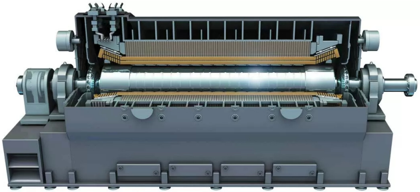
Alternateur Synchrone

S. Dufour

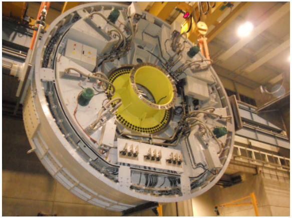
2A Energie - ENRS8AB

12 mai 2025

Turbogénérateur (vapeur)

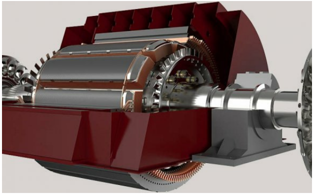


Alternateur éolien

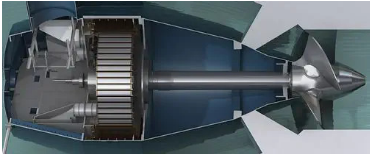


Générateurs hydrauliques

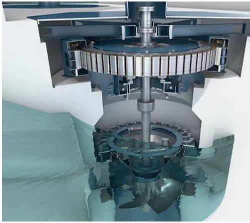
turbine Pelton

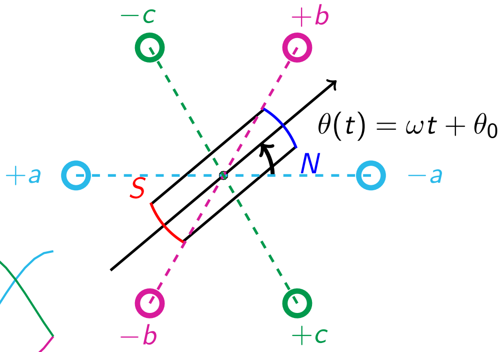


groupe bulbe (hydro)

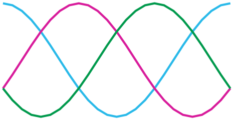


turbine Kaplan





$a \rightarrow b \rightarrow c$



Système triphasé direct

$$e_a(t) = E\sqrt{2}\cos(\omega t + \theta_0)$$

$$e_b(t) = E\sqrt{2}\cos(\omega t + \theta_0 - 2\pi/3)$$

$$e_c(t) = E\sqrt{2}\cos(\omega t + \theta_0 + 2\pi/3)$$

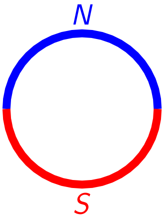
Vitesse de rotation de l'alternateur :

$$\Omega = \omega = 2\pi f$$

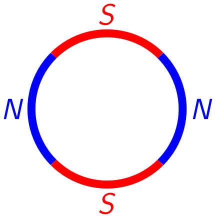
$$f = 50Hz \quad \rightsquigarrow \Omega = 3000tr/mn$$

Polarité

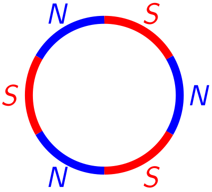
$p = 1$: 1 paire de pôles
2 pôles



$p = 2$
4 pôles



$p = 3$
6 pôles



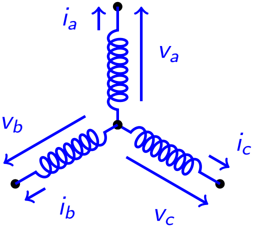
angle mécanique : $\theta_m \in [0, 2\pi/p]$

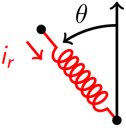
angle électrique : $\theta \in [0, 2\pi]$

$$\theta = p\,\theta_m$$

Vitesse de synchronisme : $\dot{\theta}_m = \Omega = \dfrac{\omega}{p} = \dfrac{2\pi f}{p}$

Convention générateur : courants (sortants) vers le réseau





$\theta(t) = p\,\theta_m(t)$

θ : angle électrique

θ_m : angle mécanique

$2p$: nombre de pôles

$\omega = 2\pi f$: pulsation

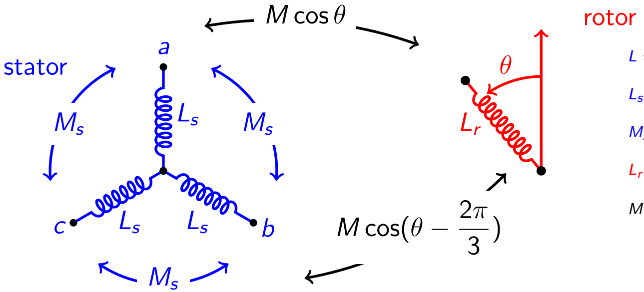
stator :
courants triphasés

rotor : $i_r = I_e$ (courant d'excitation)
courant continu

système direct équilibré

$$[i_s] = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = I\sqrt{2} \begin{bmatrix} \cos(\omega t - \varphi) \\ \cos(\omega t - \varphi - \frac{2\pi}{3}) \\ \cos(\omega t - \varphi + \frac{2\pi}{3}) \end{bmatrix} = \sqrt{2}\,\Re e \left(\bar{I}\, e^{j\omega t} \begin{bmatrix} 1 \\ a^2 \\ a \end{bmatrix} \right)$$

Alternateur synchrone : inductances



$L = L_s - M_s$ inductance phase stator

L_s auto-inductance phase stator

M_s inductance mutuelle phase stator

L_r auto-inductance rotorique

M inductance mutuelle stator-rotor

flux phase stator

$$\varphi_a = -L\, i_a + M\cos\theta\, i_r$$

$$\varphi_b = -L\, i_b + M\cos(\theta - \frac{2\pi}{3})\, i_r$$

$$\varphi_c = -L\, i_c + M\cos(\theta + \frac{2\pi}{3})\, i_r$$

flux rotor flux

$$\varphi_r = L_r i_r - M\cos\theta\, i_a - M\cos(\theta - \frac{2\pi}{3})\, i_b - M\cos(\theta + \frac{2\pi}{3})\, i_c$$

Alternateur synchrone : stator

hypothèse : $\dot{\theta}_m = \Omega = \dfrac{\omega}{p}$ vitesse de rotation constante (vitesse de synchronisme)

$$\theta = p\,\theta_m = p\Omega\,t + \theta_0 = \omega\,t + \theta_0$$

θ_0 : angle vérifiant une condition aux limites périodiques

$$[\varphi_s] = \begin{bmatrix} \varphi_a \\ \varphi_b \\ \varphi_c \end{bmatrix} = -L \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + M \begin{bmatrix} \cos \omega\,t + \theta_0 \\ \cos\left(\omega\,t + \theta_0 - \dfrac{2\pi}{3}\right) \\ \cos\left(\omega\,t + \theta_0 + \dfrac{2\pi}{3}\right) \end{bmatrix} i_r$$

$$\overline{\Phi} = -L\,\overline{I} + \frac{MI_e}{\sqrt{2}}\,e^{\,j\theta_0}$$

$\delta = \theta_0 + \dfrac{\pi}{2}$ *: angle interne*

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = -R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_a \\ \varphi_b \\ \varphi_c \end{bmatrix}$$

$$\overline{V} = -(R + jL\omega)\,\overline{I} + \underbrace{\frac{M\omega}{\sqrt{2}}\,e^{\,j\delta}\,I_e}_{\overline{E}\ \text{force électromotrice}}$$

Alternateur synchrone : rotor

hypothèse : $\dot{\theta}_m = \Omega = \dfrac{\omega}{p}$ vitesse de rotation constante (vitesse de synchronisme)

$$\theta = p\,\theta_m = p\Omega\,t + \theta_0 = \omega\,t + \theta_0$$

$\star$ Flux du rotor : *constant en fonction du temps*

$$-M\left[i_a\,\cos\theta + i_b\,\cos(\theta - \frac{2\pi}{3}) + i_c\,\cos(\theta + \frac{2\pi}{3})\right] = -\frac{3}{2}MI\sqrt{2}\cos(\theta_0 + \varphi)$$

$$\varphi_r = L_r I_e - \frac{3}{2}MI\sqrt{2}\cos(\theta_0 + \varphi)$$

$\star$ Equation de circuit électrique pour le rotor :

alimentation DC

$$V_r = R_r\,I_e + \frac{d\,\varphi_r}{dt} = R_r\,I_e$$

R_r : résistance rotor

$\leadsto$ I_e *courant d'excitation continu*

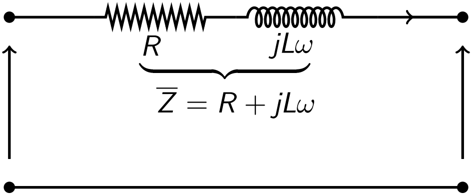
Alternateur Synchrone : schéma équivalent

FEM

Réseau

$\overline{I} = I e^{-j\varphi}$

$$\overline{E} = \frac{M\omega}{\sqrt{2}} I_e \, e^{\,j\delta}$$

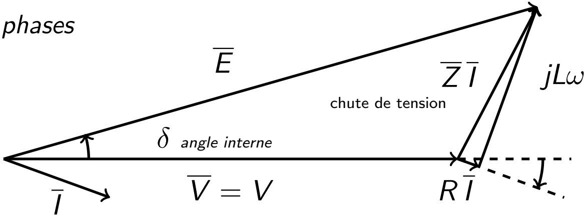


$$\overline{Z} = R + jL\omega$$

$$\overline{V} = V$$

$$\overline{E} = \overline{V} + (R + jL\omega)\overline{I} = \overline{V} + \overline{Z}\,\overline{I}$$

Diagramme des phases



choix de l'origine des phases : tension de phase réseau

Alternateur Synchrone : puissances

puissance mécanique

$P_m > 0$ ← turbine

alternateur → $P_a > 0$ → réseau

$Q > 0$

$Q < 0$

Puissance apparente : $$\overline{S} = 3\overline{V}\,\overline{I}^* = 3\overline{E}\,\overline{I}^* - 3\,(R + jL\omega)\,I^2$$

Puissance active : $$P_a = \Re e(\overline{S}) = 3\Re e(\overline{E}\,\overline{I}^*) - 3\,R\,I^2 = P_m - P_{Js}$$

Puissance réactive : $$Q = \Im m(\overline{S}) = 3\Im m(\overline{E}\,\overline{I}^*) - 3\,L\omega\,I^2$$

Couple (turbine) : $$\Gamma_m = +3\,\frac{p}{\omega}\,\Re e[\,\overline{E}\,\overline{I}^*\,] \simeq \frac{3p}{\omega}\,\frac{EV}{|\overline{Z}|}\sin\delta$$

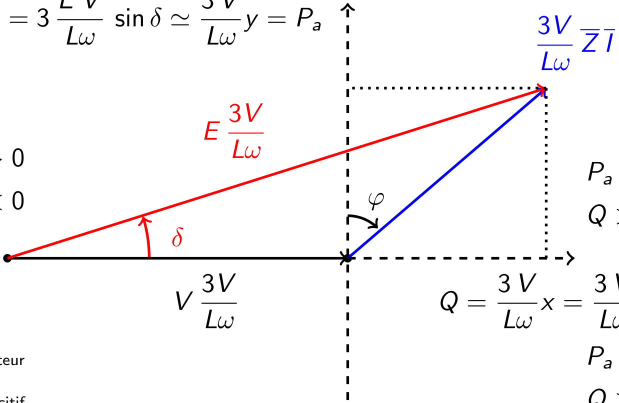
Hypothèse : $R \simeq 0 \quad \rightsquigarrow \overline{Z} \simeq j\,L\,\omega$

Chute de tension : $\overline{Z}\,\overline{I} = x + jy$

Puissance apparente : $\overline{S} = P_a + jQ = 3\,\dfrac{V}{\overline{Z}^*}\,(\overline{Z}\,\overline{I})^* = \dfrac{3\,V}{L\omega}\,(y - jx) = 3\,V\,I\,e^{j\varphi}$

envoyée au réseau

$$P_m = 3\,\frac{E\,V}{L\omega}\,\sin\delta \simeq \frac{3\,V}{L\omega}\,y = P_a$$



alternateur $P_a > 0$

capacitif $Q < 0$

$P_a > 0$ alternateur

$Q > 0$ inductif

$$Q = \frac{3\,V}{L\omega}\,x = \frac{3\,V}{L\omega}\,(E\,\cos\delta - V)$$

$P_a < 0$ moteur

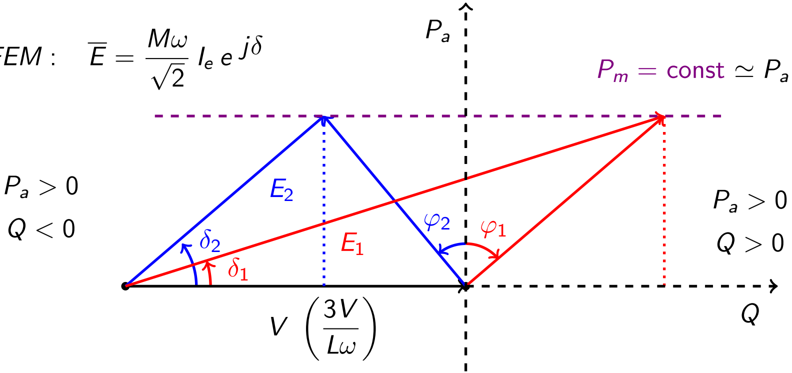
$Q < 0$ capacitif

$P_a < 0$ moteur

$Q > 0$ inductif

Contrôle : courant d'excitation

FEM : $\overline{E} = \dfrac{M\omega}{\sqrt{2}}\, I_e\, e^{\,j\delta}$



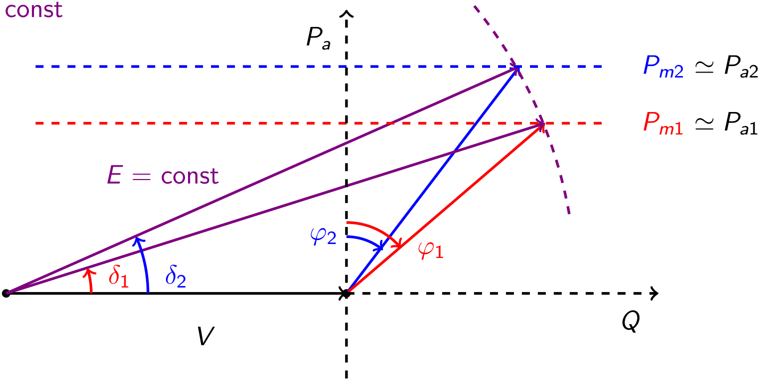
$E_2(I_{e2}) \rightsquigarrow$

$$\delta_2 = \arcsin\left(\frac{L\omega\, P_m}{3\, V\, E_2}\right)$$
$$Q_2 = \frac{3\, V}{L\omega}\,(E_2\, \cos\delta_2 - V) < 0$$

$E_1(I_{e1}) \rightsquigarrow$

$$\delta_1 = \arcsin\left(\frac{L\omega\, P_m}{3\, V\, E_1}\right)$$
$$Q_1 = \frac{3\, V}{L\omega}\,(E_1\, \cos\delta_1 - V) > 0$$

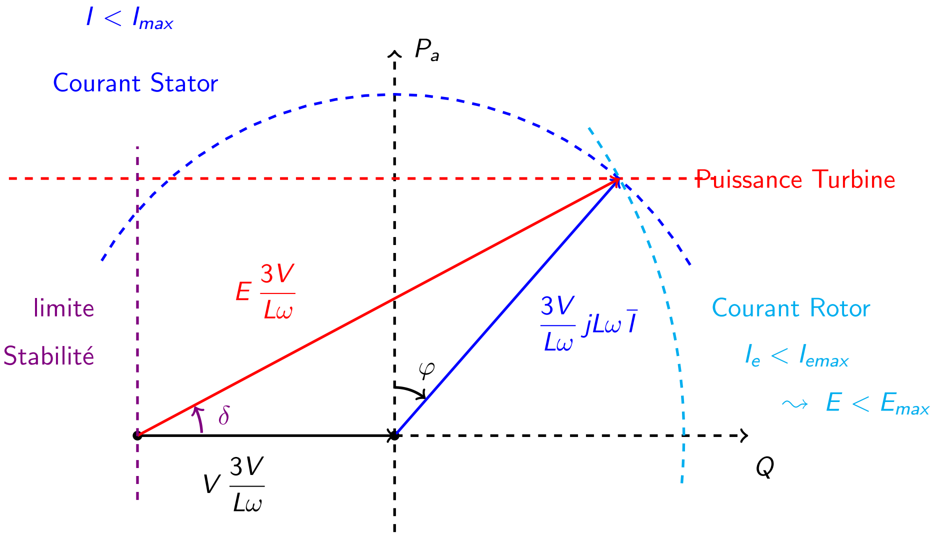
$I_e = \text{const}$



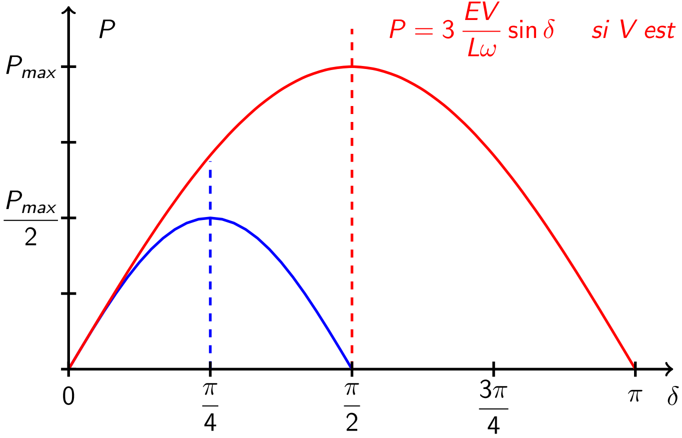
$$P_{m2} \leadsto \quad \delta_2 = \arcsin\left(\frac{L\omega\, P_{m2}}{3\, V\, E}\right) \qquad P_{m1} \leadsto \quad \delta_1 = \arcsin\left(\frac{L\omega\, P_{m1}}{3\, V\, E}\right)$$

$$Q_2 = \frac{3\,V}{L\omega}\,(E\,\cos\delta_2 - V) \qquad Q_1 = \frac{3\,V}{L\omega}\,(E\,\cos\delta_1 - V)$$

$$P_{m2} > P_{m1}\ \ \&\ \ E = const \quad \rightarrow \quad \delta_2 > \delta_1 \quad \rightarrow \quad Q_2 < Q_1$$


$I < I_{max}$
Courant Stator
P_a
Puissance Turbine
$E\,\frac{3V}{L\omega}$
$\frac{3V}{L\omega}\,jL\omega\,\bar{I}$
limite
Stabilité
Courant Rotor
$I_e < I_{emax}$
$\rightsquigarrow\ E < E_{max}$
φ
δ
$V\,\frac{3V}{L\omega}$
Q

Puissance active fournie par l'alternateur



$P = 3\,\frac{E^2}{2\,L\omega}\sin(2\delta)$ *si V n'est pas fixé (alternateur autonome)*

$\rightsquigarrow$ transmission max de la moitié de la puissance !

Rendement

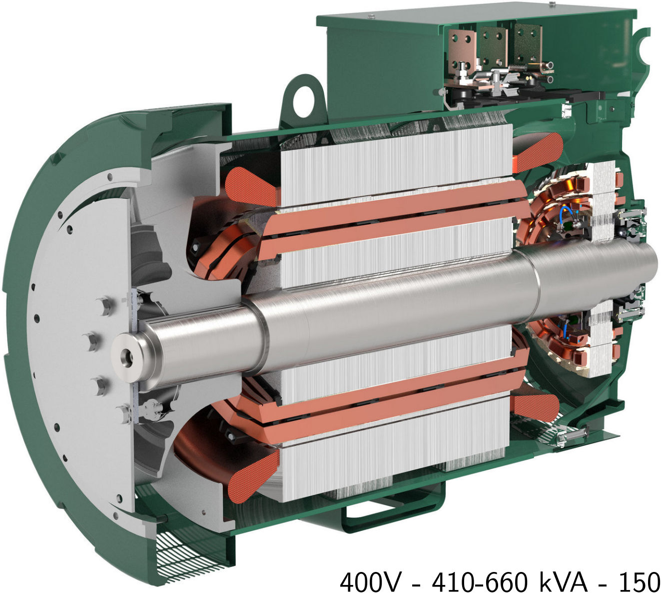
$$\text{alternateur : } \eta = \frac{P_a}{P_m}$$

pertes : $P_{Js} = 3RI^2,\qquad P_{Jr} = R_r I_e^2,\qquad P_{fe},\qquad p_{meca}$

$$\eta = \frac{P_a}{P_a + 3RI^2 + R_r I_e^2 + P_{fe} + p_{meca}}$$

	$\cos\varphi = 0.8$	$\cos\varphi = 1$
10-20 kVA	$\eta = 86 - 87\%$	$\eta = 90 - 91\%$
25-60 kVA	$\eta = 89 - 91\%$	$\eta = 91 - 93\%$
70-200 kVA	$\eta = 93 - 94\%$	$\eta = 95 - 95.5\%$
400-600kVA	$\eta = 95 - 96\%$	$\eta = 96 - 97\%$
730-1000kVA	$\eta = 95 - 96\%$	$\eta = 96 - 97\%$

Coupe d'un alternateur *LSA-47.3 Nidec (Leroy-Somer)*

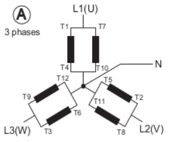


400V - 410-660 kVA - 1500 tr/mn

Connexions du stator *(Nidec)*

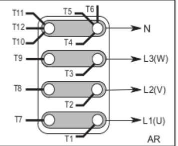
Code connexions	Tension L.L			Couplage usine

A — 3 phases

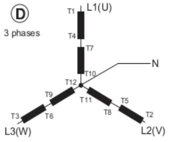


Bobinage	50 Hz	60 Hz
6	190 - 208	190 - 240
7	220 - 230	-
8	-	190 - 208

Détection de tension R220 :
0 => (T8) / 110 V => (T11)
Détection de tension D350 :
U => T1 / V => T2 / W => T3

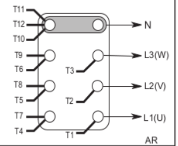


D — 3 phases

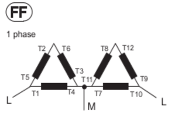


Bobinage	50 Hz	60 Hz
6	380 - 415	380 - 480
7	440 - 460	-
8	-	380 - 416

Détection de tension R220 :
0 => (T8) / 110 V => (T11)
Détection de tension D350 :
U => T1 / V => T2 / W => T3



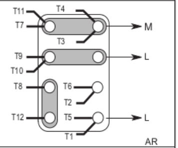
FF — 1 phase



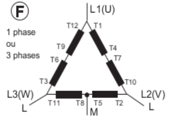
Tension LM = 1/2 tension LL
Voltage LM = 1/2 voltage LL

Bobinage	50 Hz	60 Hz
6	220 - 240	220 - 240
7	250 - 260	-
8	200	220 - 240

Détection de tension R220 :
0 => (T1) / 110 V => (T4)
Détection de tension D350 :
V => T1 / W => T10



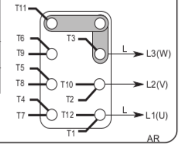
F — 1 phase ou 3 phases



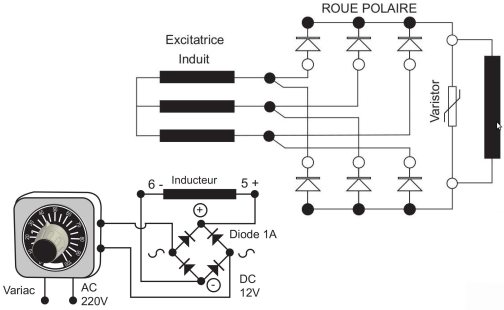
Tension LM = 1/2 tension LL
Voltage LM = 1/2 voltage LL

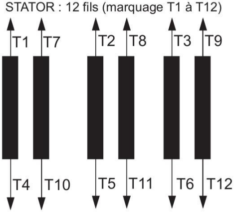
Bobinage	50 Hz	60 Hz
6	220 - 240	220 - 240
7	250 - 260	-
8	200	220 - 240

Détection de tension R220 :
0 => (T8) / 110 V => (T11)
Détection de tension D350 :
U => T1 / V => T2 / W => T3

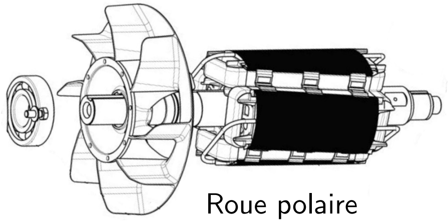


Connexions du rotor *(Nidec)*

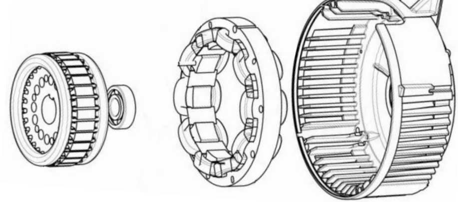




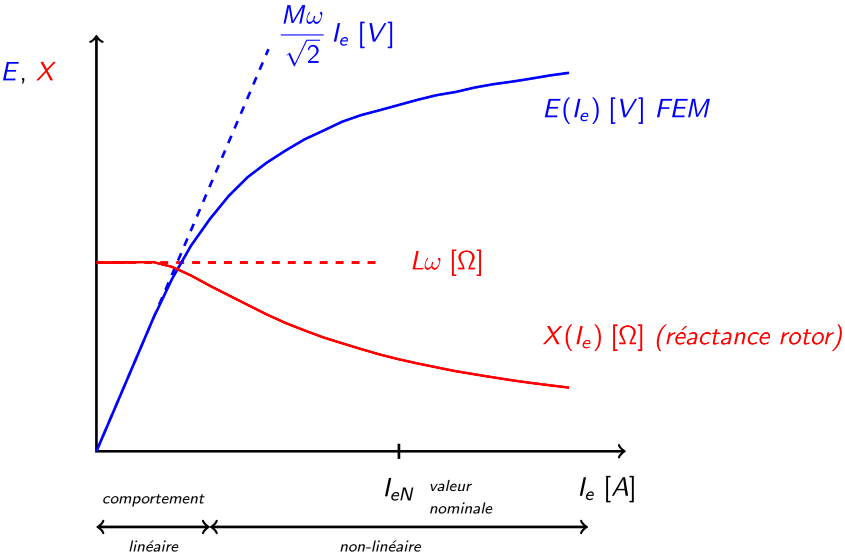
Excitatrice



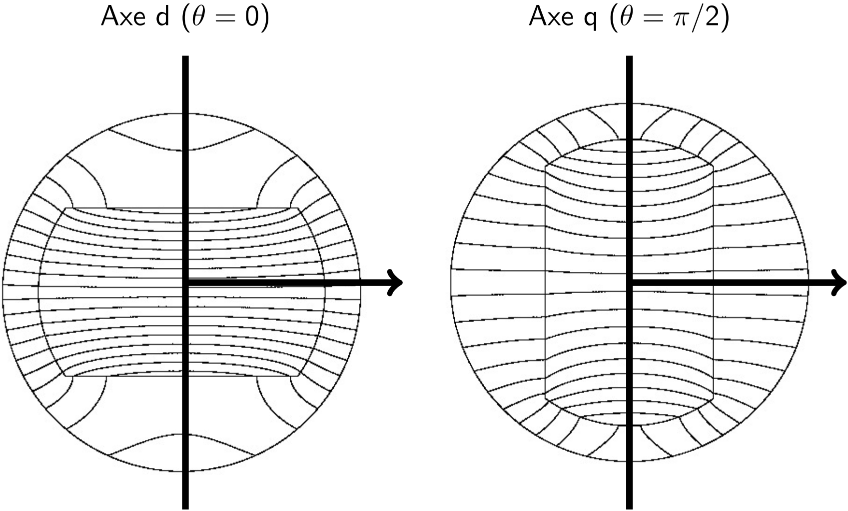
Roue polaire



Induit Inducteur


$\frac{M\omega}{\sqrt{2}}\,I_e\ [V]$
E, X
$E(I_e)\ [V]\ FEM$
$L\omega\ [\Omega]$
$X(I_e)\ [\Omega]$ (réactance rotor)
I_{eN}
valeur nominale
$I_e\ [A]$
comportement
linéaire
non-linéaire

Alternateur synchrone à pôles saillants



$$X_d > X_q$$

Alternateur à pôles saillants : composantes (d, q)

$$E = \overline{V} + jX_d I_d + jX_q I_q$$

$$\overline{V} = V_d + jV_q = V \sin\delta + jV\cos\delta$$

$R_s \simeq 0$

$$I_d = I\cos\psi = I\cos(\delta-\varphi) = \frac{V\sin\delta}{X_q}$$

$$I_q = I\sin\psi = I\sin(\delta-\varphi) = \frac{E - V\cos\delta}{X_d}$$

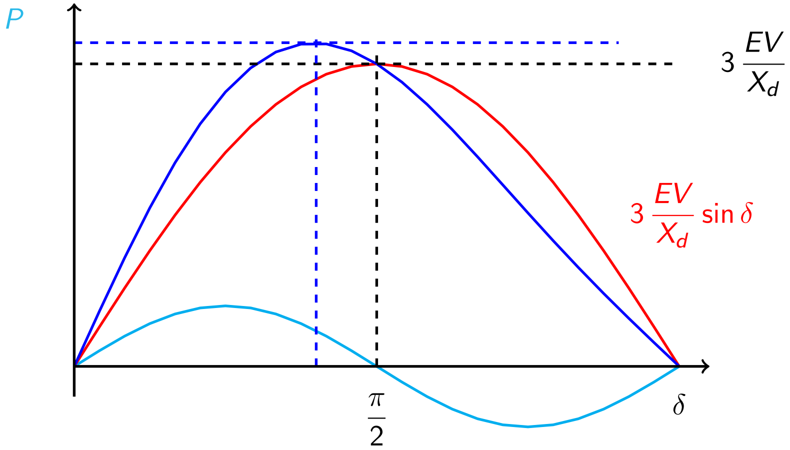
$$\overline{S} = 3(V_d + jV_q)(I_d + jI_q)^* = 3(V_d I_d + V_q I_q) + j3(V_q I_d - V_d I_q)$$

$$P = 3\left(V_d I_d + V_q I_q\right) = 3\,\frac{EV}{X_d}\sin\delta + 3\frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin(2\delta)$$

$$Q = 3(V_q I_d - V_d I_q) = 3\frac{EV}{X_d}\cos\delta - 3V^2\left(\frac{(\sin\delta)^2}{X_q} + \frac{(\cos\delta)^2}{X_d}\right)$$

Alternateur à pôles saillants : puissance de sortie

$$P = 3\,\frac{EV}{X_d}\sin\delta + 3\frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin(2\delta)$$



$$3\frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin(2\delta)$$: réluctance