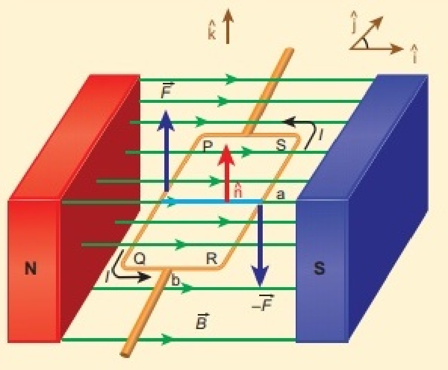
ELEC0431 - Overview of electrical machines (updated version)

François Henrotte

ACE - ULiège

3 mars 2023

DC machine = magnetic moment in a **B** field



$$\begin{aligned}
\theta &= \text{angle from } \mathbf{n} \text{ to } \mathbf{B}\\
&= \pi/2 \text{ in the picture}\\
F &= |\mathbf{F}|\ ,\ B = |\mathbf{B}|\ ,\ S = ab\\
F &= a\, I\, B \quad (\mathbf{dF} = I\,\mathbf{dL} \times \mathbf{B})\\
\mathbf{C} &= b\, F \sin\theta\, \hat{\jmath} \quad (\mathbf{C} = \mathbf{r} \times \mathbf{F})\\
&= I\, a\, b\, B \sin\theta\, \hat{\jmath}\\
&= I\, S\, \hat{n} \times \mathbf{B}
\end{aligned}$$

Magnetic moment :

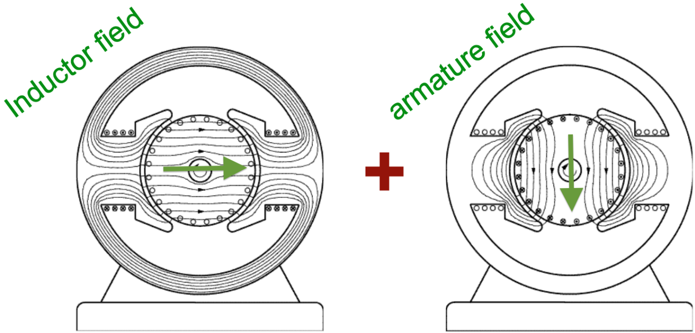
$$\mathbf{m} = I\, S\, \hat{n}$$

Torque applied to **m** :

$$\mathbf{C} = \mathbf{m} \times \mathbf{B}$$

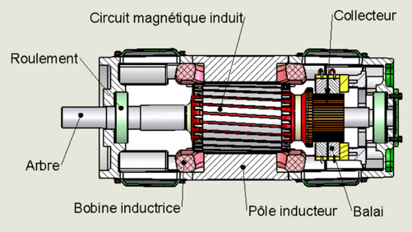
The torque **C** tends to align the magnetic moment **m** with the magnetic field **B**.

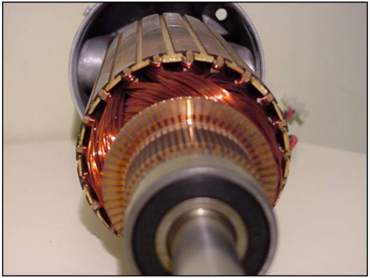
DC Machine



- DC **excitation currents** produce the **inductor field b**
- DC **armature currents** produce an **armature field** that mimics a magnetic dipole **m**
- Torque $\mathbf{m} \times \mathbf{b}$ is always maximum because $\mathbf{m} \perp \mathbf{b}$ by construction
- The current needs be **commuted** in some rotor conductors as the rotor rotates in order to maintain the armature field unchanged : this is the role of the **collector**

DC machines : collector





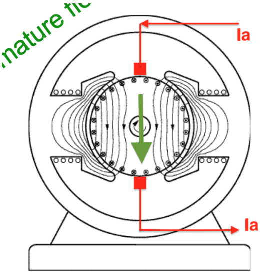
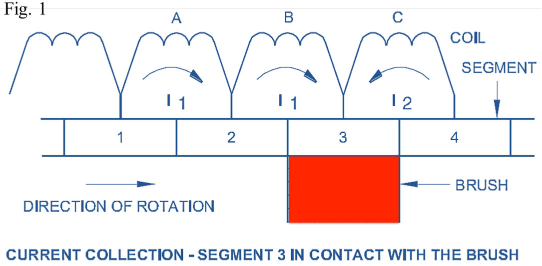
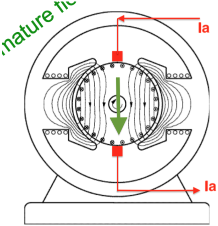


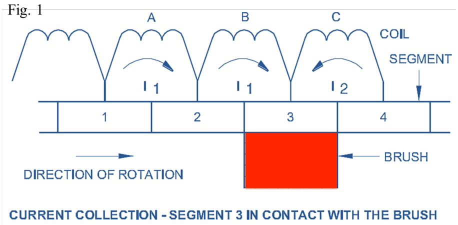
Fig. 1



Commutation in DC machines

- **Rotor conductors** (A,B,C, ...) and **collector segments** (1,2,3,4, ...) form a closed conducting loop.
- The **armature currents** I_a arrives at the upper **brush** (in red), is split in two (I_1 and I_2) in the two halves of that loop, and is recollected ($I_a = I_1 + I_2$) at the lower brush.
- Brushes are represented (left picture) at the location where the current in the rotor conductors must be commuted as the rotor rotates, in order to **maintain the same orientation** for the magnetic moment **m** materialized by the rotor.





DC machines : basic simplified equations

Due to the rotation of the rotor at angular frequency $\dot{\theta}$ in the field generated by the excitation current I_e, an **electro-motive force** (e.m.f) is induced in the rotor conductors, whose total value E (rotor conductors are in series) is measured at the brushes. The basic equations governing DC machines are :

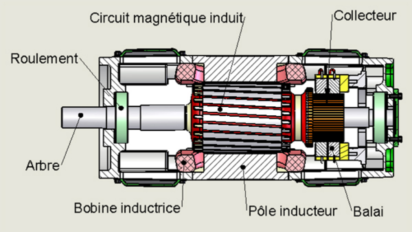
$$U = E + R_a I_a \qquad \text{(DC motor)}$$
$$E = R_a I_a + U \qquad \text{(DC generator)}$$
$$E = k\ \Phi(I_e)\ \dot{\theta} \qquad \text{(e.m.f.)}$$
$$C = k\ \Phi(I_e)\ I_a \qquad \text{(torque)}$$

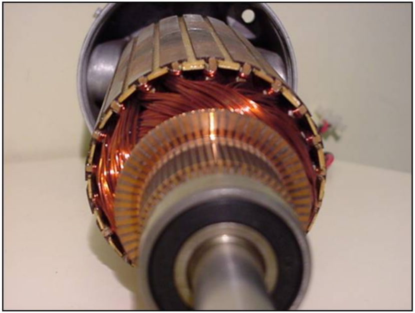
with $\dot{\theta}$ is expressed in [rad/s], and I_e the **excitation current**. In particular, one can deduce from the above equations the relationship

$$C\ \dot{\theta} = E\ I_a$$

which states the conservation of energy. $C\dot{\theta}$ is the **mechanical power**, and EI_a the **electric power** converted into (motor) or from (generator) this mechanical power.

DC machines : limitations

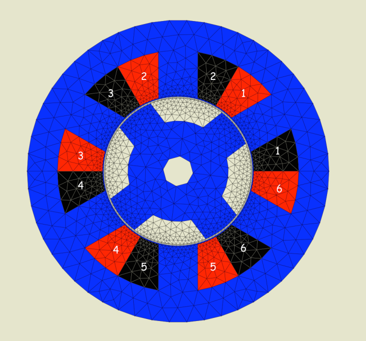


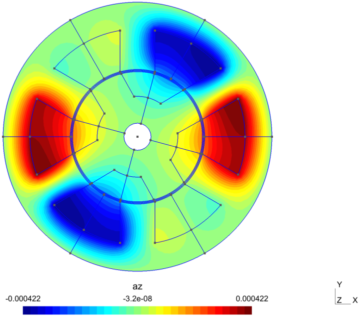


- DC machines are the **oldest** electrical machines (Zénobe Gramme, 1871)
- DC current is supplied to the rotor windings through a pair of **brushes** in contact with collector segments, which are in relative motion
- Wear, electric arcs ($L\partial_t I$ is large in the commuting rotor coil section, noted B in the picture above) and maintenance are serious issues with DC machines

Rotating field

- In a DC machine, the magnetic field is fixed/frozen
- Whereas with three-phase AC currents, one can directly generate a **rotating field**
- Pictures below : three-phase stator **concentrated pole** winding with two pole pairs ($p = 2$), Red="+" / Black="-" / Phase A=1,4 / phase B= 2,5 / phase C=3,6

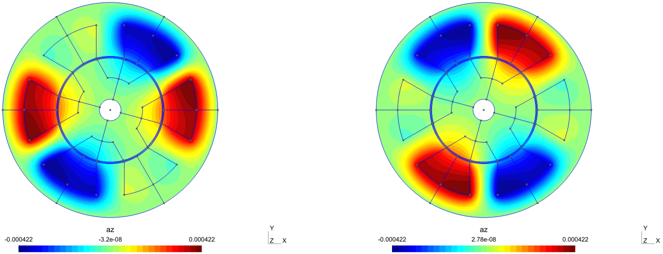




Three-phase stator currents

$$I_A(t) = I\cos(\omega t)$$
$$I_B(t) = I\cos(\omega t - 120^\circ)$$
$$I_C(t) = I\cos(\omega t - 240^\circ)$$

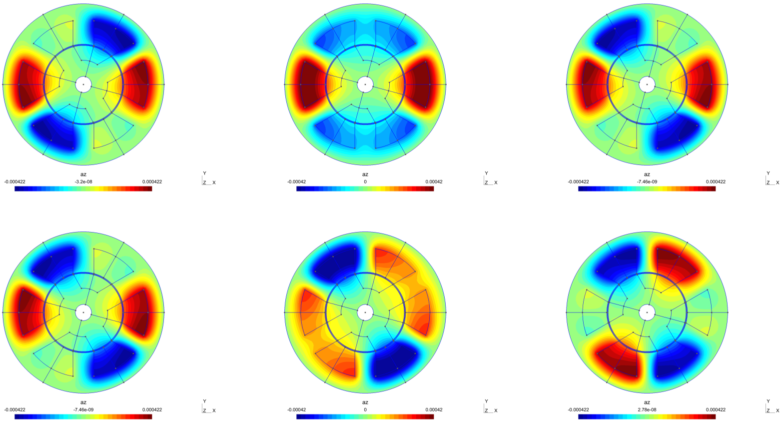
ωt	I_A	I_B	I_C
0°	1	$-1/2$	$-1/2$
120°	$-1/2$	1	$-1/2$
240°	$-1/2$	$-1/2$	1



$\omega t = 0^\circ$ and $\omega t = 120^\circ$

Shift in space of the windings + shift in time of the currents $\Rightarrow$ rotating field in the air gap at angular frequency $\dot{\theta} = \omega/p$

Rotating field : $\omega t = 0^\circ, 30^\circ, 60^\circ \quad 60^\circ, 90^\circ, 120^\circ$



- Field concentration in magnetic teeth
- Only three coils to generate a spatially sinusoidal field
- Slotting effect that makes the air gap field imperfectly sinusoidal

Improved stator windings

- The stator winding presented above is of the **concentrated pole** type. It is obtained by mounting coils around stator teeth.
- To obtain smoother (closer to sinusoidal) air gap fields, one uses **distributed windings** (and salient poles at the rotor side)
- Picture : three-phase stator distributed winding with one pole pairs ($p = 1$) and voltages induced in the three phases by the rotation of the permanent magnet.
- Distributed windings are characterized by the fact that the return conductor is not placed in a neighbouring slot. Here, for instance, A and A' flow in diametrically opposed slots.

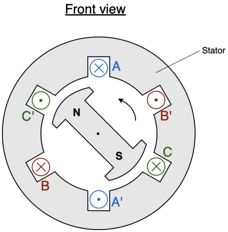


Figure 11: Schematic front view of a three-phase synchronous generator.

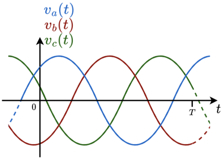
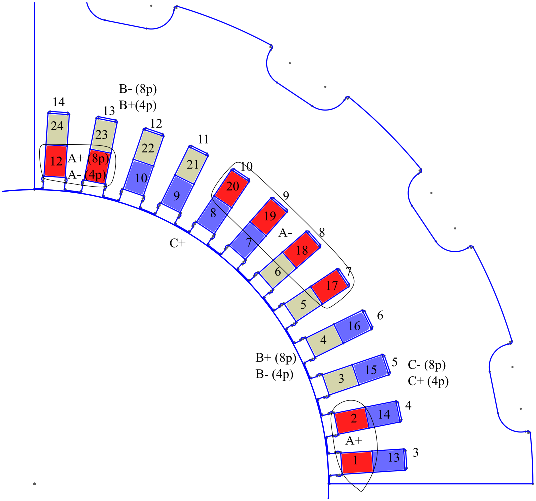
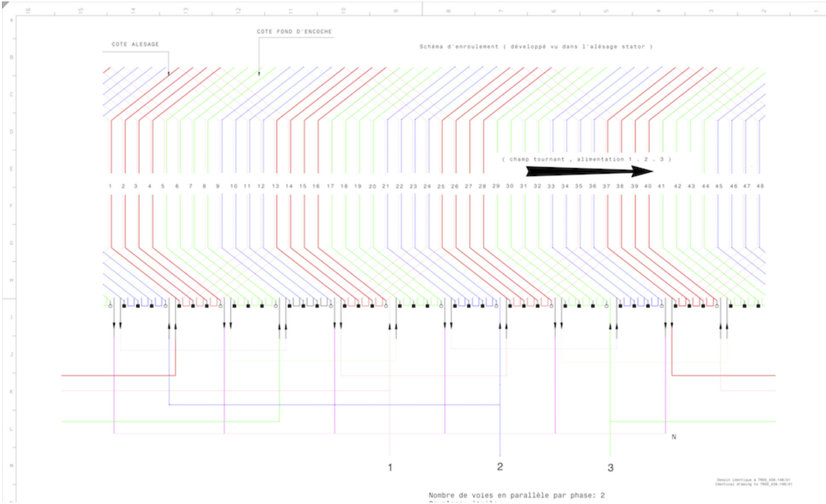


Figure 12: Three-phase signals emerging in the stator windings.

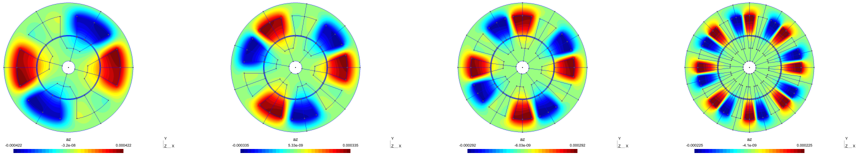
Real-life stator winding : distributed, two layers...



Real-life stator winding : wiring schematic



Number of pole pairs : $p = 2, 3, 4, 8, \ldots$



- The rotation speed of the rotating field is fixed by the working frequency f (=50Hz) and the number of pole pairs p.
- The larger p, the slower the mechanical rotation :

$$\dot{\theta} = \omega/p = 2\pi f/p$$

Electrical machines with rotating fields

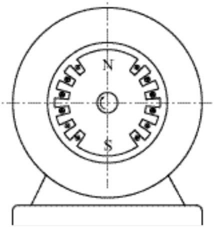
A rotating field can drive a rotor

- with electro-magnets :
  $\longrightarrow$ alternators, synchronous motors
- with permanent magnets :
  $\longrightarrow$ PMSM or BLDC machines
- made of massive conductors (and steel) :
  $\longrightarrow$ induction machines
- made of a non-cyclindrical steel core :
  $\longrightarrow$ switched reluctance machines, stepper motors

Synchronous machines : rotor = electro-magnet

- A source of **mechanical power** (combustion engine, waterfall, wind, . . .)
- that drives at constant speed the rotation of a **DC magnetized rotor**
- inside a stator equipped with **three-phase windings**
- makes up an **alternator** (synchronous generator)
- DC current injected into the rotor via **rings**
- You have one in your car.
- Left : $p = 1$, turbo-alternator, high rotation speed, small diameter
- Right : p large, salient pole machine, slow speed, large size

Turbo-alternator



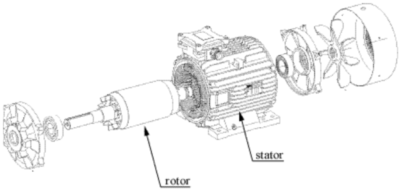
Salient poles

Salient pole alternators

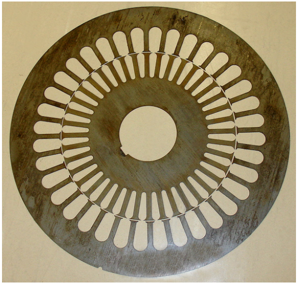
- Production of three-phase AC electricity in power plant
- Induced voltage are made nearly perfectly sinusoidal by an accurate geometric design of the salient poles
- Can be huge in size

Asynchronous machines : rotor = conductors

- Usually **motors**
- Distributed stator windings are powered with three-phase currents $\longrightarrow$ **rotating field**
- Rotor is made of massive conductors (squirell cage) or short circuited-coils, and steel for flux concentration
- Rotor currents (magnetizing currents) are induced, and not produced with a DC source or a magnet $\Rightarrow$ induction machine



Construction of squirell cage induction machines



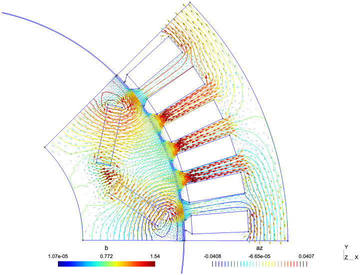
- Finely cut **electrical steel**
- **Stator slots** filled with distributed three-phase windings
- **rotor slots** filled with the massive conductors (usually Aluminium) short-circuited by rings at both ends.
- Very thin air gap
- Stack of hundreds of thin laminations isolated from each other to reduce eddy currents

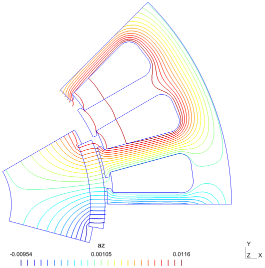
Assets and drawbacks of induction machines

- The rotor is passive (not supplied with currents)
- This machine is only supplied at the stator side.
- No collector, no rings
- Robust rotor construction
- One-size-fits-all motor utility in industry
- Speed varies by a few percents (slip) when the motor is loaded, but cannot be controlled if the frequency of the stator currents f is fixed

PMSM - BLDC : rotor = permanent magnet

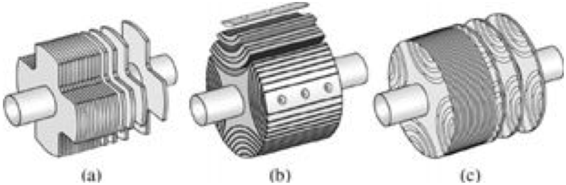
- PMSM : **Permanent Magnet Synchronous** Machine
- BLDC : **Brushless** DC machine
- Usually motors
- Rotor magnetised with permanent magnets $\Rightarrow$ compact machines
- Excitation I_e cannot be modified
- Stator currents controlled according to the position of the rotor (**m**) to position the air gap flux (**b**) so as to control torque (**m** $\times$ **b**) and speed
- Power electronics needed for that (end 20^{th} century)



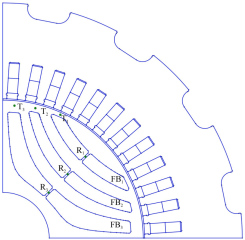


Switched reluctance machine : rotor = plain steel

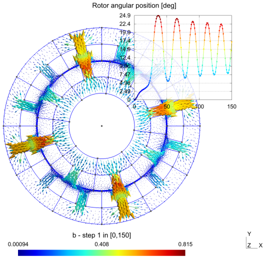
- Massive steel rotor with reluctance polar structure (poles, flux barriers)
- Less efficient. The rotor is not magnetized (no currents, no magnets)
- Cheaper than and induction motor rotor



ALSTOM :



CSL :



200 years of technological history

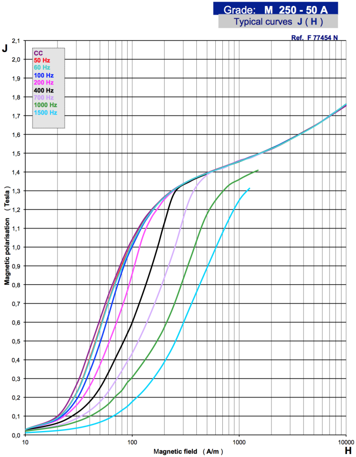
Historique [modifier | modifier le code]

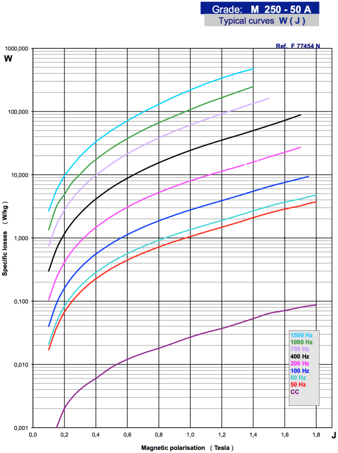
En 1821, après la découverte du phénomène du lien entre électricité et magnétisme, l'électromagnétisme, par le chimiste danois Ørsted, le théorème d'Ampère et la loi de Biot et Savart, le physicien anglais Michael Faraday construit deux appareils pour produire ce qu'il appela une « rotation électromagnétique » : le mouvement circulaire continu d'une force magnétique autour d'un fil, en fait la démonstration du premier moteur électrique.

Evolution of rotating machines

- DC machines **but** the collector is a problem
- Synchronous machines **but** rotor must still be supplied with DC current
- Asynchronous machines rotors ae passive **but** one wishes to control speed
- PMSM - BLDC are spee controlled **but** magnets are expensive and fragile
- Switched reluctance machine are robust **but** performances are less good
- . . .

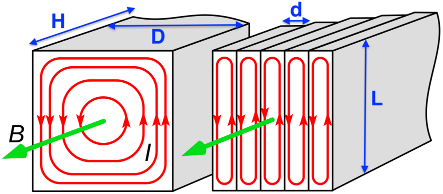
Electrical steels : saturation, eddy currents, hysteresis





Saturation curves $B(H)$ (left) and losses $W(B)$ at different frequencies

Laminated ferromagnetic cores : less Joule losses



$$U(d) = \omega\phi = \omega BLd\ [V] \quad \text{(e.m.f. in one lamination)}$$

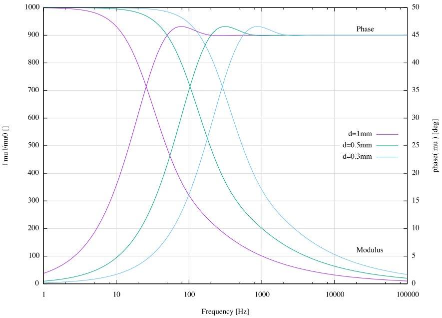
$$R(d) \approx \frac{2(L+d)}{\sigma(d/2)H} \approx \frac{4L}{\sigma dH} \quad (d << L)\ [\Omega]$$

$$P(d) = \frac{U^2}{R} \approx \frac{\sigma}{4}(B\omega)^2 LHd\ d^2\ [W] \text{ per lamination}$$

$$p_F(d) = \frac{P(d)}{LdH} \approx \frac{\sigma}{4}(B\omega)^2 d^2\ [W/m^3]$$

Specific Joule losses (p.u. volume) in a lamination stack are thus proportional to the square of the lamination thickness. Reducing the lamination thickness d by a factor 2 (one has then 2 times more laminations to maintain the same volume), decreases Joule losses in the whole stack by a factor 4.

Laminated ferromagnetic cores : larger apparent μ



The apparent magnetic permeability decreases as f increases, because the induced flux due ton eddy currents in the laminations opposes the imposed flux : less flux $\Rightarrow$ less **B** for the same stator currents $\Rightarrow$ smaller apparent μ.

Electric steel grades :
0.50 mm : M600-50A M400-50A M310-50A M250-50A
0.35 mm : M330-35A M270-35A M235-35A
0.30 mm : M230-30A

Credits

https://people.montefiore.uliege.be/geuzaine/ELEC0431

Magnetic moment:
    https://www.brainkart.com/article/Expression-for-torque-on-a-current-loop-placed-in-a-magnetic-field_38481/
Commutation in DC Machine:
    https://howelectrical.com/commutation-in-dc-machine/
DC machine:
    http://colbertserv.lyceecolbert-tg.org:3007/cours_motorisation_electrique/medias/2250.jpg
Salient pole alternator:
    https://www.jeumontelectric.com/
Induction machine:
    https://www.indiamart.com
    https://gearmotorblog.wordpress.com/2016/06/08/ac-induction-gearmotors/
    http://sa.ge.sts.free.fr/Wiki/pmwiki.php?n=SA.MCCDescription inductionMachine2.png:
Laminations:
    http://szjiarun.en.made-in-china.com
    http://www.polarislaserlaminations.com/motor-laminations.html
    https://commons.wikimedia.org/wiki/File:Motor_laminations_by_Zureks.jpg
Citation Faraday:
    https://fr.wikipedia.org/wiki/Machine_électrique
Laminated core:
    https://fr.m.wikipedia.org/wiki/Fichier:Laminated_core_eddy_currents_2.svg