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

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

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

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

\[ E_v = k_E \dot{\theta} \Phi_v(I_e) \]

1. First magnetization
2. Decreasing $I_e$
3. Increasing $I_e$

Nonlinear with hysteresis

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

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

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

$e.m.f.$ with load

armature reaction

$$\psi(I_a) = k_E \frac{\dot{\theta}}{I_a}$$

DC machines
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. pole axis

**disadvantages:**
- for a single value of \( I_a \)
- shift direction depends on rotation direction
- shift direction depends on functioning 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

DC machines
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 \( \rightarrow \) 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

DC machines
Series excitation generator

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

\( R_s << \) since \( I_e = I \) is high coherent: section >, \( n_s < \)

\[ \Psi(I) = \psi(I) + (R_a + R_s)I \]

Speed modification

Inductor shunting

Quasi-linear

U almost fixed

I almost constant

useful zone

Current source

DC machines
**Shunt excitation generator**

\[
I = I_a - I_e
\]
\[
U = E_v(I_e) - \psi(I_a) - R_d I_a
\]
\[
U = R_d I_e
\]
\[
\Psi(I_a) = \psi(I_a) + R_a I
\]

**Picou construction**

- \(E_v(I_e)\) and \(\Psi(I_a)\) known
- \(R_d I_e = U(I_e)\)
- For \(I_{a1}\) (point by point procedure)
  - \(\Psi(I_a) \rightarrow \Psi(I_a) + R_d I_e = E_{v1} + E_{v2}\)
  - \(I_{el1} \text{ and } I_{el2} \rightarrow U_1 \text{ and } U_2\)

- \(I = I_a - I_e = I_a - \frac{U}{R_d}\)
Shunt excitation generator

**Exterior characteristic**

Delivered voltage almost independent of the delivered current → Voltage source

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

Functioning point of the generator driving a resistance $R$

DC machines
Shunt excitation generator

Speed modification

Excitation circuit modification

If the speed is too low or if $R_d$ is too large → no functioning point

Effect of hysteresis

2 branches:
$I_e$ increasing and decreasing

Short-circuit current

DC machines
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.)

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

DC machines
Self-starting generator

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

Example: shunt generator

Condition: $R_d + R_a$ not too large!
**DC network connection**

*Conditions:*
- $E \approx U$
- $E$ et $U$ in opposition

**After connection (1):**

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

If $E << Ia >>$ !

*Then, increase $E$ (2) $\Rightarrow$ the generator produces energy*

*Slope should be large (to reduce the current variations due to voltage perturbations)*

$\Rightarrow$ compound antagonist generator OK

*If $E$ decreases*

$\Rightarrow$ the generator receives energy (motor for shunt and compound machines!)

DC 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

\[ E = E_v - \psi(I_a) \]
\[ \psi(I_a) = k_E \theta \Delta \Phi(I_a) \]

\[ U = E + R_a I_a \]
\[ U = E - R_a I_a \]

DC motor

DC generator

Total armature reaction
Motor torque

\[ U = E + R_a I_a = E_v - \psi(I_a) + R_a I_a \]

\[ U I_a = E I_a + R_a I_a^2 = (E_v - \psi(I_a)) I_a + R_a I_a^2 \]

Electric power provided to the armature

Electromagnetic power

Joule losses in the armature

Electromagnetic torque

\[ C = \frac{P_{elm}}{\dot{\theta}} = \frac{E I_a}{\dot{\theta}} \]

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

DC machines
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
- series
- compound

DC machines
Shunt excitation motor

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

with \( I_e \) constant

\[ f(I_e, I_a) = \frac{\Phi_v(I_e) - \Delta \Phi(I_a)}{\Phi_v(I_e)} \leq 1 \]

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

\[ U = E + R_a I_a = k_E \dot{\theta} \left[ \Phi_v(I_e) - \Delta \Phi(I_a) \right] + R_a I_a \]

\[ \dot{\theta} = \frac{U - R_a I_a}{k_E \left[ \Phi_v(I_e) - \Delta \Phi(I_a) \right]} = \dot{\theta}_0 \frac{1}{f(I_e, I_a)} \]

Speed almost independent of torque
Shunt excitation motor

Stable and unstable zones

Small perturbation: e.g. speed increase

From P:
- motor torque $P'' <$ resisting torque $P'$
  $\Rightarrow$ speed decreases, back to $P \Rightarrow$ stable

From Q:
- motor torque $Q'' >$ resisting torque $Q'$
  $\Rightarrow$ speed increases! $\Rightarrow$ unstable

Influence of $I_e$

Limited speed range (saturation)

DC machines
Shunt excitation moteur

Influence of the voltage $U$

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

Poor efficiency!

+ power electronics...

High dynamic torque control (since $\lambda_a <<$)

DC machines
Series excitation motor

Non saturated machine

Saturated machine

DC machines

Maximum current!
Series excitation motor

Influence of the voltage source $U$

$$I_e = \frac{R_s}{R_s + R_m} I_a \leq I_a$$

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

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

Typical use

Electric traction and lifts (large startup torque)

+ power electronics...
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

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

DC machines
Zero speed at startup $\Rightarrow$ 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 $I_a$)

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

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

(One allows $I_{ad} = 1.5 I_{an}$)

Moteur shunt

Moteur série

Startup rheostat (value progressively reduced down to short-circuit)
Inverting the rotation direction

Shunt motor

Series motor

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

Torque changes sign

Opposite direction

C = k_E \Phi(I_e) I_a

Same direction

DC machines
Losses in DC machines

❖ Mechanical losses
  – friction losses in bearings (+ v) \( (v = \text{speed}) \)
  – windage losses (+ \( v^2 \))
  – friction losses from brushes on the collector (+ v)

❖ Magnetic losses
  – eddy current losses in armature(+ \( v^2 \), + \( b_{\text{max}}^2 \))
  – hysteresis losses in armature(+ \( v \), + \( b_{\text{max}}^{1.5} \rightarrow 2 \))

❖ 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