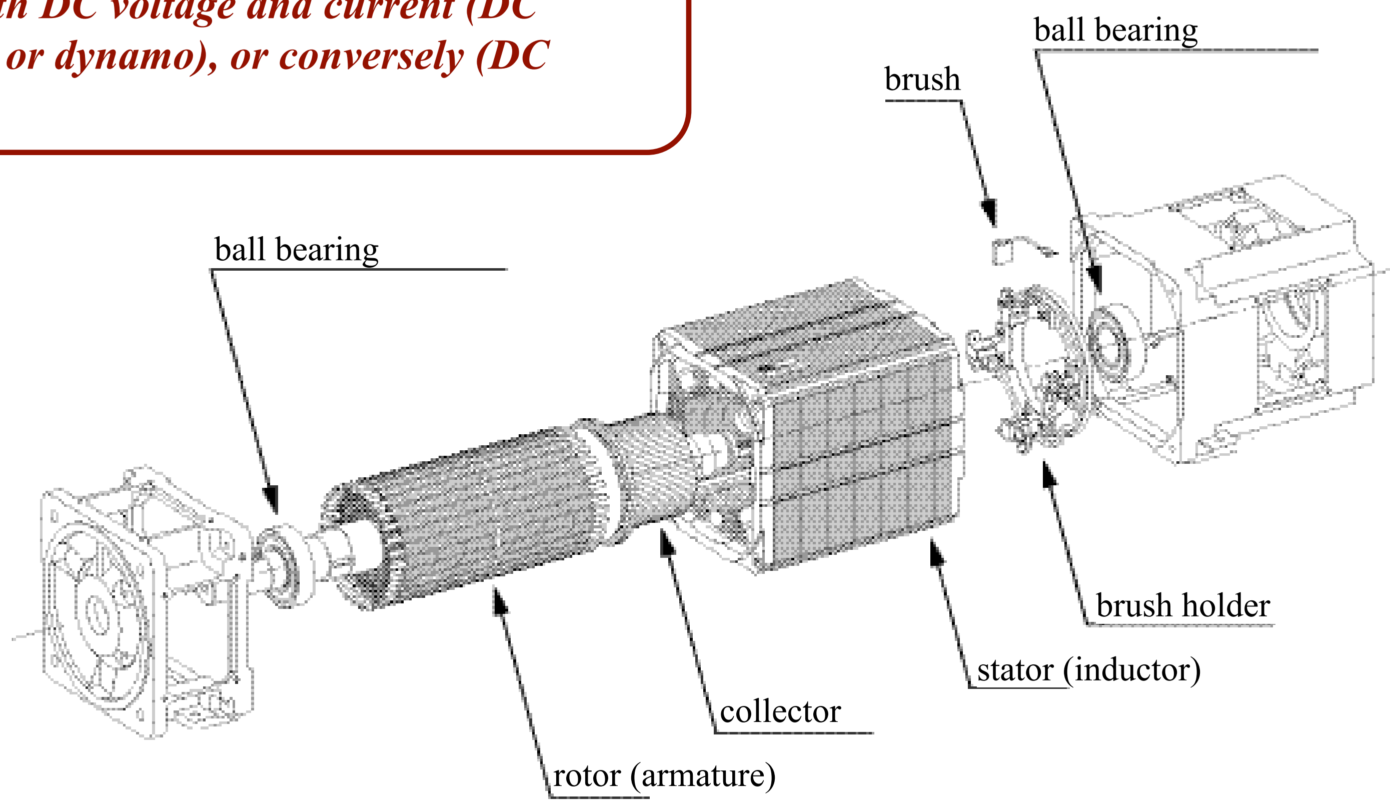
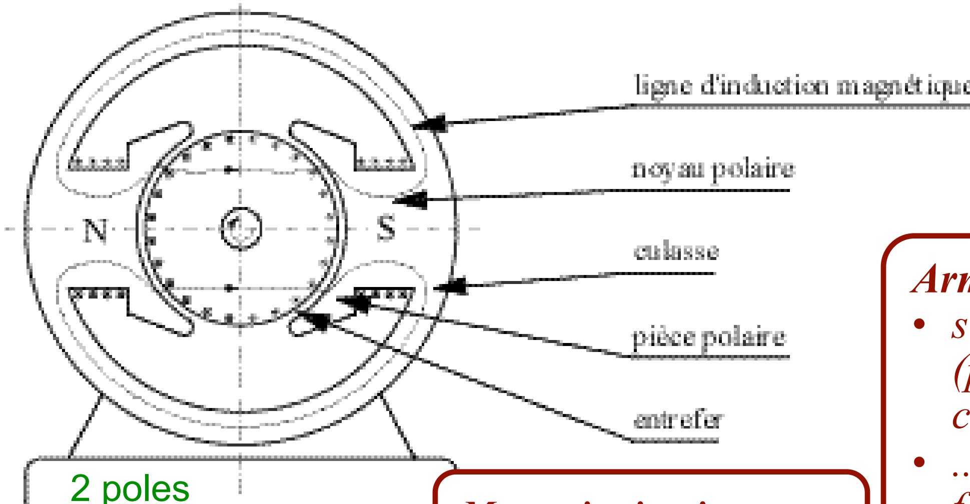
DC machines

Transforms mechanical energy into electric energy with DC voltage and current (DC generator or dynamo), or conversely (DC motor)



DC generators

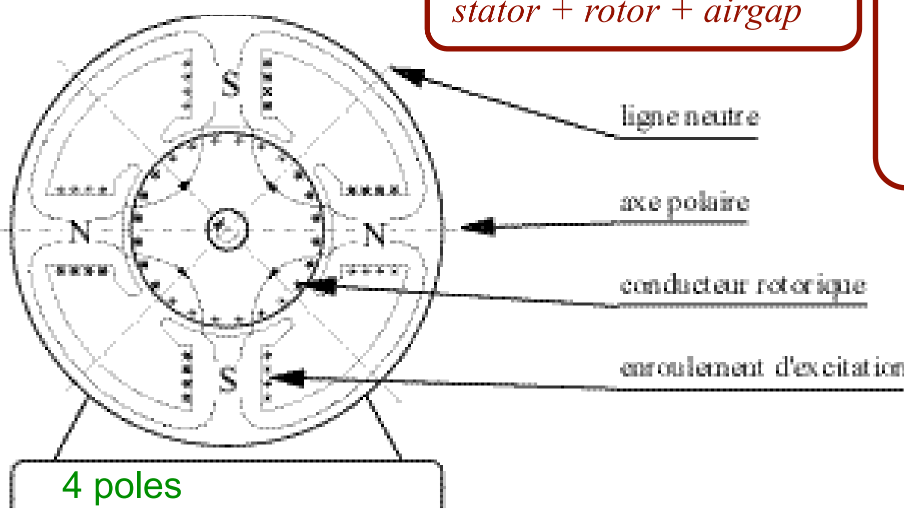


Inductor *or* ***stator****: 2p poles with excitation windings carrying DC current*

Magnetic circuit*:*
stator + rotor + airgap

Armature *or* ***rotor*** *:*

- *stack of thin magnetic sheets (some tenth of a mm) (perpendicular to the machine axis to reduce eddy currents) ...*
- *... supporting conductors in which electromotive forces (e.m.f.s) appear when the armature rotates (*$\mathbf{e} = \mathbf{v} \times \mathbf{b}$*) ...*
- *... these e.m.f.s are time-varying and change sign each time the collector crosses a neutral line (bissector between 2 successive poles)*



Collector*: copper strips isolated from each other, and connected to equidistant points of the armature winding. Fixed brushes slide on the collector and rectify (mechanically) the e.m.f.s*

No-load characteristic

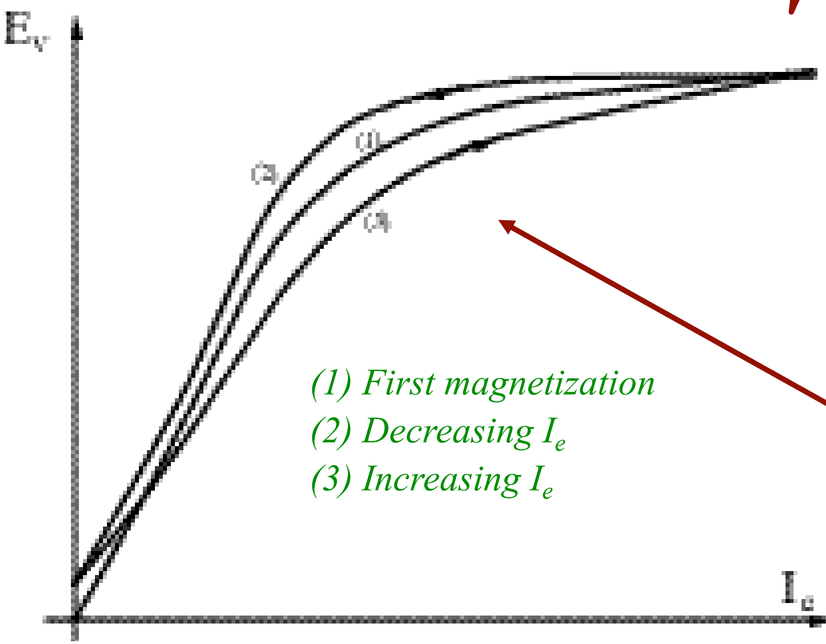
No-load characteristic

Variation of the voltage E_v as a function of the excitation current I_e, at constant speed and with no delivered current

$$E_v = f(I_e) \quad \text{with} \quad \begin{cases} \text{speed } \dot{\theta} = \text{constant} \\ I_a = 0 \end{cases}$$

$$E_v = k_E \, \dot{\theta} \, \Phi_v(I_e)$$

Magnetic flux produced by the inductor and seen by the armature winding



(1) First magnetization
(2) Decreasing I_e
(3) Increasing I_e

Nonlinear with hysteresis

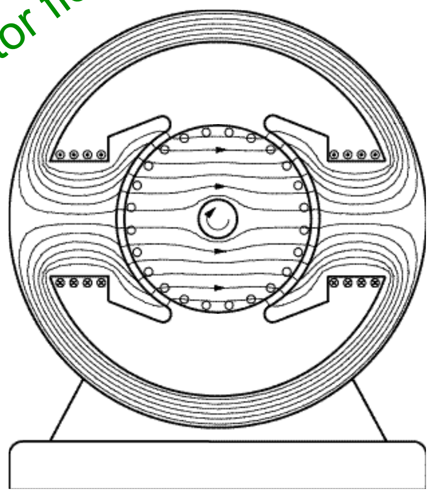
Armature reaction

Armature reaction (magnetic)

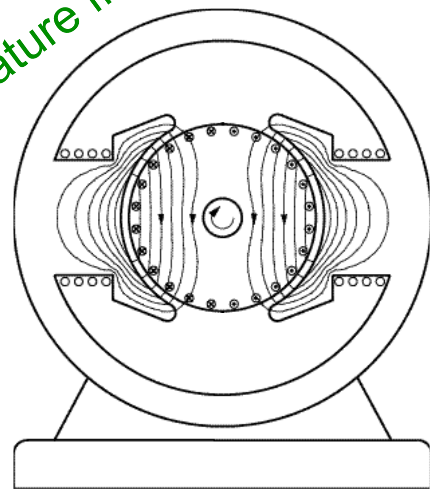
Magnetic phenomena due to the currents in the armature

1. Neutral line shifted (rotated) in the rotation direction
⇒ decrease of the e.m.f.

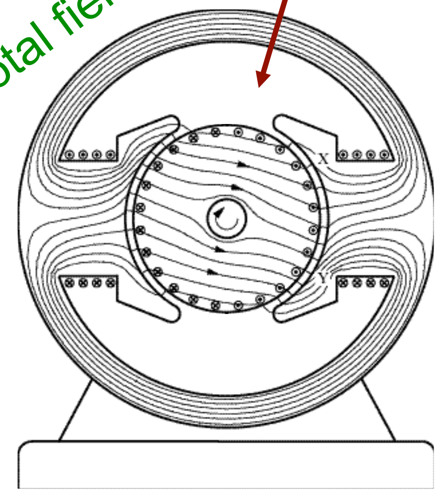
Inductor field



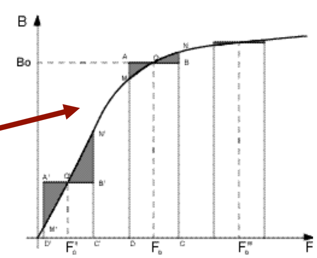
\+ armature field



= Total field



2. Local magnetic field reduction (entry part) and increase (exit part) not compensated due to nonlinearity
⇒ flux and e.m.f. reduction (+ incr. p_{mag})



⇒ $E = E_v - \psi(I_a)$

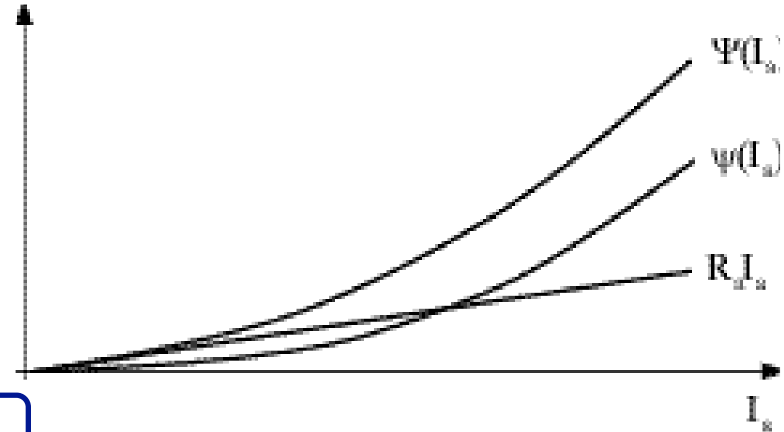
1. and 2. *e.m.f. with load* *armature reaction*

$$\psi(I_a) = k_E\, \dot{\theta}\, \Delta\Phi(I_a)$$

Armature reaction

Total armature reaction

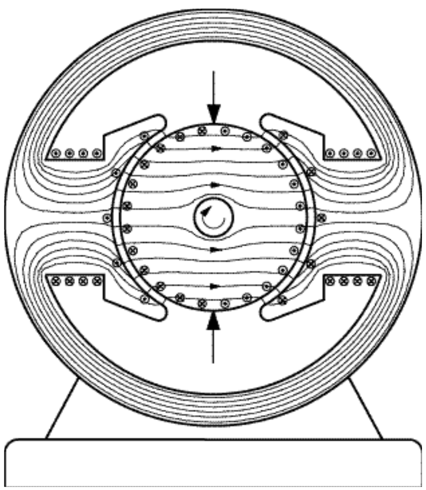
$$\Psi(I_a) = \psi(I_a) + R_a I_a$$



Compensating winding

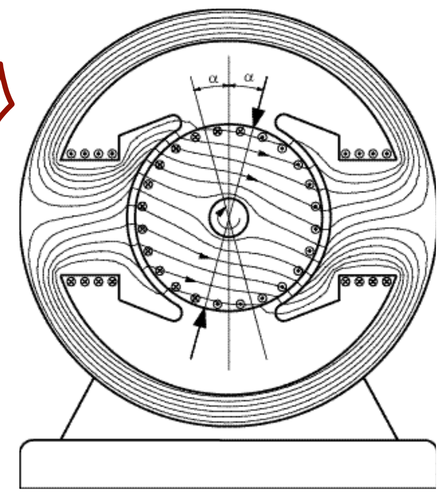
Reduction of the armature reaction

Shift of the brushes w.r.t. neutral axis



disadvantages:

- *for a single value of I_a*
- *shift direction depends on rotation direction*
- *shift direction depends on operating mode (generator or motor)*



Exterior characteristics

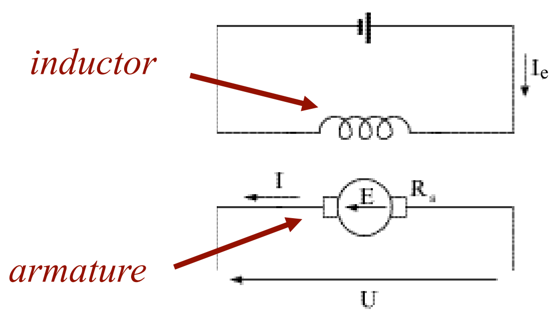
Exterior characteristic of a generator

Variation of delivered voltage U in terms of the delivered current I, at constant speed and excitation circuit

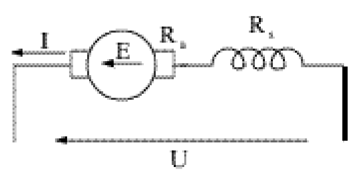
$$U = f(I) \quad \text{with} \quad \begin{cases} \text{speed } \dot{\theta} = \text{ constant} \\ \text{fixed excitation circuit} \end{cases}$$

Excitation type...

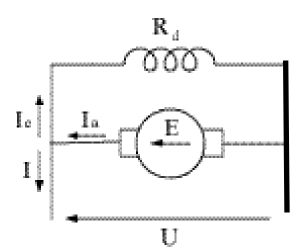
independent



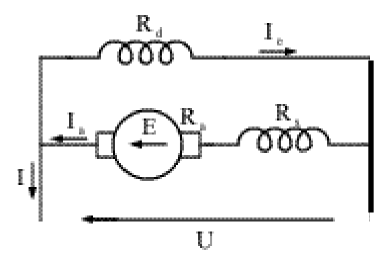
series



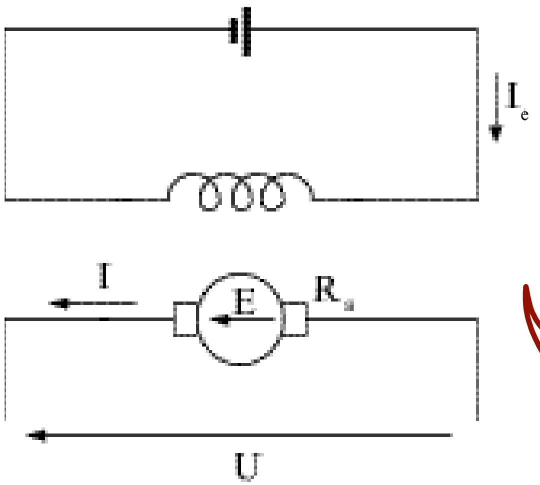
shunt



compound



Independent excitation generator

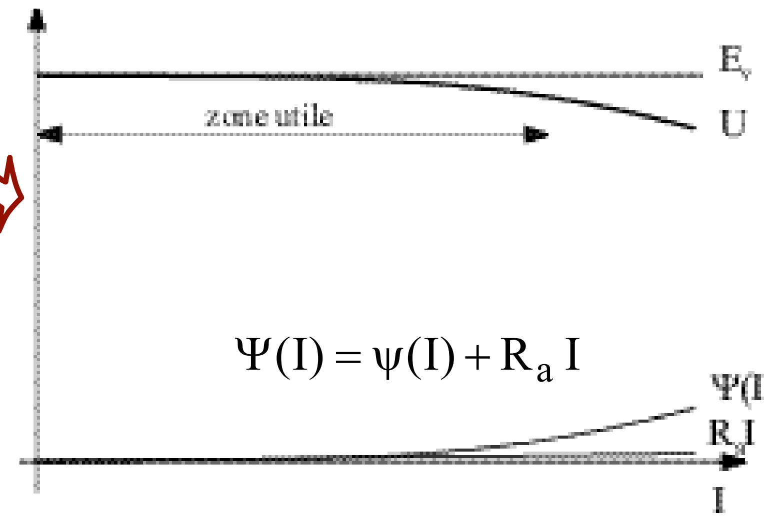


$$I = I_a$$

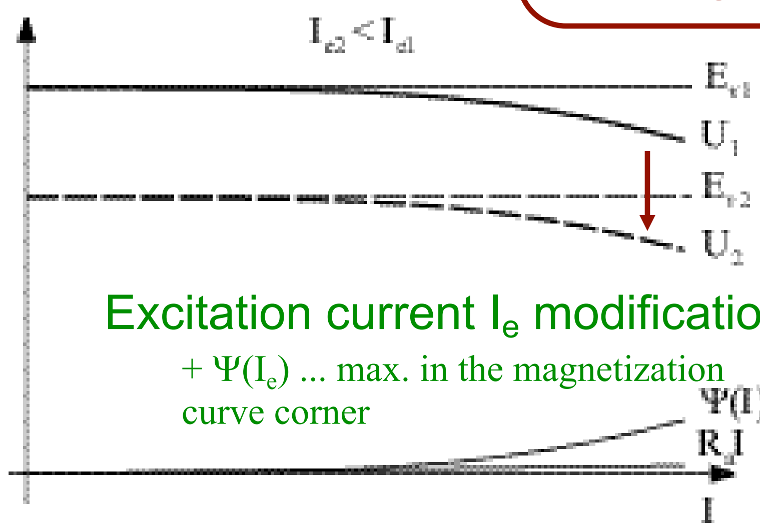
$$U = E_v(I_e) - \psi(I) - R_a\, I$$

$R_a \approx 0.1\ \Omega$ (110V/50A machine)
Compensated armature reaction

Delivered voltage quasi independent of delivered current
→ Voltage source

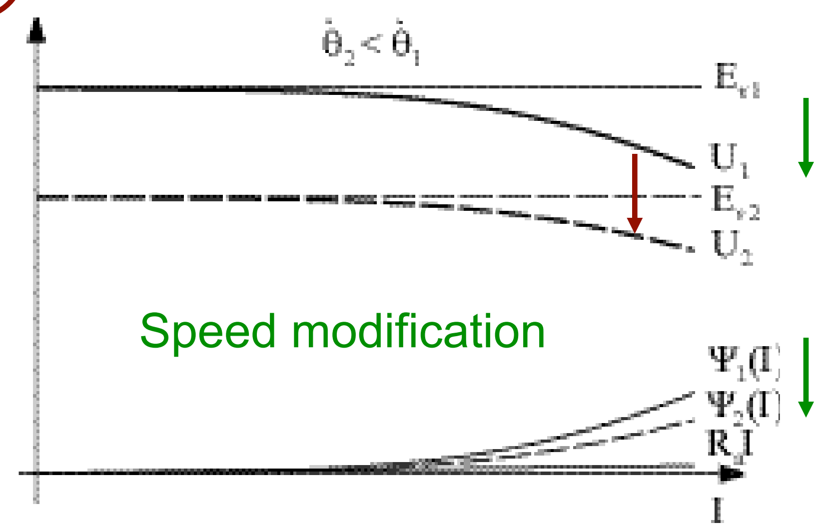


$$\Psi(I) = \psi(I) + R_a\, I$$



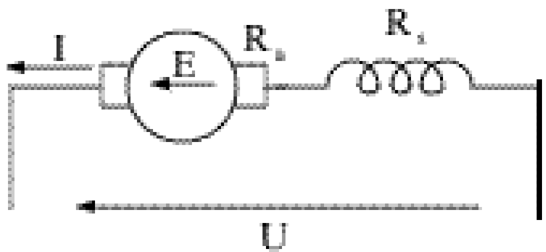
Excitation current I_e modification

+ $\Psi(I_e)$ ... max. in the magnetization curve corner



Speed modification

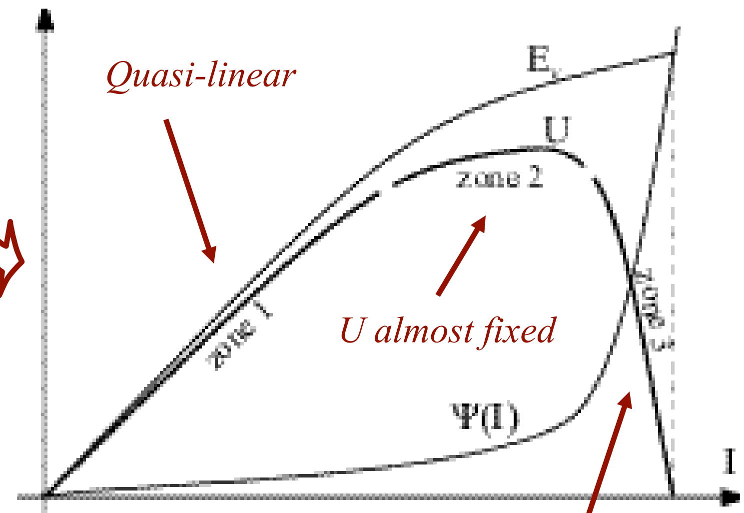
Series excitation generator



$$I = I_a = I_e$$
$$U = E_v(I) - \psi(I) - (R_a + R_s)I$$

$R_s \ll$ since $I_e = I$ is high
coherent: section >, n_s <

$$\Psi(I) = \psi(I) + (R_a + R_s)I$$

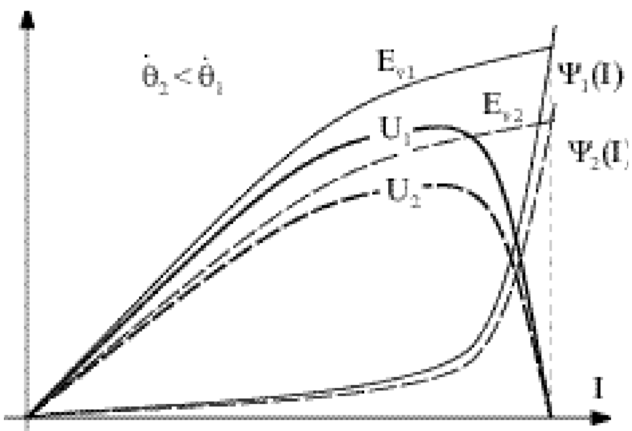


I almost constant

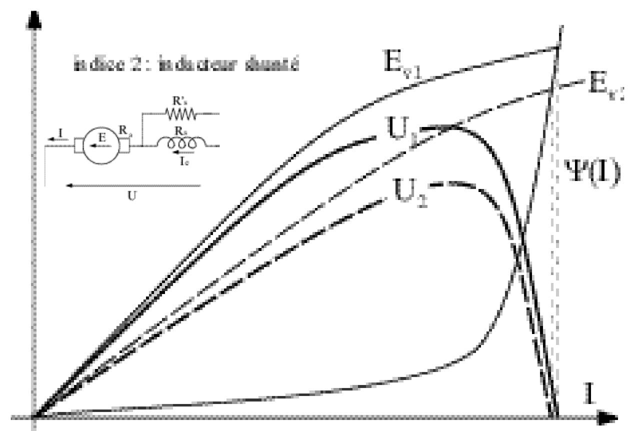
useful zone

Current source

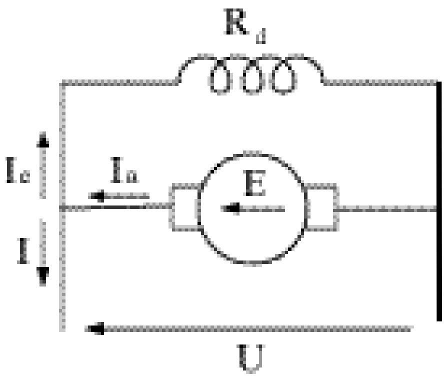
Speed modification



Inductor shunting



Shunt excitation generator



$$I = I_a - I_e$$
$$U = E_v(I_e) - \psi(I_a) - R_a I_a$$
$$U = R_d I_e$$

$$\Psi(I_a) = \psi(I_a) + R_a I$$

R_d >> to reduce Joule losses

$I_e < \;\Rightarrow\; n_s >$

Picou construction

$E_v(I_e)$ & $\Psi(I_a)$ known

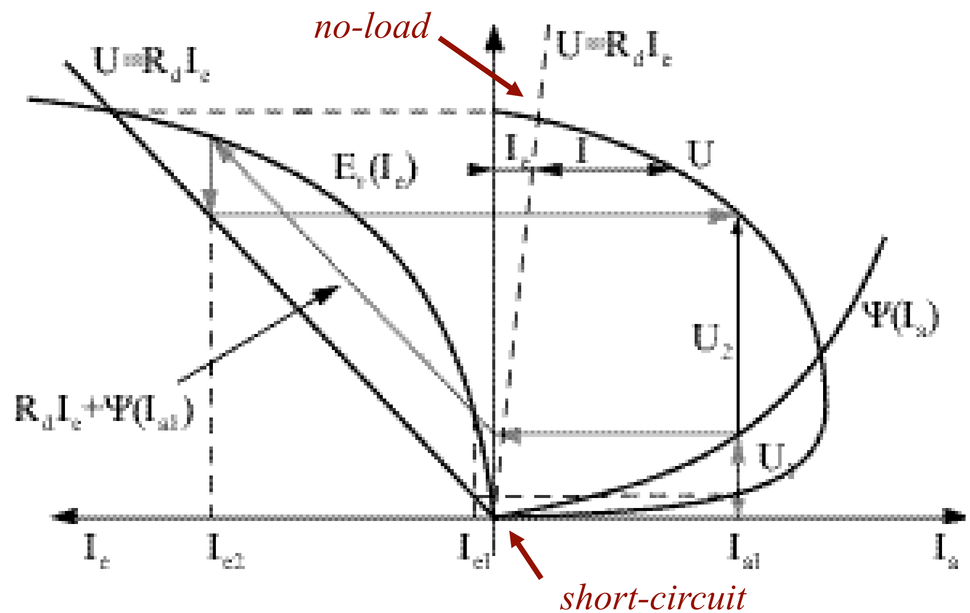
$R_d I_e = U(I_e)$

For I_{a1} (point by point procedure)

$\rightarrow \Psi(I_a) \rightarrow \Psi(I_a) + R_d I_e \equiv E_{v1}$ & E_{v2}

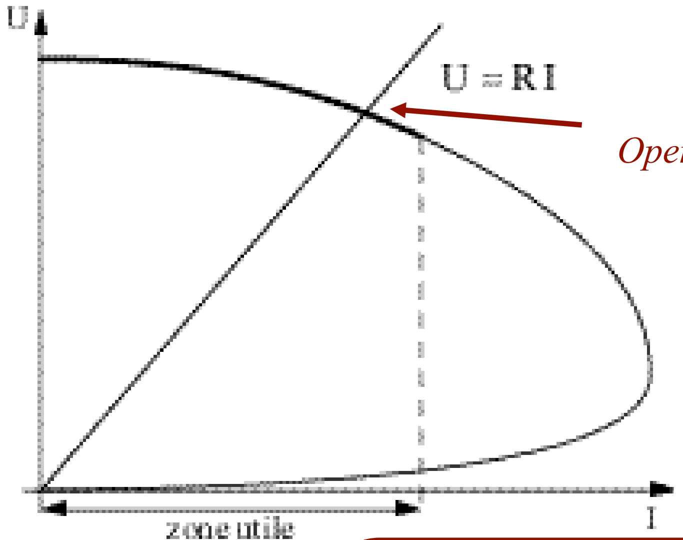
$\rightarrow I_{e1}$ & $I_{e2} \rightarrow U_1$ & U_2

$$I = I_a - I_e = I_a - \frac{U}{R_d}$$



Shunt excitation generator

Exterior characteristic



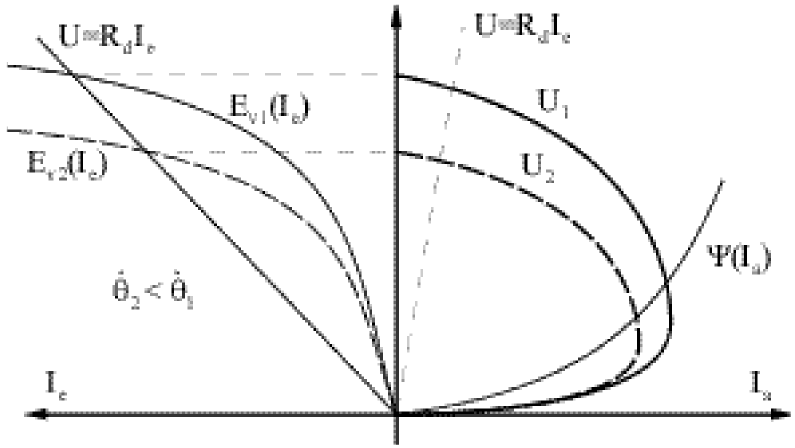
Operating point of the generator driving a resitance R

Delivered voltage almost independent of the delivered current
→ Voltage source

... the voltage varies however more than for the generator with independent excitation

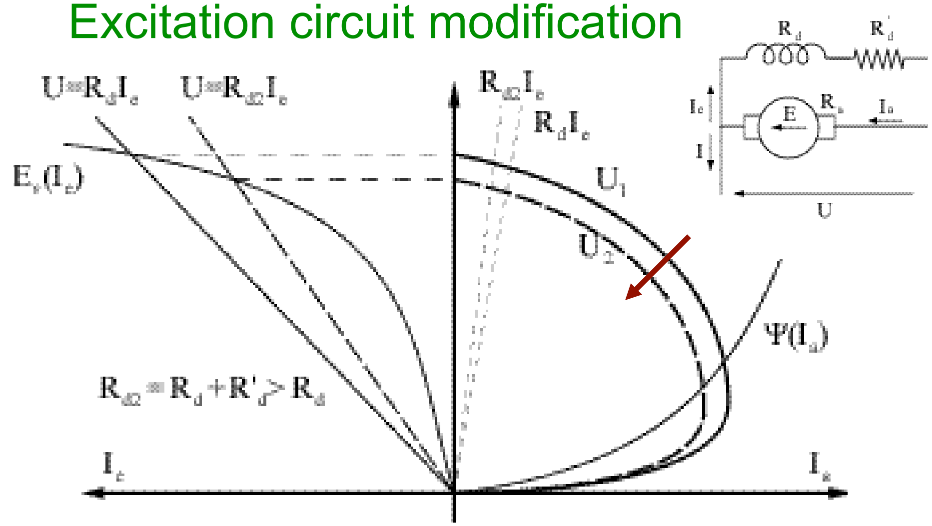
Shunt excitation generator

Speed modification



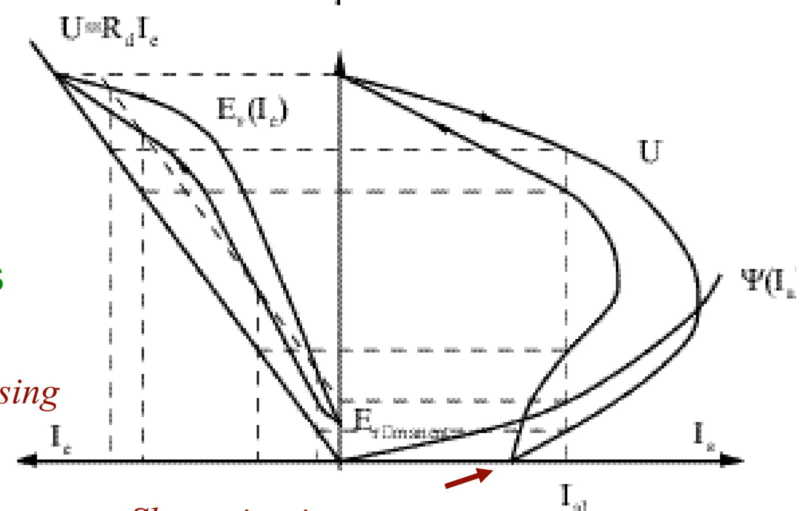
If the speed is too low of if R_d is too large
→ no operating point

Excitation circuit modification



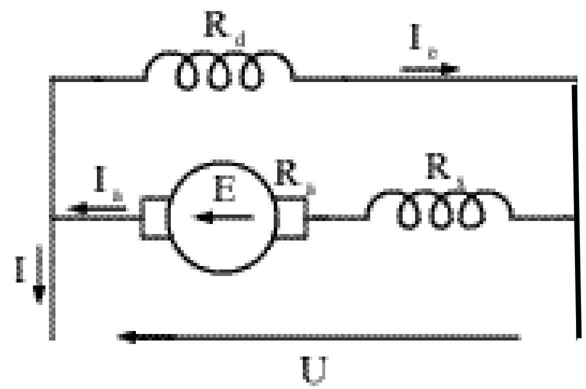
Effect of hysteresis

2 branches :
I_e increasing and decreasing



Short-circuit current

Compound excitation generator

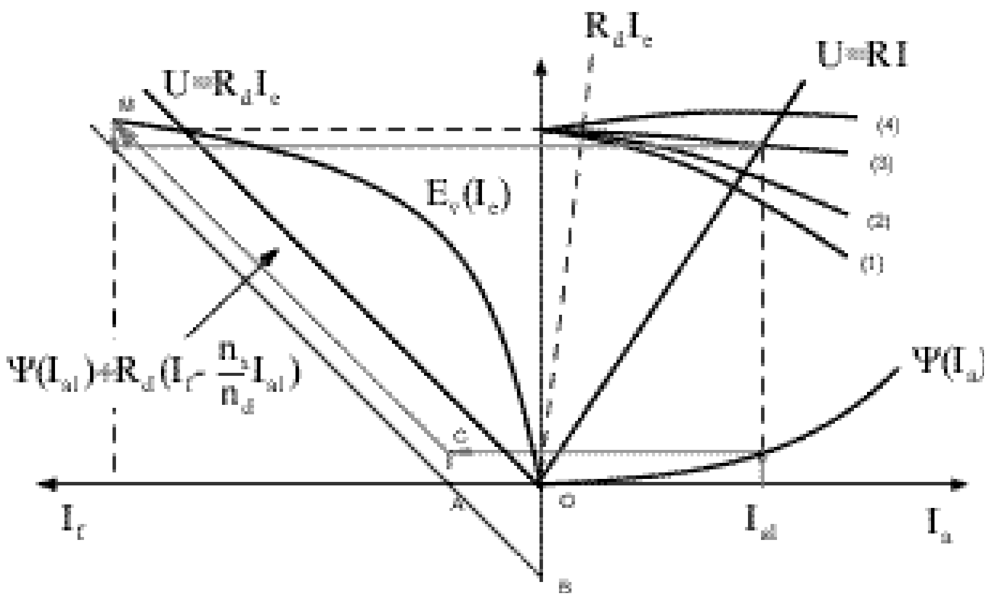


Mixed excitation: *shunt inductor and series inductor wound on the same poles*

$$\text{m.m.f.} = n_d I_e \pm n_s I_a = n_d \left(I_e \pm \frac{n_s}{n_d} I_a \right) = n_d I_f$$

$$U = E_v(I_f) - \Psi(I_a)$$

$$U = R_d I_e = R_d \left(I_f \mp \frac{n_s}{n_d} I_a \right)$$



(4) hypercompound (n_s >>)

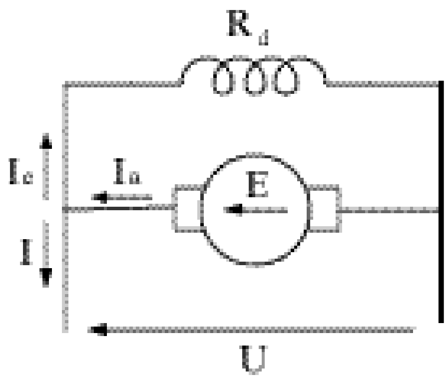
(3) concordant compound (same direction m.m.f.)

(2) shunt dynamo

(1) antagonist compound (opposite m.m.f.)

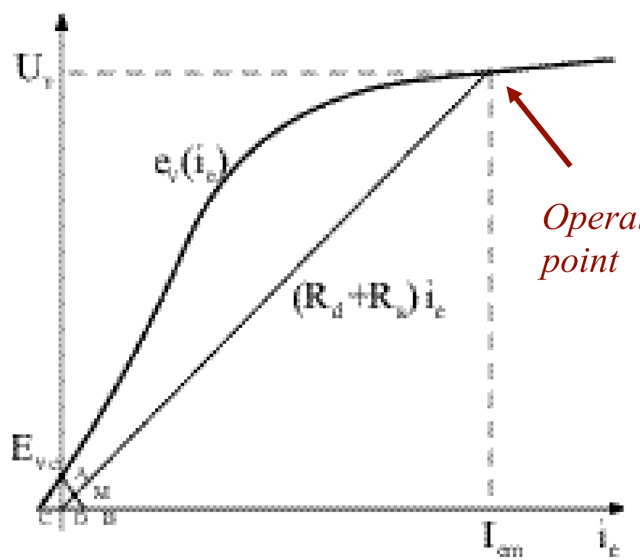
$$E_v(I_f) = \Psi(I_a) + R_d \left(I_f \mp \frac{n_s}{n_d} I_a \right)$$

Self-starting generator

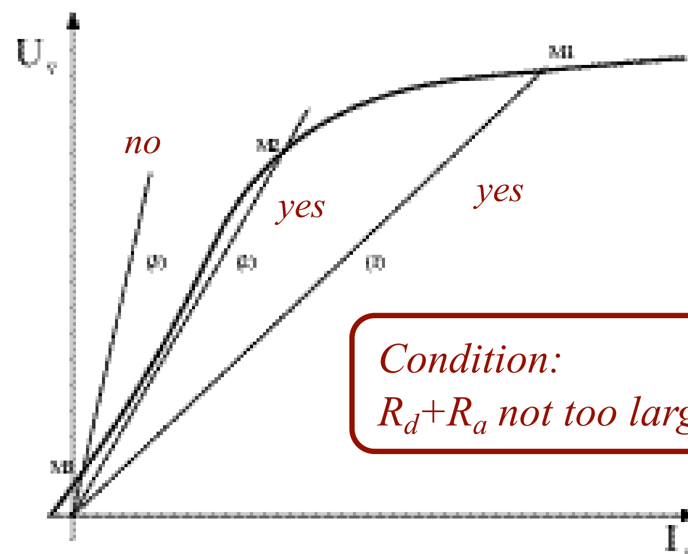


Example: shunt generator

Self-starting is possible thanks to the remanent magnetization of the inductor



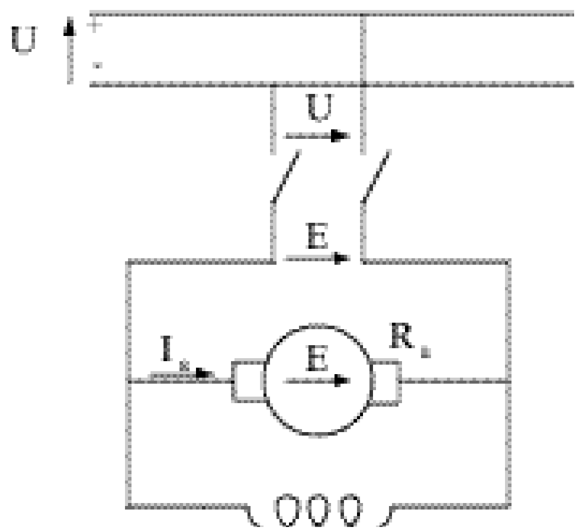
Operating point



Condition:
R_d+R_a not too large!

DC network connection

Conditions :
E ≈ U
E and U in opposition

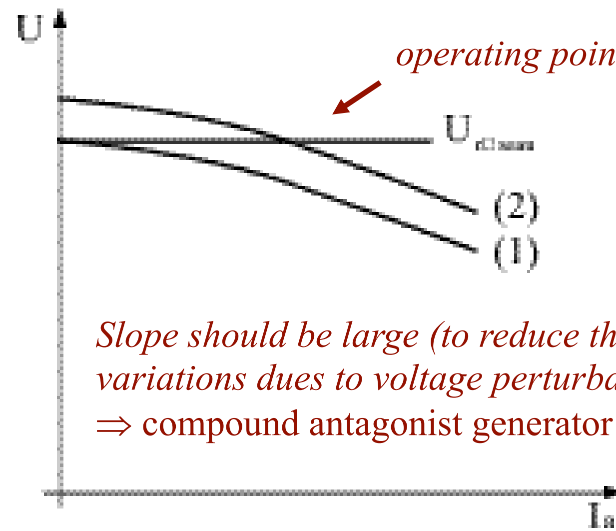


After connexion (1) :

$$I_a = \frac{E(I_e, I_a) - U}{R_a}$$

If E <<, I_a >> !

Then, increase E (2) ⇒ the generator produces energy



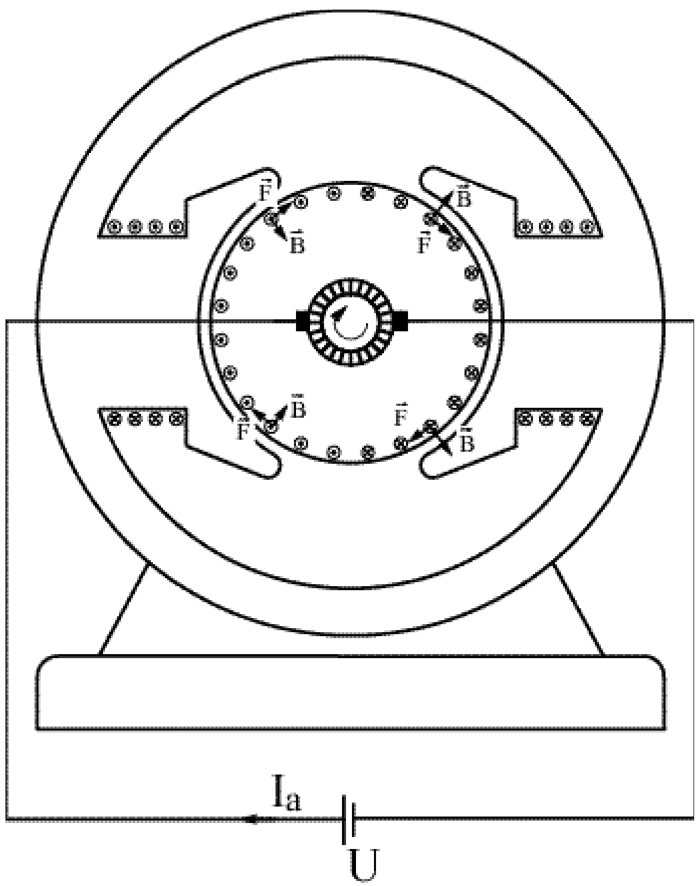
operating point

Slope should be large (to reduce the current variations dues to voltage perturbations)
⇒ compound antagonist generator OK

If E decreases
⇒ the generator receives energy (motor for shunt and compound machines!)

DC motors

Main principle



Excitation current I_e and armature current I_a

The armature conductors are subjected to the magnetic flux density created by the inductor

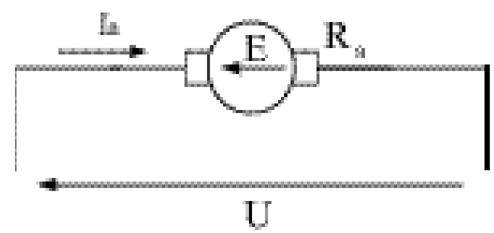
… hence to the Laplace force $\mathbf{f} = \mathbf{j} \times \mathbf{b}$

… hence to a torque that tends to make the armature rotate

Electromotive force (e.m.f.)

… in the armature conductors as soon as they rotate, opposed to the current

Total e.m.f. (E) on brushes is equal to the integral of the electromotive field along the armature conductors



$$U = E + R_a\ I_a$$

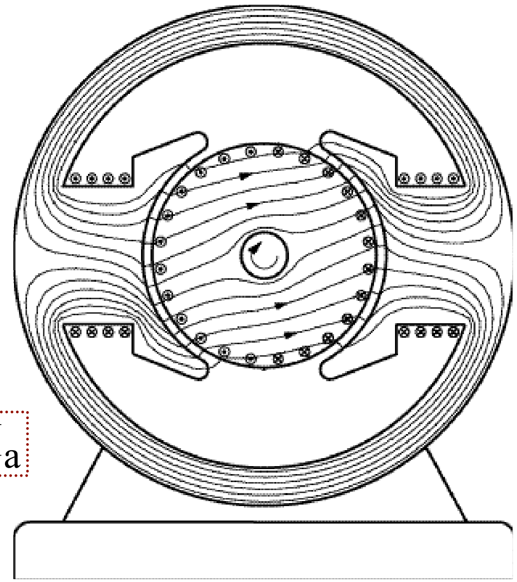
Armature reaction

$$E = E_v - \psi(I_a)$$

e.m.f. with load

armature reaction

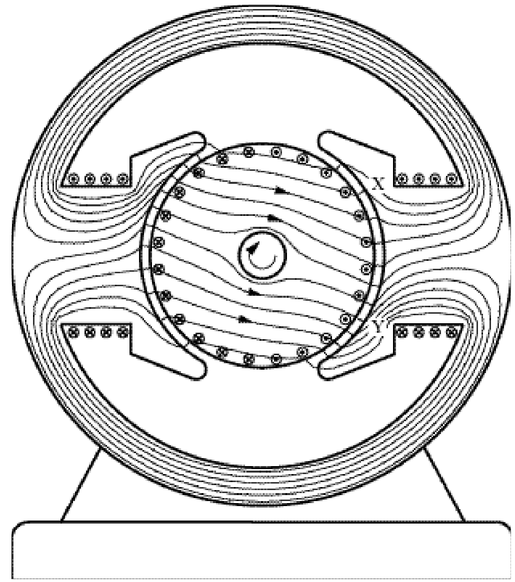
$$\psi(I_a) = k_E\, \dot{\theta}\, \Delta\Phi(I_a)$$



$$U = E + R_a\, I_a$$

DC motor

$$\Psi(I_a) = \psi(I_a) - R_a\, I_a$$



$$U = E - R_a\, I_a$$

DC generator

$$\Psi(I_a) = \psi(I_a) + R_a\, I_a$$

Total armature reaction

Motor torque

$$U = E + R_a\, I_a = E_v - \psi(I_a) + R_a\, I_a$$

$\times I_a$

$$U\, I_a = E\, I_a + R_a\, I_a^2 = \left(E_v - \psi(I_a)\right) I_a + R_a\, I_a^2$$

Electric power provided to the armature

Electromagnetic power

Joule losses in the armature

Electromagnetic torque

$$C = \frac{P_{elm}}{\dot{\theta}} = \frac{E\, I_a}{\dot{\theta}}$$

$$C = k_E\, \Phi(I_e, I_a)\, I_a = k_E \left[\Phi_v(I_e) - \Delta\Phi(I_a)\right] I_a$$

Mechanical characteristics

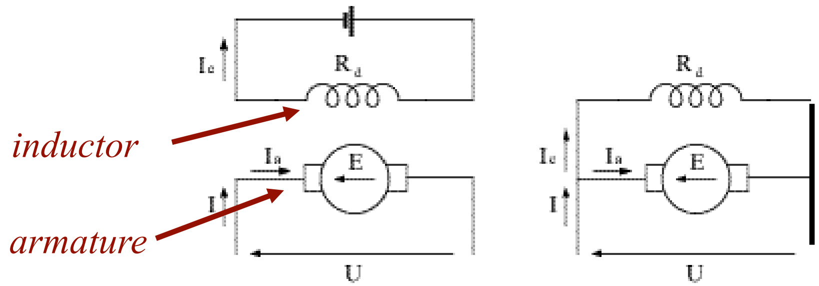
Machanical characteristic of a motor

Motor speed in terms of the electromagnetic torque, with fixed voltage and excitation circuit

$$\dot{\theta} = f(C) \quad \text{with} \quad \begin{cases} U = \text{ constant} \\ \text{fixed excitation circuit} \end{cases}$$

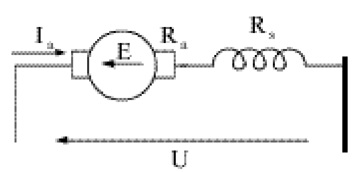
Excitation type... !

independent or shunt

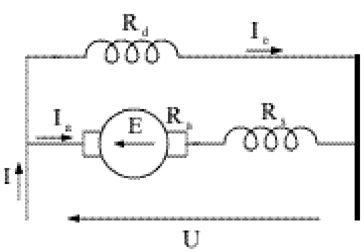


(a) (b)

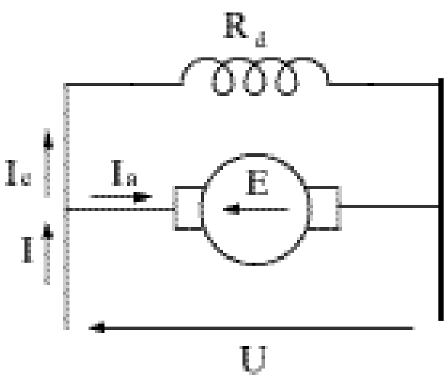
series



compound



Shunt excitation motor

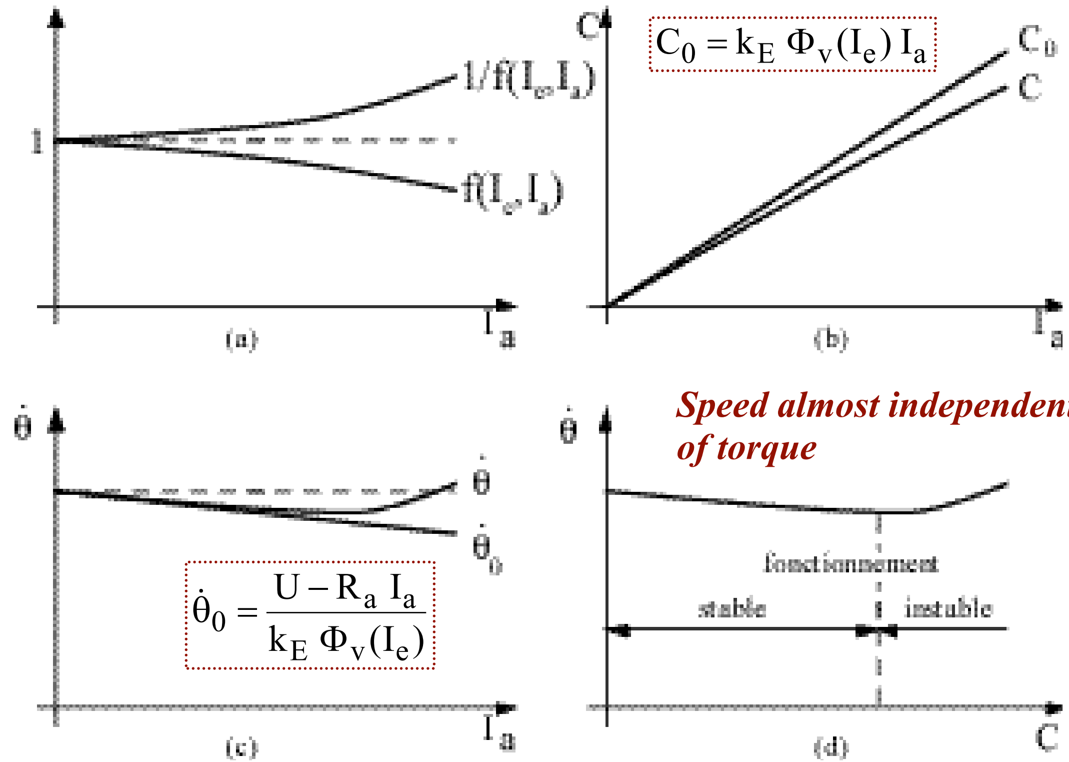


$$C = k_E\,[\Phi_v(I_e) - \Delta\Phi(I_a)]\,I_a$$
$$= C_0\, f(I_e, I_a)$$

with (I$_e$ constant)

$$f(I_e, I_a) = \frac{\Phi_v(I_e) - \Delta\Phi(I_a)}{\Phi_v(I_e)} \le 1$$

C_0 = torque produced by the motor
if there was no armature reaction

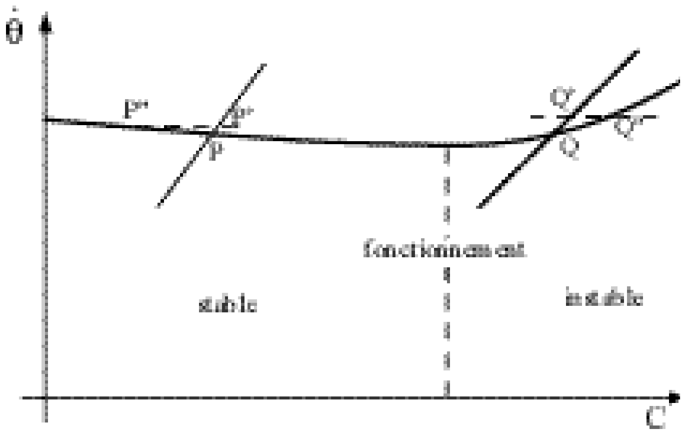


$$U = E + R_a I_a = k_E\,\dot\theta\,[\Phi_v(I_e) - \Delta\Phi(I_a)] + R_a I_a$$

$$\dot\theta = \frac{U - R_a I_a}{k_E\,[\Phi_v(I_e) - \Delta\Phi(I_a)]} = \dot\theta_0\,\frac{1}{f(I_e, I_a)}$$

Shunt excitation motor

Stable and unstable zones

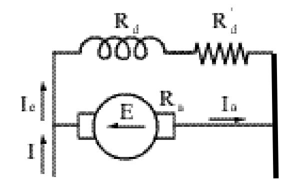


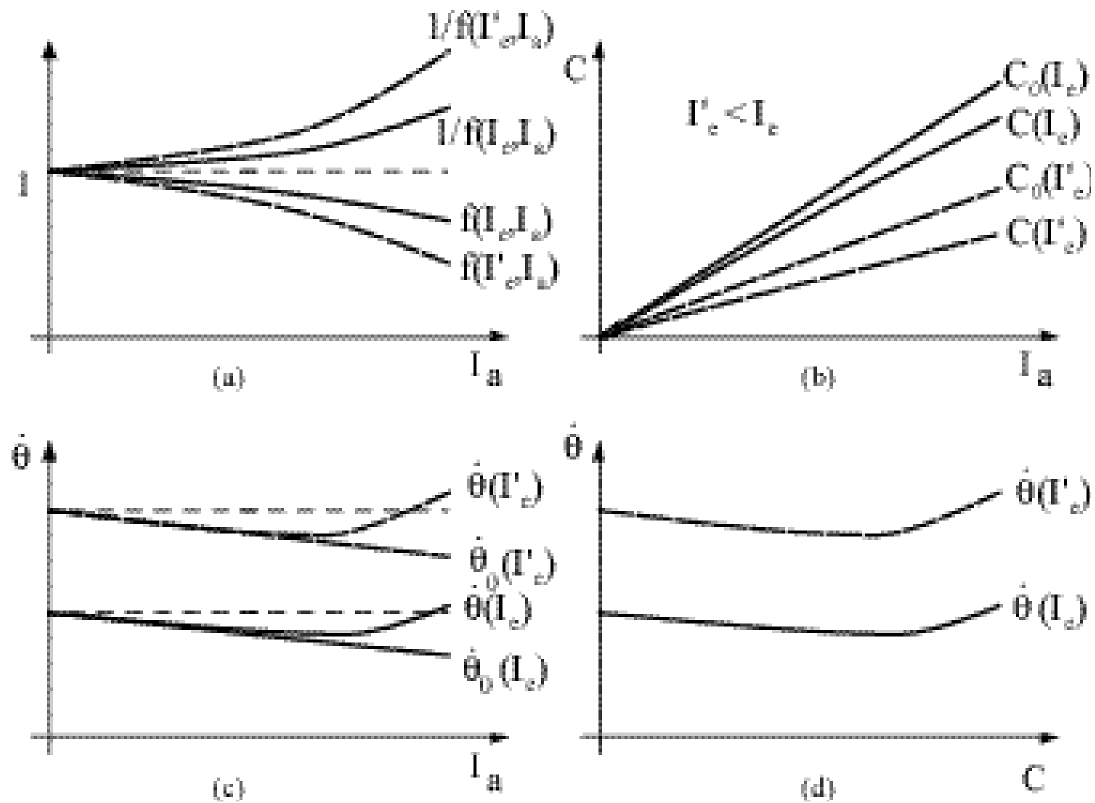
Small perturbation: e.g. speed increase

From P:
motor torque P'' < resisting torque P'
⇒ speed decreases, back to P ⇒ **stable**

From Q:
motor torque Q'' > resisting torque Q'
⇒ speed increases! ⇒ **unstable**

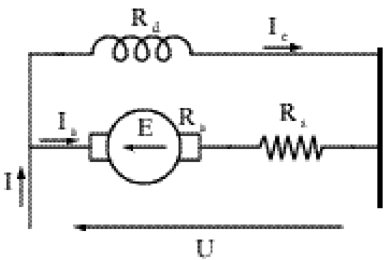
Influence of I_e





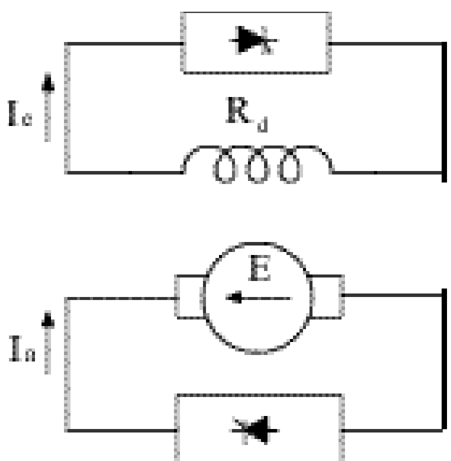
Limited speed range (saturation)

Shunt excitation motor



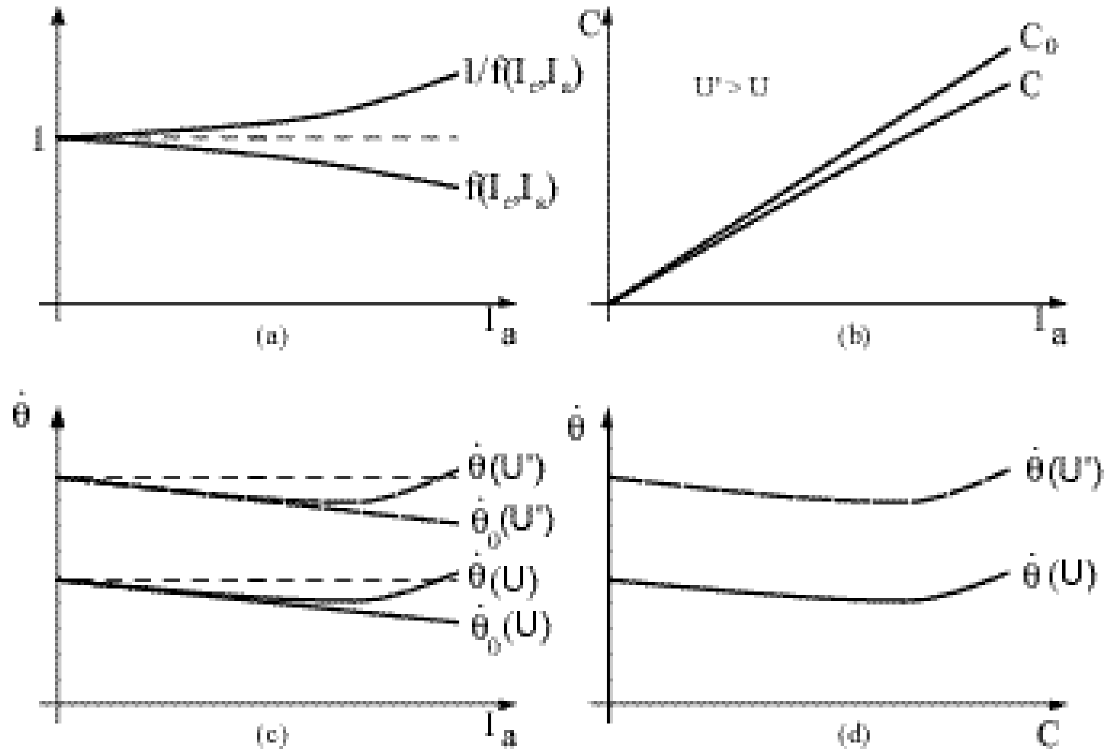
Poor efficiency!

+ power electronics...



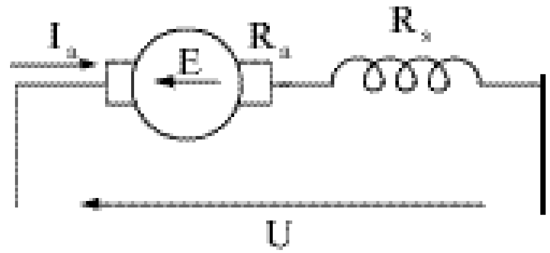
Influence of the voltage U

$$\dot{\theta} \approx \frac{U}{k_E \, \Phi_v(I_e)}$$



High dynamic torque control (since λ_a <<)

Series excitation motor

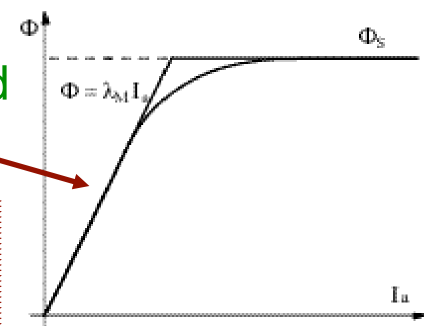


$$C = k_E\ \Phi(I_a)\ I_a$$
$$U = k_E\ \dot{\theta}\ \Phi(I_a) + (R_a + R_s)\ I_a$$

Non saturated machine

$$C \approx k_E\ \lambda_M\ I_a^2$$
$$U \approx k_E\ \lambda_M\ \dot{\theta}\ I_a + (R_a + R_s)\ I_a$$

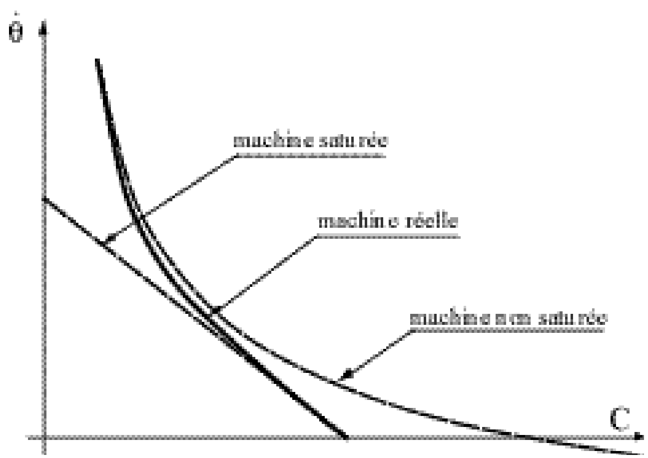
$$C \approx k_E\ \lambda_M \frac{U^2}{(k_E\ \lambda_M\ \dot{\theta} + R_a + R_s)^2} \approx \frac{1}{k_E\ \lambda_M}\ \frac{U^2}{\dot{\theta}^2}$$

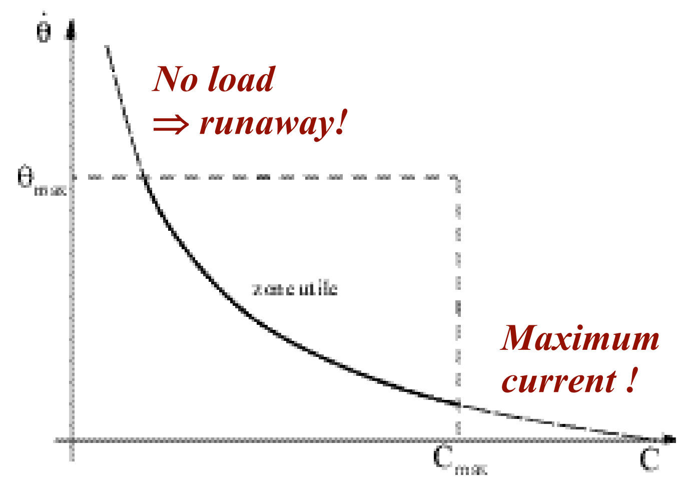


Saturated machine

$$C \approx k_E\ \Phi_S\ I_a$$
$$U \approx k_E\ \Phi_S\ \dot{\theta} + (R_a + R_s)\ I_a$$

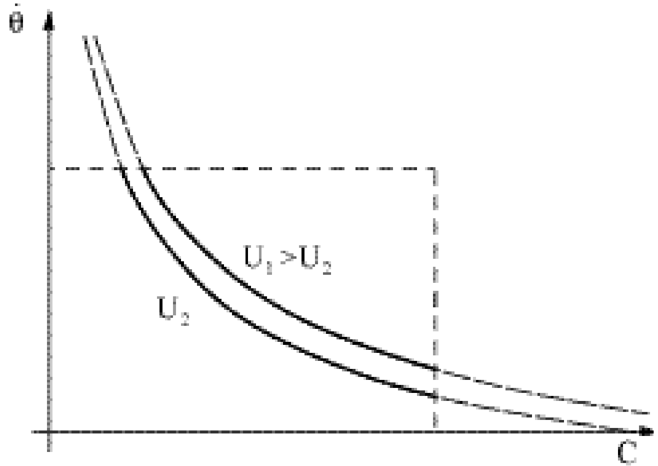
$$C \approx k_E\ \Phi_S \frac{U - k_E\ \Phi_S\ \dot{\theta}}{R_a + R_s}$$





Series excitation motor

Influence of the voltage source U



+ power electronics...

Typical use

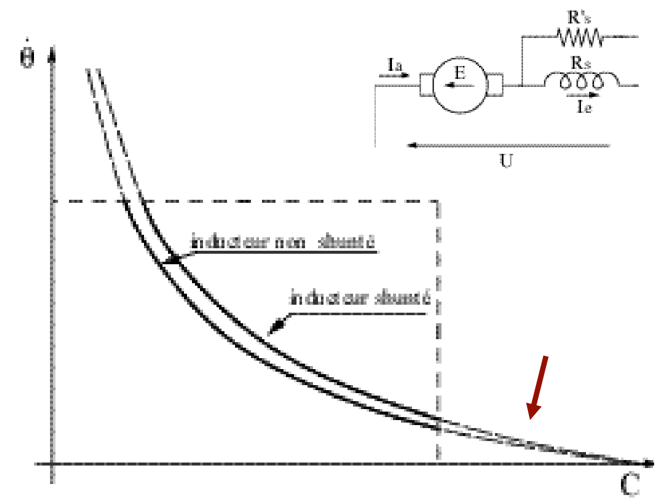
Electric traction and lifts (large startup torque)

Shunting the inductor

$$I_e = \frac{R_s'}{R_s + R_s'} I_a \le I_a$$

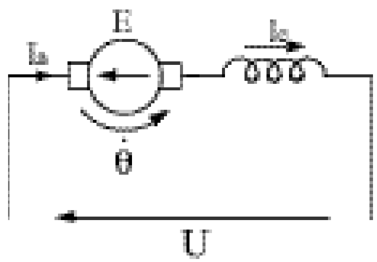
$$\lambda'_M = \frac{R_s'}{R_s + R_s'} \lambda_M \le \lambda_M$$

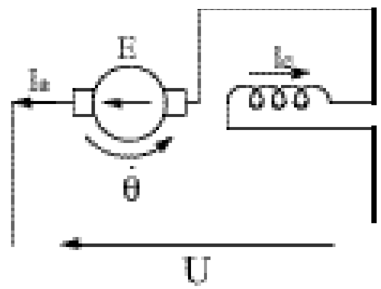
$$\Phi(I_e) \approx \lambda_M I_e = \lambda'_M I_a \le \lambda_M I_a = \Phi(I_a)$$



Series excitation motor

Braking



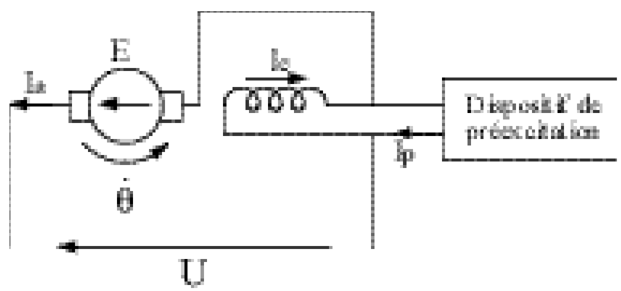


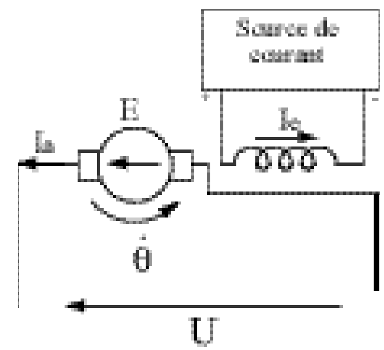
$$C = k_E \, \Phi(I_a) \, I_a$$

Change the sign of the torque to work as a brake

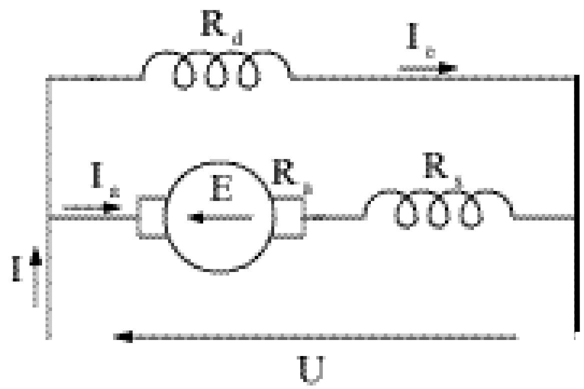
Electric power changes sign (recovers energy)

Different modes



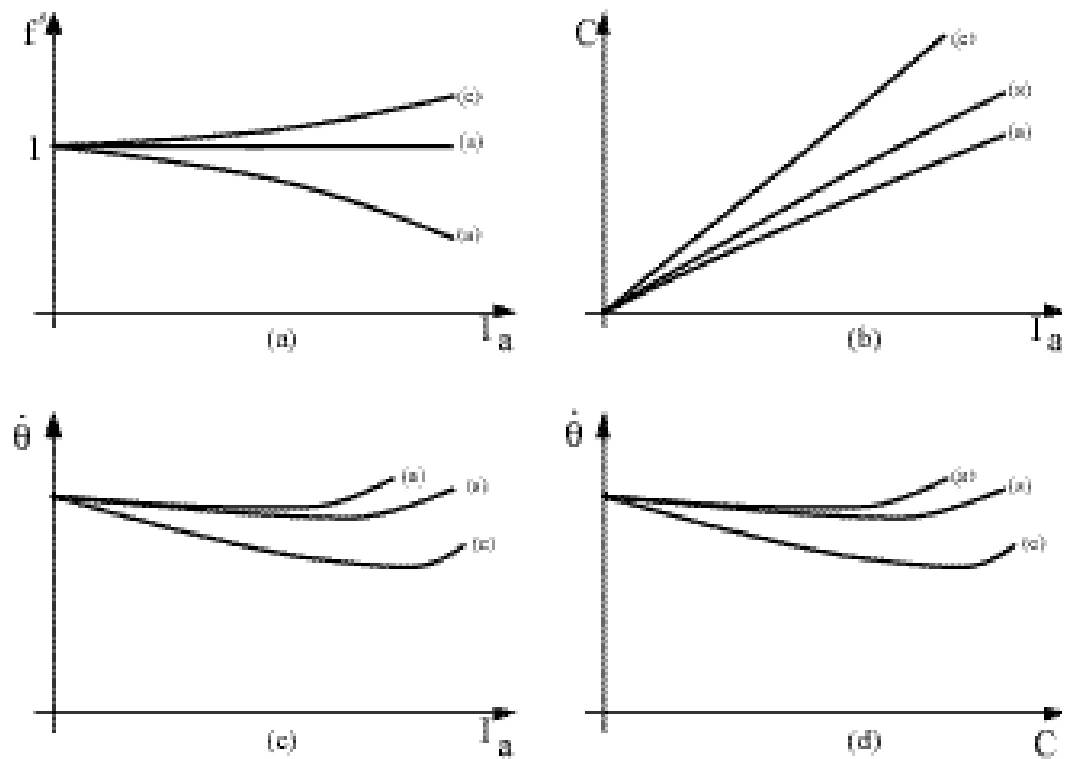


Compound excitation motor



Mixed excitation: *shunt and series inductor wound on the same poles*

$$\text{m.m.f.} = n_d I_e \pm n_s I_a$$
$$= n_d \left(I_e \pm \frac{n_s}{n_d} I_a \right)$$
$$= n_d I_f$$



DC motor startup

Zero speed at startup ⇒ zero e.m.f. E

Induced current I_a limited only by the armature resistance R_a

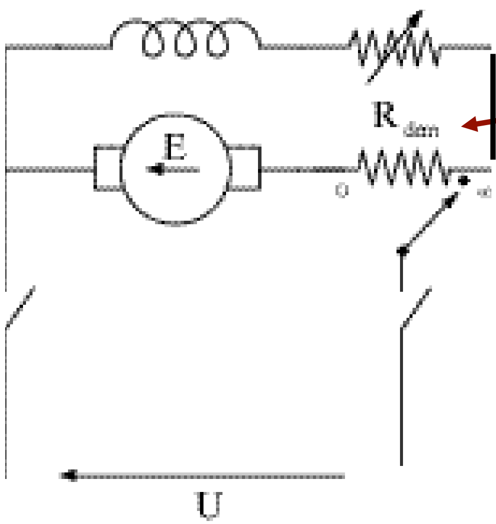
Startup rheostat in series with the armature (to limit I_a)

$$I_a = \frac{U - E}{R_a} = \frac{U - k_E\,\dot{\theta}\,\Phi}{R_a}$$

$$I_a = \frac{U}{R_a} \gg$$

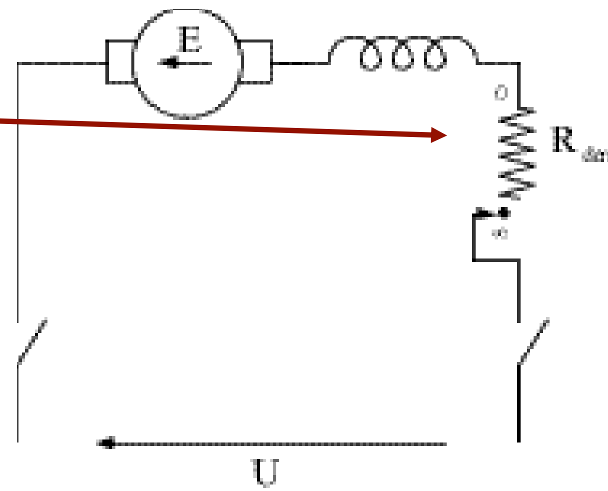
(One allows $I_{as} = 1.5\ I_{an}$)

Shunt motor



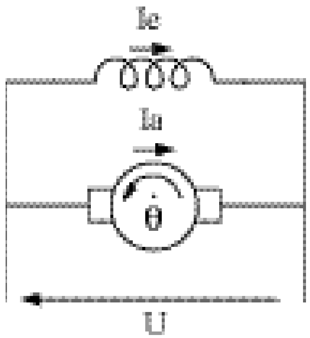
Startup rheostat
(value progressively reduced down to short-circuit)

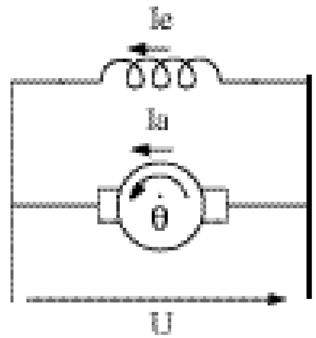
Series motor



Inverting the rotation direction

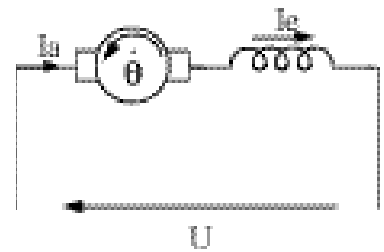
Shunt motor

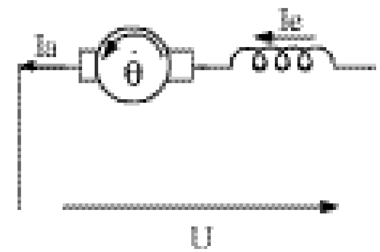




Series motor

Same direction

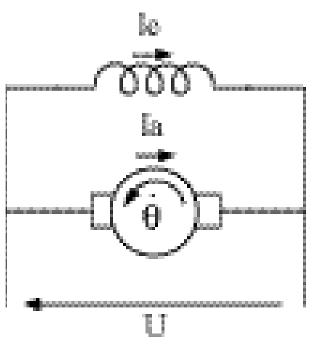


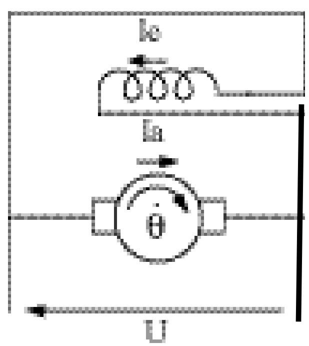


$$C = k_E\ \Phi(I_e)\ I_a$$

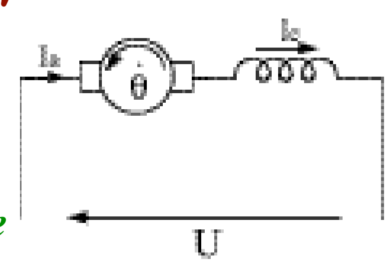
Modify the direction of the current in the excitation circuit w.r.t. the rotor

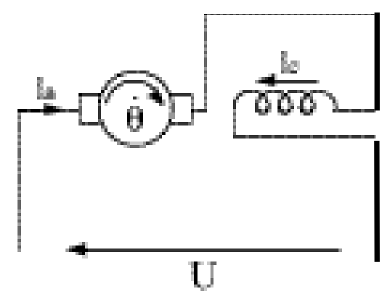
Torque changes sign





Opposite direction





Losses in DC machines

- **Mechanical losses**
  - friction losses in bearings (÷ v) (v = speed)
  - windage losses (÷ v^2)
  - friction losses from brushes on the collector (÷ v)
- **Magnetic losses**
  - eddy current losses in armature (÷ v^2, ÷ $b_{max}{}^2$)
  - hysteresis losses in armature (÷ v, ÷ $b_{max}{}^{1.5 \rightarrow 2}$)
- **Electric losses**
  - Joule losses in armature, inductor and brushes (÷ I^2, function of temperature)
- **Supplementary losses**
  - due to skin effect in the rotor and sparks at brushes/collector contact
  - increased magnetic losses due to the magnetic reaction