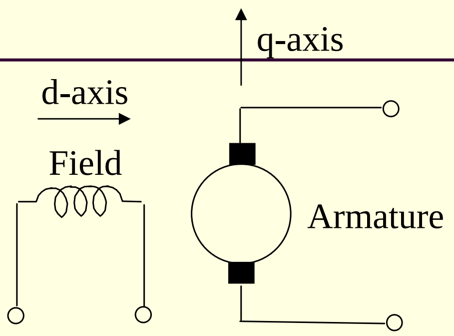
Cumulative compound



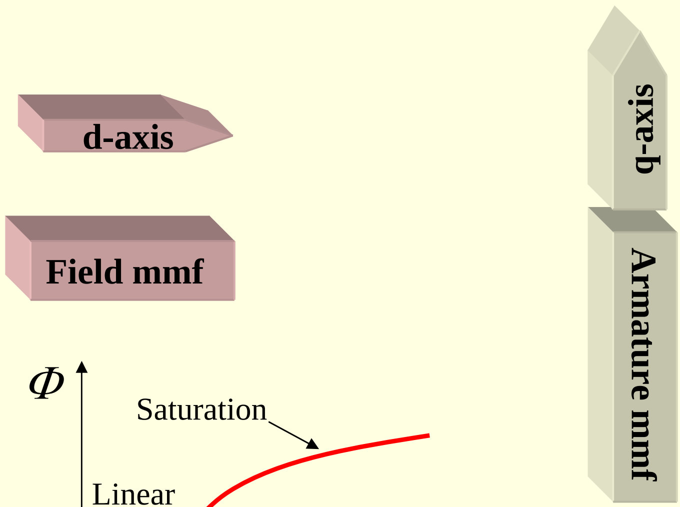
Differential compound

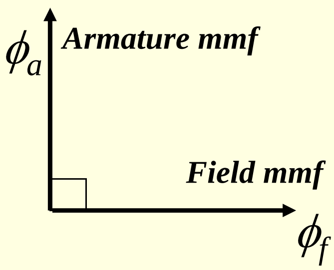
Motor operation
Generator operation

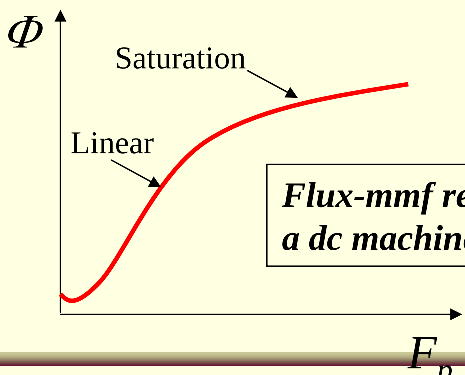
DC Machine Representation



The mmf's produced by the field circuit and the armature circuit are in quadrature.

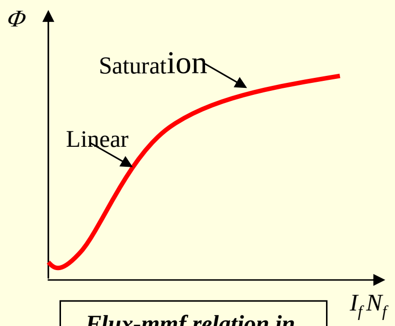




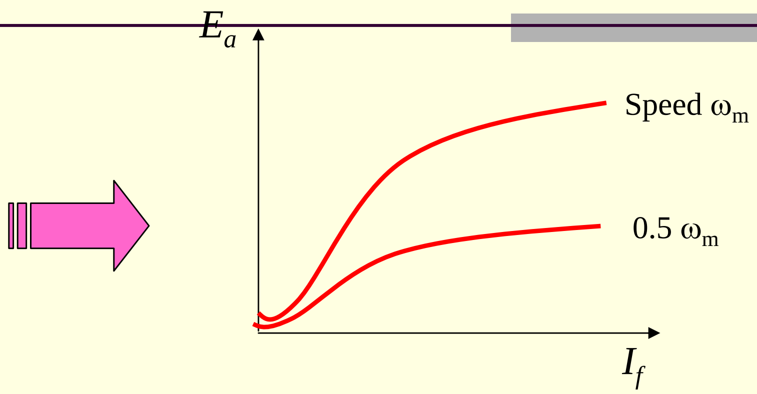


Flux-mmf relation in a dc machine

Magnetization (or Saturation) Curve of a DC Machine



Flux-mmf relation in a dc machine



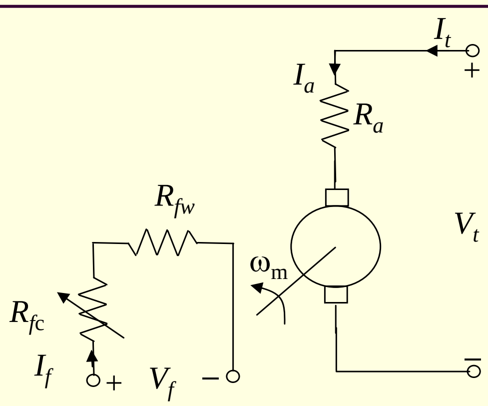
Magnetization curve

The magnetizing curve is obtained experimentally by rotating the the dc machine at a given speed and measuring the open-circuit armature terminal voltage as the current in the field winding is changed.

Magnetization Curve ⟺ **Represents the saturation level in the magnetic system of the dc machine for various values of *excitation mmf* .**

Dc Motors Equations

Separately Excited DC Motor

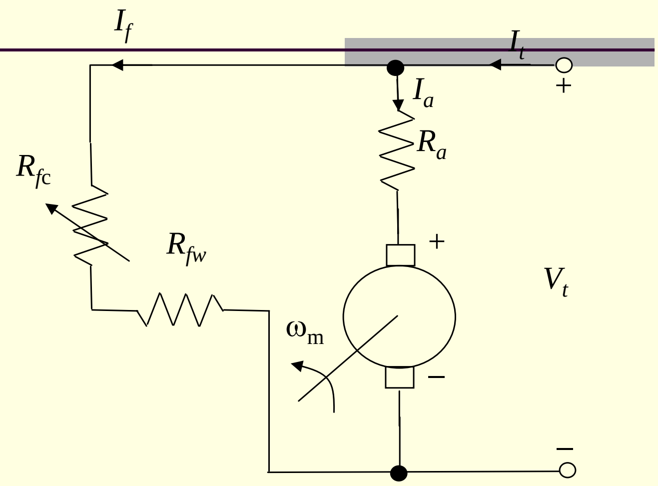


$$V_f = R_f I_f$$
$$E_a = V_t - I_a R_a$$
$$E_a = K_a \Phi \omega_m$$
$$T_e = K_a \Phi I_a$$

- R_{fw}: resistance of field winding.
- R_{fc}: resistance of control rheostat used in field circuit.
- $R_f=R_{fw}+R_{fc}$: total field resistance
- R_a: resistance of armature circuit, including the effect of brushes. Sometimes R_a is shown as the resistance of armature winding alone; the brush-contact voltage drop is considered separately and is usually assumed to be about 2V.

Dc Motors Equations

Shunt or Self-Excited DC Motor



$$V_f = R_f I_f = V_t$$

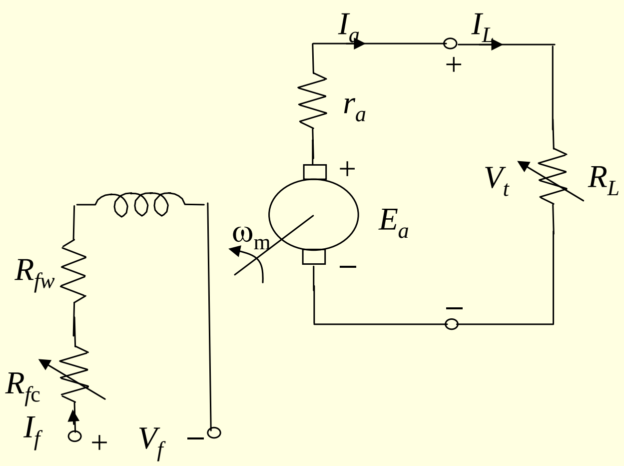
$$E_a = V_t - I_a R_a$$

$$E_a = K_a \Phi \omega_m, \qquad T_e = K_a \Phi I_a$$

$$V_t = I_t R_L, \qquad I_a = I_t - I_f$$

Dc Generator Equations

Separately Excited DC Generator



$$V_f = (R_{fw} + R_{fc}) I_f = R_f I_f$$

$$E_a = V_t + I_a r_a$$

$$E_a = K_a \Phi \omega_m$$

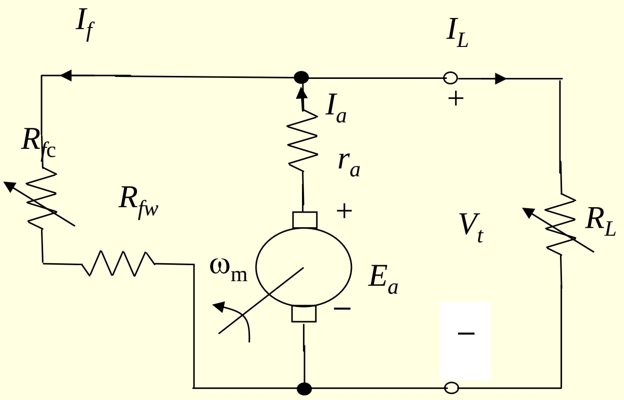
$$V_t = I_L R_L$$

$$I_a = I_L$$

Dc Generator Equations

Self-Excited DC Generators

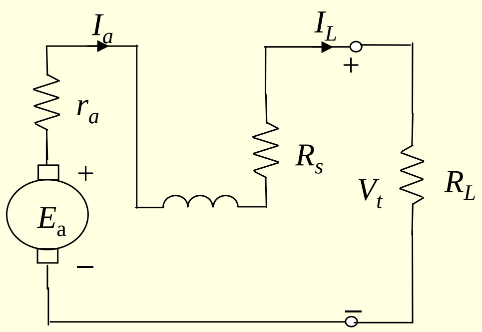
1. Shunt generator



$$V_f = R_f I_f = V_t$$
$$E_a = V_t + I_a r_a$$
$$E_a = K_a \Phi \omega_m$$
$$V_t = I_L R_L$$
$$I_a = I_L + I_f$$

Dc Generator Equations

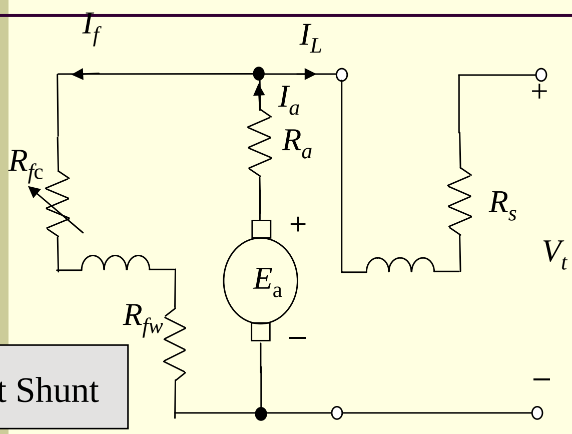
2. Series Generator



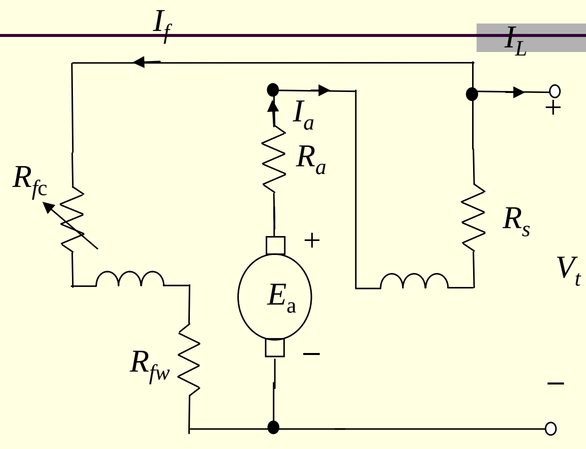
$$V_t = E_a - I_a(r_a + R_s)$$
$$I_L = I_a = I_f$$
$$E_a = K_a \Phi_s \omega_m$$

Dc Generator Equations

3. Compound DC Generator



Short Shunt



Long Shunt

Short Shunt:

$$V_t = E_a - I_a R_a - I_L R_s$$

$$I_L = I_a - I_f$$

$$I_f = \frac{E_a - I_a R_a}{R_{fw} + R_{fc}}$$

$$E_a = K_a(\Phi_{sh} \pm \Phi_s)\omega_m$$

$$E_a = K_a(\Phi_{sh} \pm \Phi_s)\ \omega_m$$

$\boxed{+}$ **Cumulative** $\qquad$ $\boxed{-}$ **Differential**

Long Shunt:

$$V_t = E_a - I_a(R_a + R_s)$$

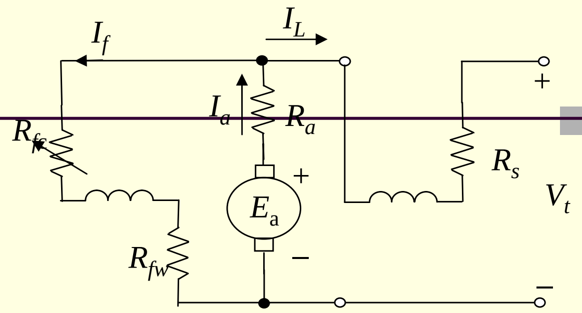
$$I_L = I_a - I_f$$

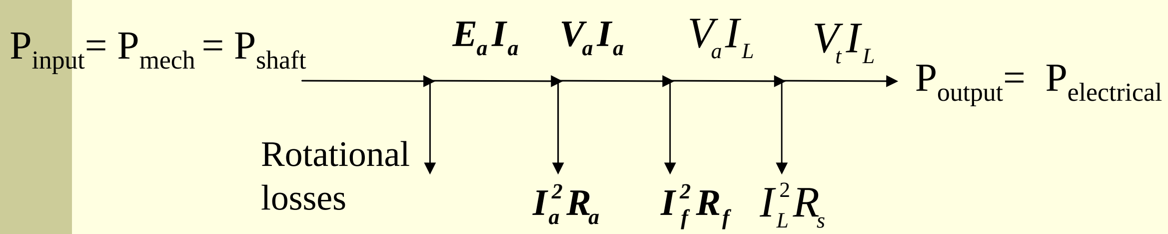
$$I_f = \frac{V_t}{R_{fw} + R_{fc}}$$

$$E_a = K_a(\Phi_{sh} \pm \Phi_s)\omega_m$$

Power Flow and Efficiency

DC Generators





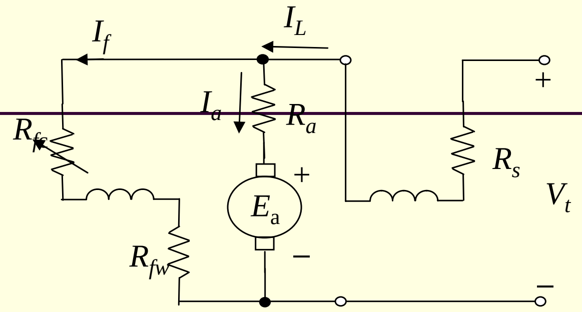
$$\eta = \frac{P_{output}}{P_{input}} = \frac{P_{output}}{P_{output} + Losses}$$

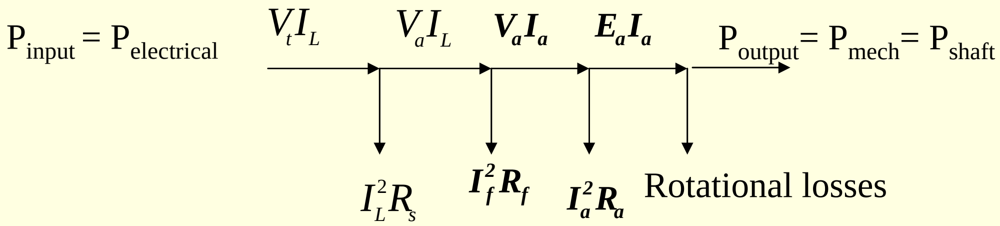
$$\eta = \frac{V_t I_L}{V_t I_L + \sum I^2 R + Rotational\ \ Losses}$$

$$\eta = \frac{V_t I_L}{E_a I_a + Rotational\ \ Losses}$$

Power Flow and Efficiency

DC Motors





$$\eta = \frac{P_{output}}{P_{input}} = \frac{P_{input} - Losses}{P_{input}}$$

$$\eta = \frac{V_t I_L - \sum I^2 R - Rotational \quad Losses}{V_t I_L}$$

$$\eta = \frac{E_a I_a - Rotational \quad Losses}{V_t I_L}$$

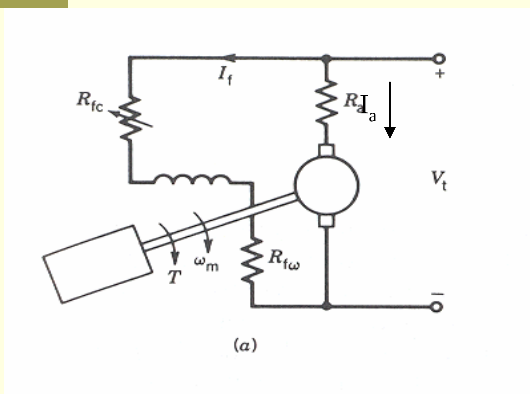
Torque-Speed Characteristics

Separately excited & Shunt motors

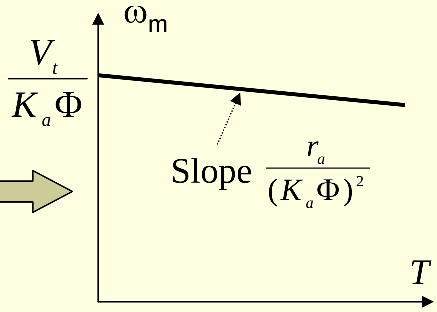
(ϕ is independent of the load torque)

$$\left.\begin{aligned} V_t &= E_a + I_a r_a \\ E_a &= K_a \Phi \ \omega_m \end{aligned}\right\} \quad \omega_m = \frac{V_t - I_a r_a}{K_a \Phi}$$

$$T = K_a \Phi \ I_a$$

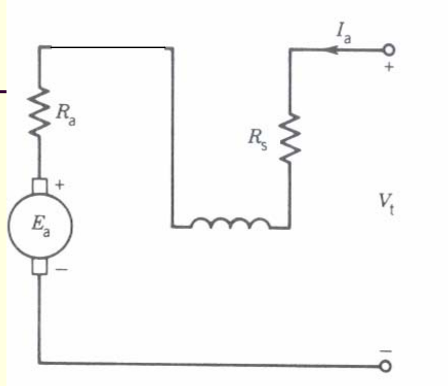


Therefore , $\boxed{\omega_m = \frac{V_t}{K_a \Phi} - \frac{r_a}{(K_a \Phi)^2} T}$



Torque-Speed Characteristics

Series motors



$$E_a = V_t - I_a(R_a + R_s)$$

$$E_a = K_a \phi \, \omega_m$$

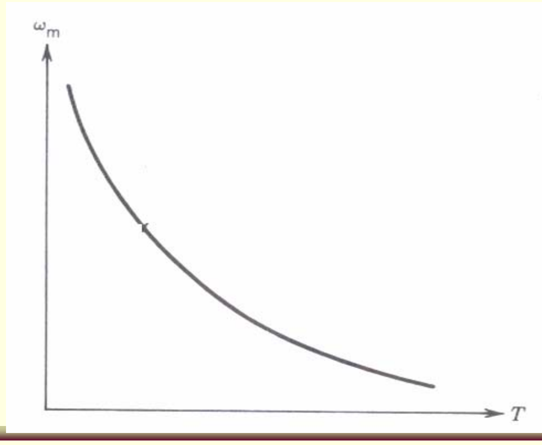
Neglecting saturation $\quad \phi = K_1 I_f = K_1 I_a$

$$E_a = K_a K_1 I_a \omega_m = K_s I_a \omega_m$$

$$\omega_m = \frac{V_t}{K_s I_a} - \frac{R_a + R_s}{K_s}$$

But $\quad T = K_a \phi \, I_a = K_a K_1 I_a^2 = K_s I_a^2$

$$\therefore \omega_m = \frac{V_t}{\sqrt{K_s}\sqrt{T}} - \frac{R_a + R_s}{K_s}$$



Torque-Speed Characteristics

Compound motors

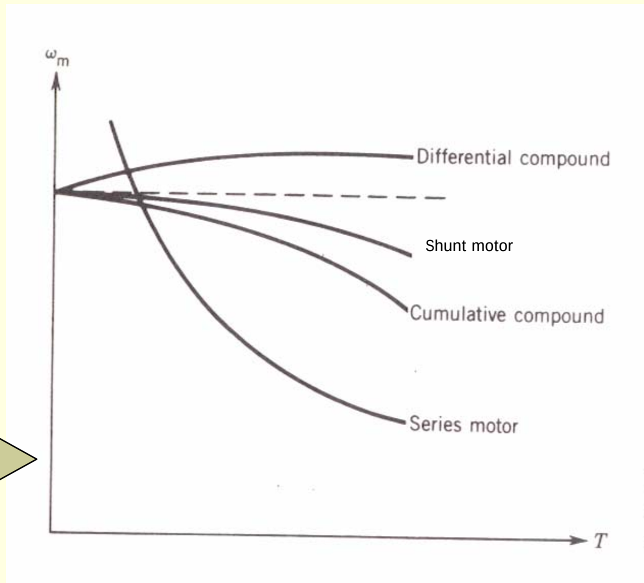
Cumulative Compound

$$AT_t = AT_{shunt} \pm AT_{series}$$

Differential Compound

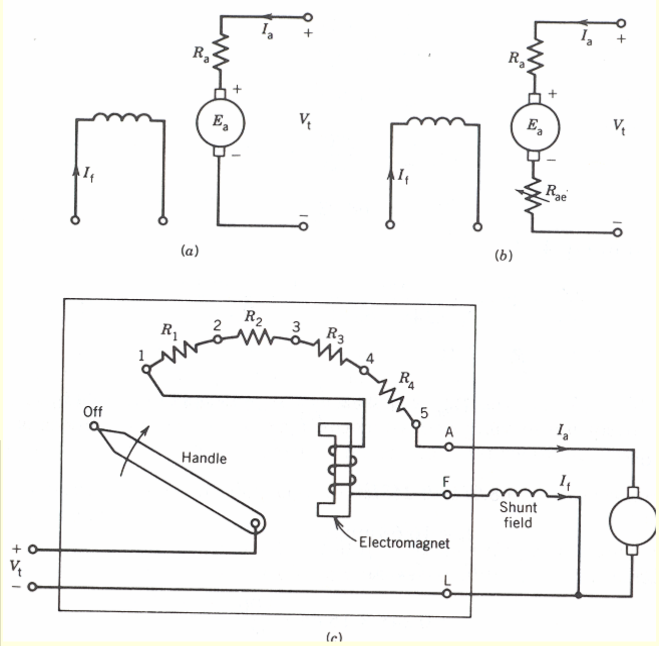
$$\phi_t = \phi_{shunt} \pm \phi_{series}$$

$$\boxed{\omega_m = \frac{V_t}{K_a \phi_t} - \frac{r_a}{(K_a \phi_t)^2} T}$$



Starting of DC Machine

If a d.c. motor is directly connected to a d.c. power supply, the starting current will be dangerously high.



$$I_a = \frac{V_t - E_a}{r_a} \quad \text{at starting} \quad \boldsymbol{\omega = 0 \rightarrow E_a = 0}$$

$$\therefore I_a \Big|_{Starting} = \frac{V_t}{r_a}$$

Since r_a is small, the starting current is very large.

The starting current can be limited by the following methods:

1- Use a variable-voltage supply.

2- Insert an external resistance at start, as shown in the Figure.