ELEC0014 - Introduction to electric power and energy systems

The synchronous machine (simplified model) – Part 1 –

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Synchronous machines:

- produce the major part of the electric energy
  - range from a few kVA to a few hundred MVA
  - the biggest are rated 1500 MVA
- play an important role:
  - they impose the frequency of sinusoidal voltages and currents
  - they provide an "energy buffer" (through the kinetic energy stored in their rotating masses)
  - they can produce or consume reactive power (needed to regulate voltage).

In this chapter:

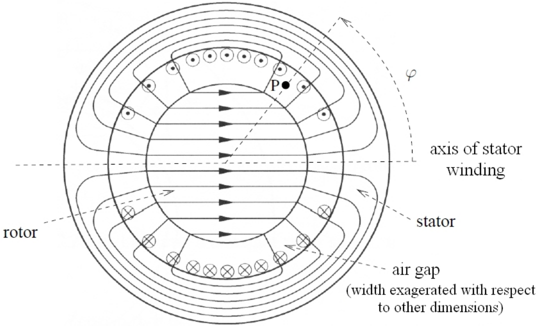
- first, the principle of operation is recalled
- then, a simplified model is derived
- before focusing on steady-state operation.

Recall: principle of operation

Magnetic field created by the stator

- stator (or *armature*) = motionless, separated from the rotor by a small air gap
- subjected to varying magnetic flux ⇒ built up of thin laminations to decrease *eddy (or Foucault)* currents
- equipped with three windings, distributed 120 degrees apart in space.

Magnetic field created by a direct current flowing in one of the stator windings:

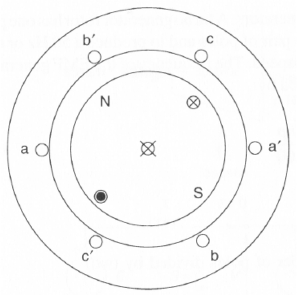


The magnetic field lines cross the air gap radially.

The amplitude $B(\varphi)$ of the magnetic flux density at point P :

- is a periodic function of φ with period 2π
- this function has a "staircase" shape
- is made as close as possible to a sinusoid, by properly distributing the conductors along the air gap.

Layout of the three phases:



(each winding is represented by a single turn for clarity !)

Total flux density created by the three phases at point P corresponding to angle φ:

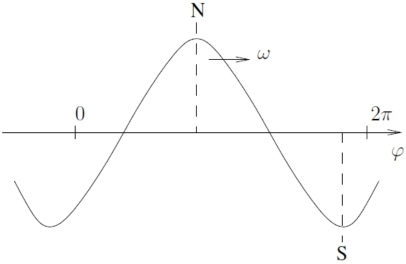
$$B_{3\phi}(\varphi) = ki_a \cos\varphi + ki_b \cos(\varphi - \frac{2\pi}{3}) + ki_c \cos(\varphi - \frac{4\pi}{3})$$

If three-phase alternating currents are flowing in the windings:

$$\begin{aligned}
B_{3\phi}(\varphi) &= \sqrt{2}kI \Big[\cos(\omega t + \psi)\cos\varphi + \cos(\omega t + \psi - \frac{2\pi}{3})\cos(\varphi - \frac{2\pi}{3}) + \\
&\quad + \cos(\omega t + \psi - \frac{4\pi}{3})\cos(\varphi - \frac{4\pi}{3})\Big] \\
&= \frac{\sqrt{2}kI}{2}\Big[\cos(\omega t + \psi + \varphi) + \cos(\omega t + \psi - \varphi) + \cos(\omega t + \psi + \varphi - \frac{4\pi}{3}) \\
&\quad + \cos(\omega t + \psi - \varphi) + \cos(\omega t + \psi + \varphi - \frac{2\pi}{3}) + \cos(\omega t + \psi - \varphi)\Big] \\
&= \frac{3\sqrt{2}kI}{2}\cos(\omega t + \psi - \varphi)
\end{aligned}$$

This the equation of a wave rotating in the air gap at the angular speed ω

If the air gap was "unrolled":



The three-phase alternating currents all together produce the same magnetic field as a magnet (or a coil carrying a direct current) rotating at the angular speed ω

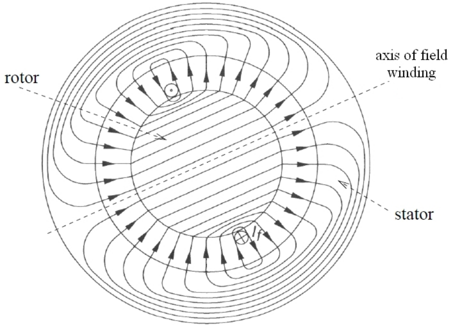
North pole of magnet $\equiv$ maximum of $B(\varphi)$

South pole of magnet $\equiv$ minimum of $B(\varphi)$

Magnetic field created by the rotor

- rotor = rotating part, separated from the rotor by the air gap
- carries a winding in which a direct current flows, in steady-state operation
- referred to as *field* winding[1].

Magnetic field created by this direct current:



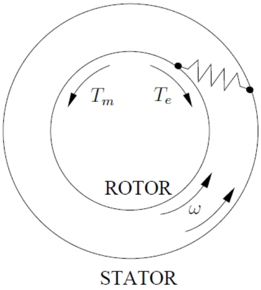
(field winding represented by a single turn for clarity !)

[1] in French: *enroulement d'excitation*

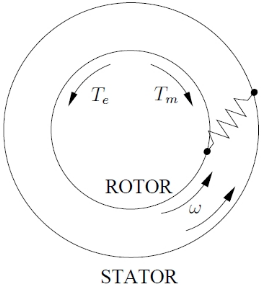
Interaction between magnetic fields and electromechanical conversion

- In a synchronous machine, in steady state, the rotor rotates at the same angular speed ω as the magnetic field produced by the stator
- thus, the stator and rotor magnetic fields are fixed with respect to each other
- both fields tend to align in the manner of two magnets
- if one pulls apart those two magnets, an electromagnetic torque appears.

Mechanical analogy:



generator operation



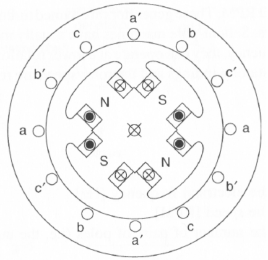
motor operation

There exists a max value of the electromagnetic torque T_e $\rightarrow$ loss of synchronism

Machines with multiple pairs of poles

- Some turbines operate at a lower speed
- but AC voltages and currents at the stator must keep the same period $T = \frac{1}{f}$

- the rotor carries p pairs of poles
- during a period T, the rotor makes only $1/p$ of a whole revolution
- the stator carries p sets of (a, b, c) windings
- one winding spans an angle of π/p radians
- during a period T, each stator winding is still swept by one North and one South pole of rotor.



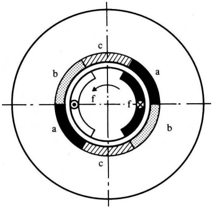
example : $p = 2$

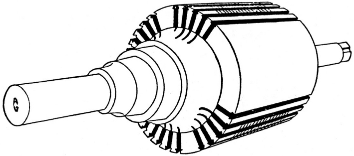
speed: $\dfrac{3000}{p}$ rev/min at 50 Hz $\qquad \dfrac{3600}{p}$ rev/min at 60 Hz

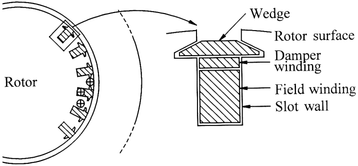
The various windings relative to a given phase are connected (in series or parallel) to end up with a three-phase machine.

The two types of synchronous machines

Round-rotor generators (or turbo-alternators)







- Driven by steam or gas turbines, which rotate at high speed
- $p = 1$ (conventional thermal units) or $p = 2$ (nuclear units)
- cylindrical rotor made up of solid steel forging
- diameter $<<$ length (centrifugal force !)
- field winding made up of conductors distributed on the rotor, in milled slots
- even if the generator efficiency is around 99 %, the heat produced by Joule losses has to be evacuated !
  Large generators are cooled by hydrogen (heat evacuation 7 times better than air) or water (12 times better) flowing in the hollow stator conductors.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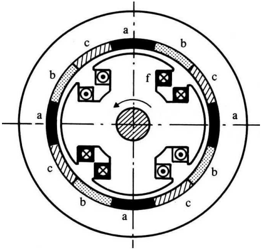
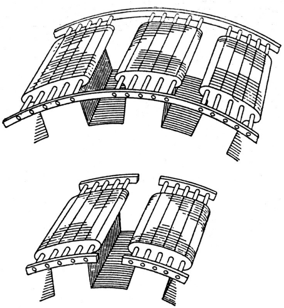
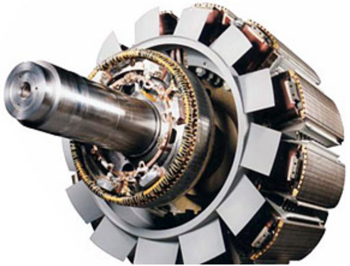
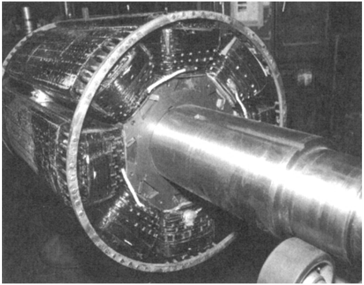
Salient-pole generators

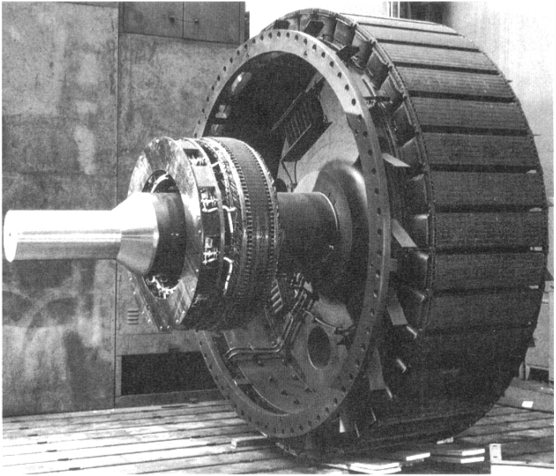




- Driven by hydraulic turbines (or diesel engines), which rotate at low speed
- p is much higher (at least 4) $\Rightarrow$ it is more convenient to have field windings concentrated and placed on the poles
- air gap is not constant: min. in front of a pole, max. in between two poles
- poles are shaped to also minimize space harmonics (see slide # 4)
- diameter $>>$ length (to have space for the many poles)
- rotor is laminated (poles easier to construct)
- generators usually cooled by the flow of air around the rotor.







Damper windings (or amortisseurs)

- round-rotor machines: copper/brass bars placed in the same slots at the field winding, and interconnected to form a damper cage (similar to the squirrel cage of an induction motor)
- salient-pole machines: copper/brass rods embedded in the poles and connected at their ends to rings or segments.

Why?

- in perfect steady state: the magnetic fields produced by both the stator and the rotor are fixed relative to the rotor $\Rightarrow$ no current induced in dampers
- after a disturbance: the rotor moves with respect to stator magnetic field $\Rightarrow$ currents are induced in the dampers. . .
  . . . which, according to Lenz's law, create a *damping torque* helping the rotor to align on the stator magnetic field.

Eddy currents in the rotor

Round-rotor generators: the solid rotor offers a path for eddy currents, which produce an effect similar to those of amortisseurs.