DC machines

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

2 poles

Magnetic circuit: stator + rotor + airgap

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

4 poles

DC machines
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

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

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

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.

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})

\[ E = E_V - \psi(I_a) \]
e.m.f. with load armature reaction

\[ \psi(I_a) = k_E \dot{\theta} \Delta \Phi(I_a) \]

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. 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

$U = f(I)$ with

\[
\begin{aligned}
\text{speed } \dot{\theta} &= \text{constant} \\
\text{fixed excitation circuit}
\end{aligned}
\]

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 → 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

\[ I = I_a = I_e \]
\[ U = \mathcal{E}_V(I) - \psi(I) - (R_a + R_s)I \]

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

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

Speed modification

Inductor shunting

Quasi-linear

U almost fixed

I almost constant useful zone

Current source

DC machines
**Shunt excitation generator**

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

\[ \psi(I_a) = \psi(I_a) + R_d I \]

**Picou construction**

- \( E_v(I_e) \) & \( \psi(I_a) \) known
- \( R_d I_e = U(I_e) \)

For \( I_{a1} \) (point by point procedure)
- \( \psi(I_a) \rightarrow \psi(I_a) + R_d I_e \equiv E_{v1} \) & \( E_{v2} \)
- \( I_{el1} \) & \( I_{e2} \) → \( U_1 \) & \( U_2 \)

\[ I = I_a - I_e = I_a - \frac{U}{R_d} \]

- \( R_d \gg \) to reduce Joule losses
- \( I_e < \Rightarrow n_s > \)

DC machines
Shunt excitation generator

Exterior characteristic

Delivered voltage almost independent of the delivered current → Voltage source

Operating point of the generator driving a resistance R

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

**Speed modification**

If the speed is too low or if $R_d$ is too large
$\rightarrow$ no operating point

**Excitation circuit modification**

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

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

\[ U = E_v(I_f) - \Psi(I_a) \]

\[ U = R_d I_e = R_d \left( I_f \pm \frac{n_s}{n_d} I_a \right) \]

(4) hypercompound \( (n_s >>) \)
(3) concordant compound (same direction m.m.f.)
(2) shunt dynamo
(1) antagonist compound (opposite m.m.f.)

\[ E_v(I_f) = \Psi(I_a) + R_d \left( I_f \pm \frac{n_s}{n_d} I_a \right) \]
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:**
- \( E \approx U \)
- \( E \) 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) \( \Rightarrow \) 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 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 $f = j \times b$

... 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_

\[ \psi(I_a) = k_E \dot{\theta} \Delta \Phi(I_a) \]

\[ U = E + R_a I_a \]

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

DC machines
Motor torque

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

- Electric power provided to the armature
- Electromagnetic power
- Joule losses in the armature

Electric power

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

Electromagnetic torque

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

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

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

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

with \((I_e \text{ constant})\)

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

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

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

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

Speed almost independent of torque
Shunt excitation motor

Stable and unstable zones

Influence of $I_e$

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

Limited speed range (saturation)

DC machines
Shunt excitation motor

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

\[ C = k_E \Phi(I_a) I_a \]
\[ U = k_E \dot{\Phi}(I_a) + (R_a + R_s) I_a \]

Non saturated machine

\[ C \approx k_E \lambda_M I_a^2 \]
\[ U \approx k_E \lambda_M \dot{\Phi} I_a + (R_a + R_s) I_a \]

Saturated machine

\[ C \approx k_E \Phi_S I_a \]
\[ U \approx k_E \Phi_S \dot{\Phi} + (R_a + R_s) I_a \]

No load ⇒ runaway!

Maximum current!
Series excitation motor

Influence of the voltage source $U$

Shunting the inductor

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

Typical use

Electric traction and lifts (large startup torque)

+ power electronics...

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

\[ \text{m.m.f.} = n_d I_e \pm n_s I_a \]

\[ = n_d \left( I_e \pm \frac{n_s}{n_d} I_a \right) \]

\[ = n_d I_f \]
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 $I_a$)

Shunt motor

Series motor

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

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

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

Shunt motor

\[ C = k_E \Phi(I_e) I_a \]

Series motor

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

Torque changes sign

Same direction

Opposite direction

DC machines
Losses in DC machines

- **Mechanical losses**
  - friction losses in bearings ($\div v$) ($v = \text{speed}$)
  - windage losses ($\div v^2$)
  - friction losses from brushes on the collector ($\div v$)

- **Magnetic losses**
  - eddy current losses in armature ($\div v^2$, $\div b_{\text{max}}^2$)
  - hysteresis losses in armature ($\div v$, $\div b_{\text{max}}^{1.5 \rightarrow 2}$)

- **Electric losses**
  - Joule losses in armature, inductor and brushes ($\div I^2$, 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