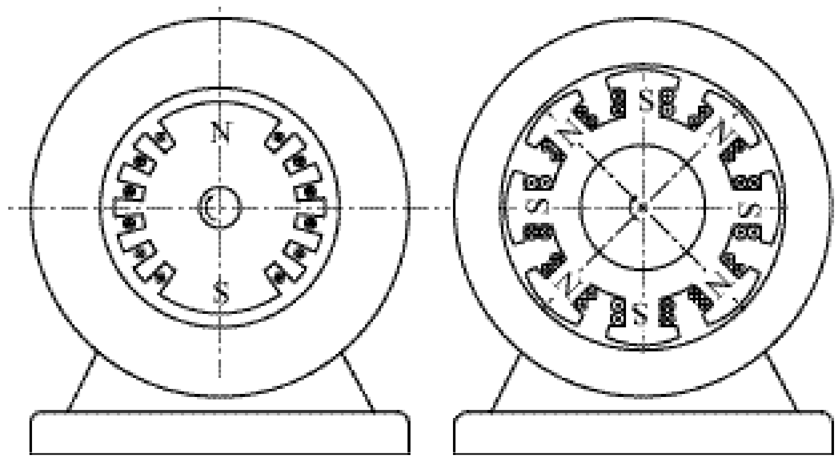
Synchronous machines

***Synchronous generator (alternator)**: transforms mechanical energy into electric energy; designed to generate sinusoidal voltages and currents; used in most power plants, for car alternators, etc.*
***Synchronous motor**: transforms electric energy into mechanical energy; used for high-power applications (ships, original TGV, electric cars…)*

Turbo-alternator

Saliant poles



***Rotor (inductor)** : 2p poles with excitation windings carrying DC current; non-laminated magnetic material*

$\dot{\theta} = \omega / p$

***Stator**: polyphase (e.g. 3-phase) winding in slots; laminated magnetic material*

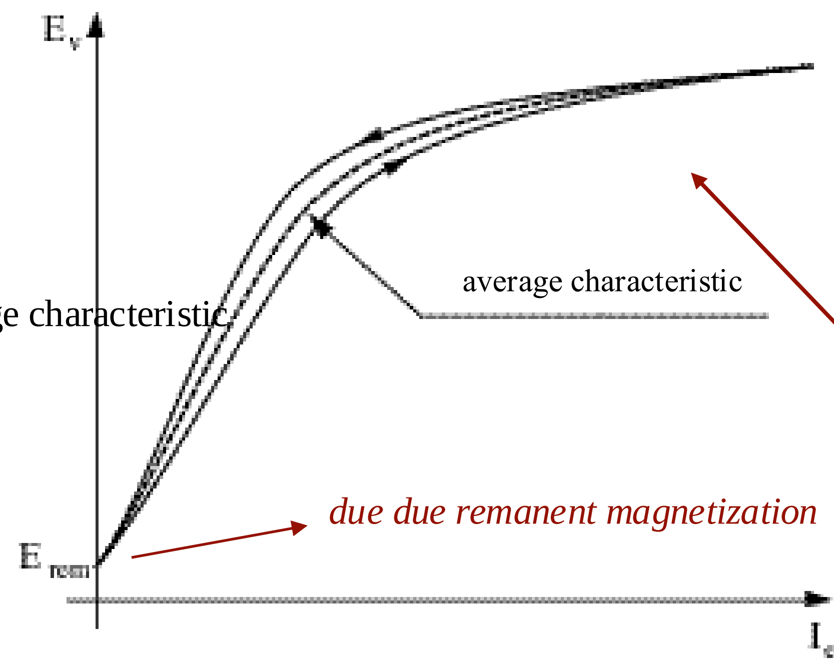
…

No-load characteristic

Evolution of the voltage E_v in a stator phase vs. intensity of the excitation current I_e, for a given rotation speed and with no generated stator current

- *The rotor winding, carrying the DC current I_e and rotating at speed ω/p, produces in the airgap a sliding m.m.f. F_e (as seen from the stator).*
- *F_e generates a magnetic flux density B_r (with the same phase) in the airgap, which induces sinusoidal e.m.f.s E_v in the stator windings, with a phase lag of $\pi/2$.*

average characteristic



due due remanent magnetization

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

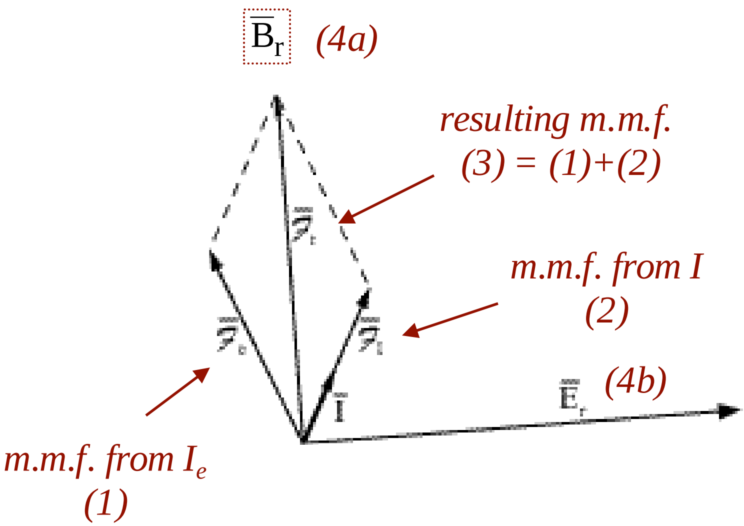
$$E_v = k_E \, \dot{\theta} \, \Phi_v(I_e)$$

Magnetic flux produced by the inductor and seen by the stator winding

Non linearity with hysteresis

Vector diagram with load

Diagram of magnetomotive forces and magnetic flux densities



$\boxed{\overline{F}_e = \gamma\, \overline{I}_e}$ *and* $\boxed{\overline{F}_I = \delta\, \overline{I}}$

(1) *The rotor winding, carrying the DC current* I_e *and rotating at speed* ω/p, *produces in the airgap a sliding m.m.f.* $\overline{F}_e$ *(as seen from the stator).*

(2) *The polyphase current* $\overline{I}$ *in the stator winding produces a sliding m.m.f.* $\overline{F}_I$ *(in phase with* $\overline{I}$*).*

(3) *The resulting m.m.f. is* $\overline{F}_r = \overline{F}_e + \overline{F}_I$.

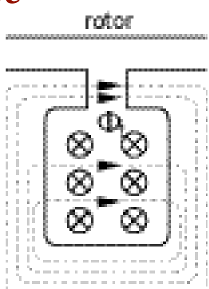
(4) $\overline{F}_r$ *generates a magnetic flux density* $\overline{B}_r$ *(with the same phase) in the airgap,, which induces sinusoidal e.m.f.s in the stator windings, with a phase lag of* $\pi/2$.

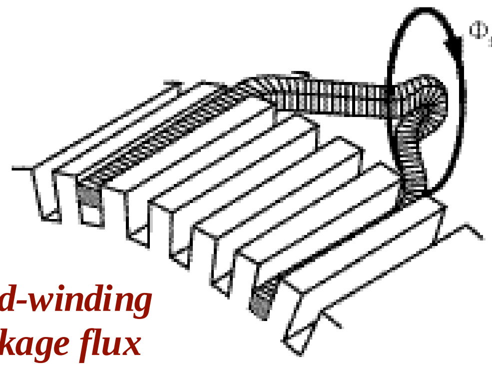
Vector diagram with load

Stator leakage flux

(seen by the stator but not coming from the rotor)

Slot leakage flux





End-winding leakage flux

e.m.f. induced by leakage flux

$$\boxed{\begin{aligned} e_\lambda(t) &= -\lambda\,\partial_t i_1 - \lambda_m\,\partial_t i_2 - \lambda_m\,\partial_t i_3 \\ &= -(\lambda - \lambda_m)\,\partial_t i_1 \end{aligned}}$$

because $i_1 + i_2 + i_3 = 0$

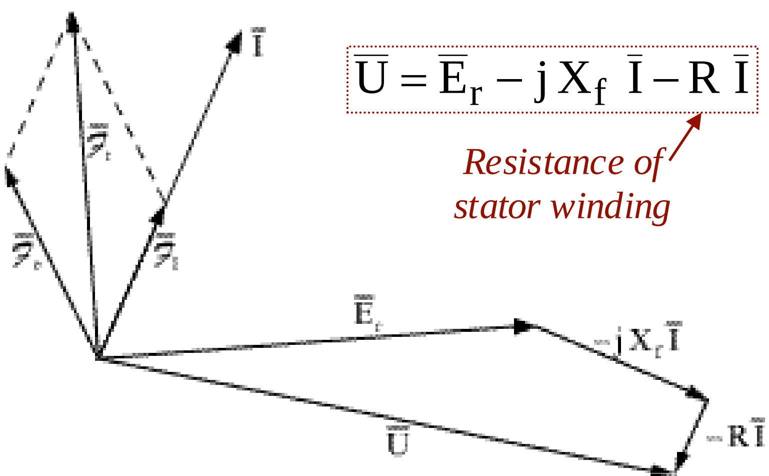
$$\boxed{\bar{E}_\lambda = -j\,X_f\,\bar{I}} \quad \textit{with} \quad \boxed{X_f = \omega\,(\lambda - \lambda_m)}$$

Stator leakage reactance

$$\boxed{\bar{E}_t = \bar{E}_r - j\,X_f\,\bar{I}}$$

total e.m.f.

Diagrams



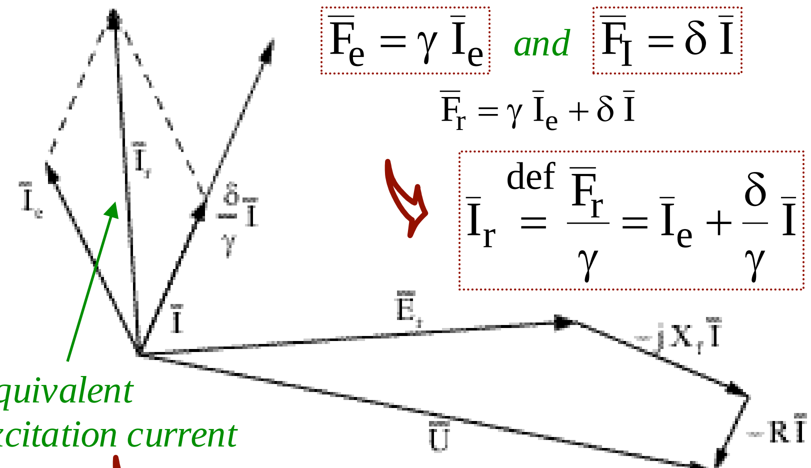
$$\boxed{\bar{U} = \bar{E}_r - j\,X_f\,\bar{I} - R\,\bar{I}}$$

Resistance of stator winding

$$\boxed{\bar{F}_e = \gamma\,\bar{I}_e} \quad \textit{and} \quad \boxed{\bar{F}_I = \delta\,\bar{I}}$$

$$\bar{F}_r = \gamma\,\bar{I}_e + \delta\,\bar{I}$$

$$\boxed{\bar{I}_r \overset{\text{def}}{=} \frac{\bar{F}_r}{\gamma} = \bar{I}_e + \frac{\delta}{\gamma}\,\bar{I}}$$



Equivalent excitation current

$E_r \equiv$ *no-load e.m.f. produced by* I_r

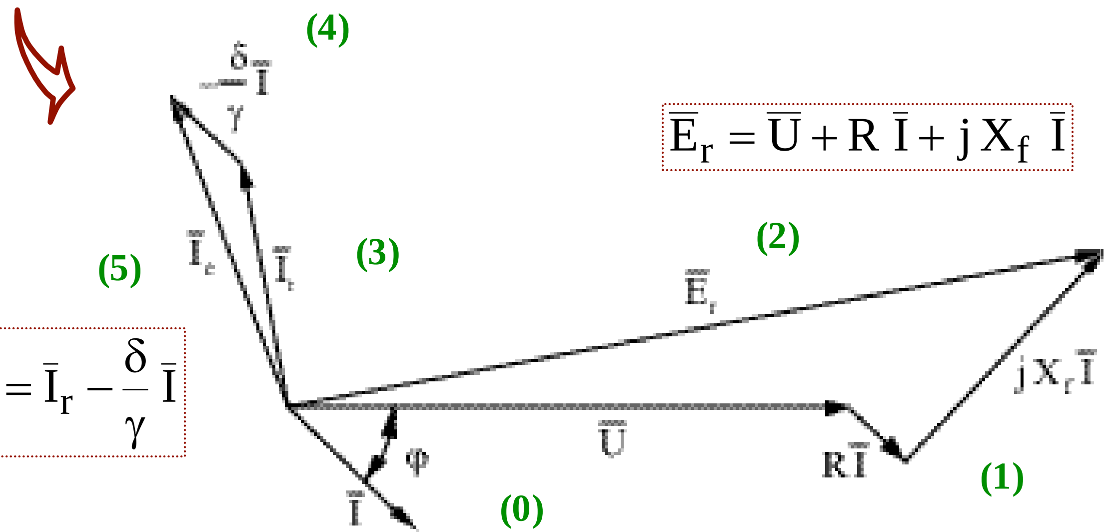
Potier diagram

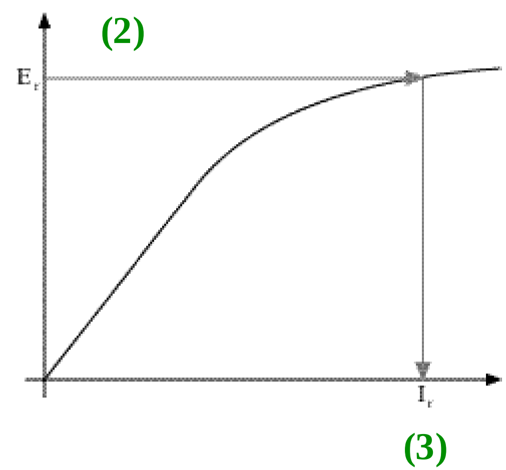
'Which excitation current I_e *should one impose in the synchronous machine to reach the operating point corresponding to a given voltage* U *and current* I in the stator, *with a phase shift of* φ *between* U *and* I*?'*

$E_r \equiv$ *no-load e.m.f produced by the equivalent current* I_r

$$\overline{E}_r = \overline{U} + R\,\overline{I} + j\,X_f\,\overline{I}$$

$$\overline{I}_e = \overline{I}_r - \frac{\delta}{\gamma}\,\overline{I}$$

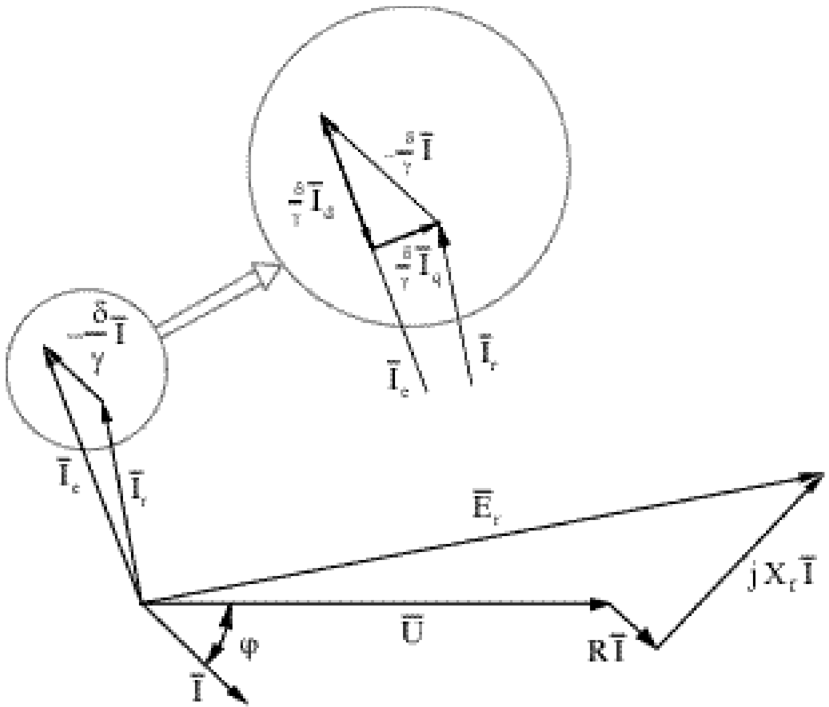




Reaction

Demagnetizing reaction

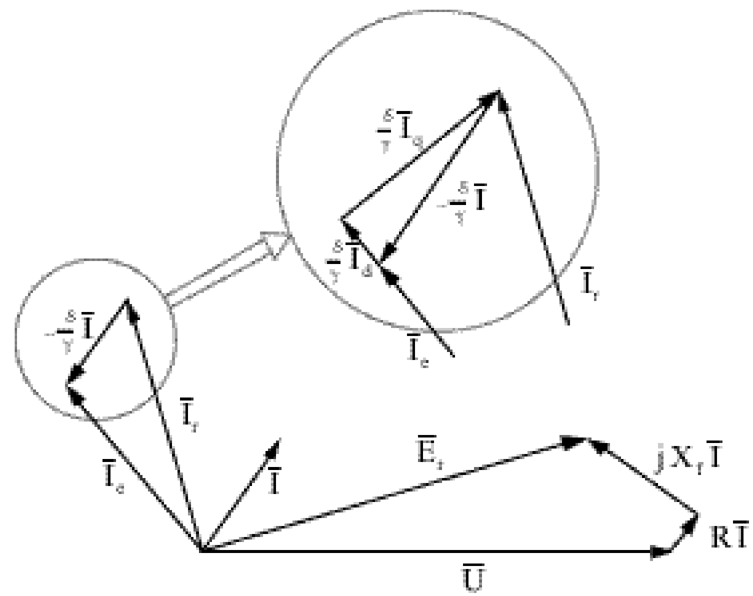
The m.m.f. is smaller than the no-load m.m.f. ($I_r < I_e$)



Inductive behaviour of the load
(I lagging behind U)

Magnetizing reaction

The m.m.f. is larger than the no-load m.m.f. ($I_r > I_e$)

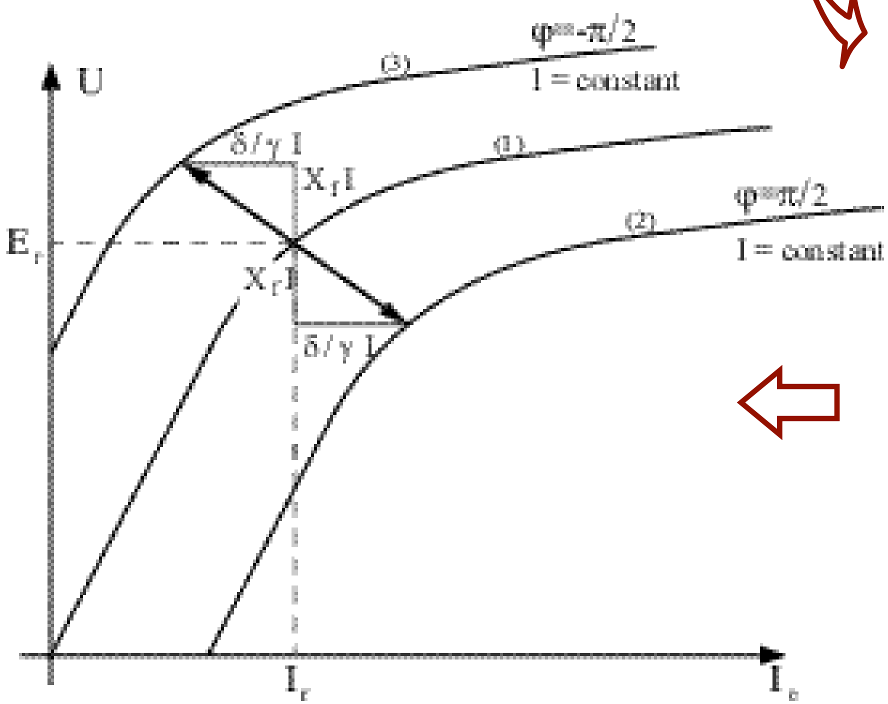


Capacitive behaviour of the load
(I in front of U)

Zero power factor characteristic

Evolution of the stator voltage U as a function of the excitation current I_e, for a given rotation speed and stator current, with a zero power factor

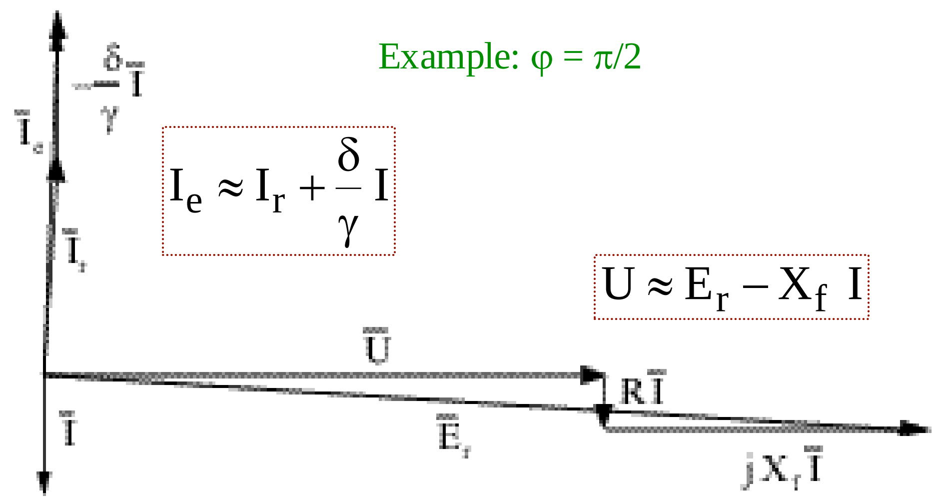
$$U = f(I_e) \quad \text{with} \quad \begin{cases} \text{speed } \dot{\theta} = \text{constant} \\ I = \text{constant} \\ \cos\varphi = 0 \ \ (\varphi = \pm\pi/2) \end{cases}$$



Example: $\varphi = \pi/2$

$$I_e \approx I_r + \frac{\delta}{\gamma} I$$

$$U \approx E_r - X_f\ I$$



Short-circuit characteristic

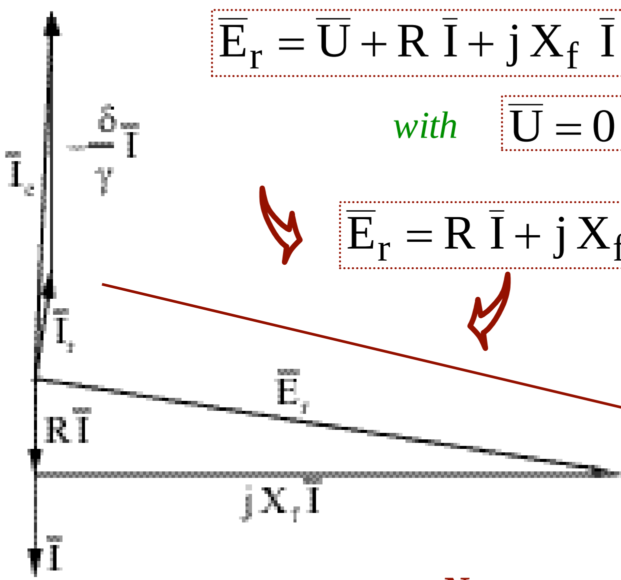
Evolution of the stator current as a function of the excitation current I_e, for a given rotation speed and with the stator windings in short-circuit

$$I = f(I_e) \quad \text{with} \quad \begin{cases} \text{speed } \dot{\theta} = \text{constant} \\ U = 0 \end{cases}$$

$$\bar{E}_r = \bar{U} + R\,\bar{I} + j\,X_f\,\bar{I}$$

with $\bar{U} = 0$

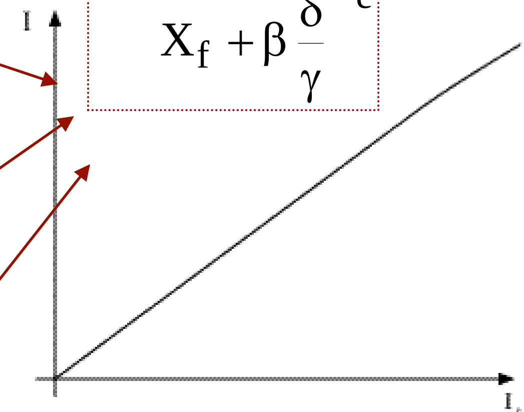
$$\bar{E}_r = R\,\bar{I} + j\,X_f\,\bar{I} \longrightarrow E_r \approx X_f\,I$$



$$I_e \approx I_r + \frac{\delta}{\gamma}\,I$$

Non saturated machine $\longrightarrow$ $E_r = \beta\,I_r$

$$I \approx \frac{\beta}{X_f + \beta\,\frac{\delta}{\gamma}}\,I_e$$

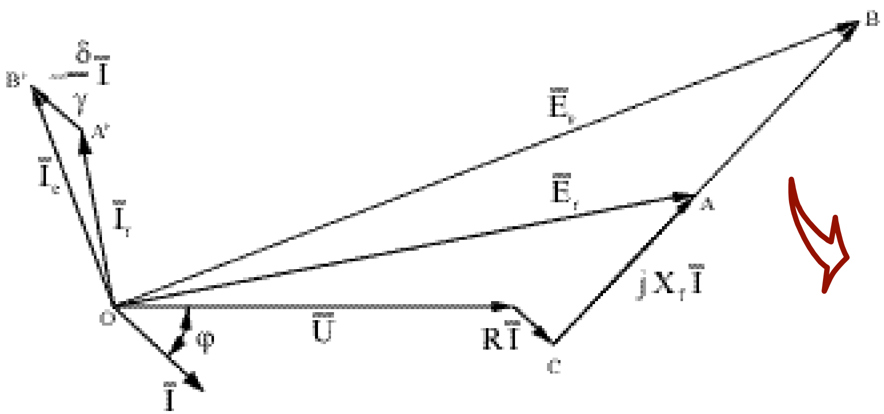


Simplified vector diagram

Behn-Eschenburg's method – Synchronous reactance X_s

When the magnetic materials are not saturated, the combined effect of the reaction and of stator leakage fluxes can be taken into account thanks to a single parameter: the synchronous reactance

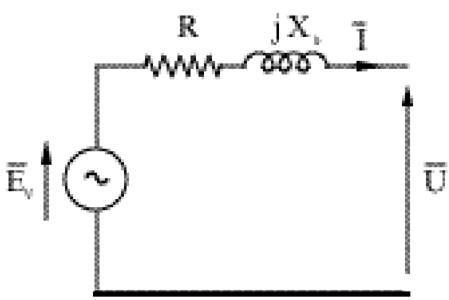
$$\frac{E_v}{I_e} = \frac{E_r}{I_r} = \text{constant}$$



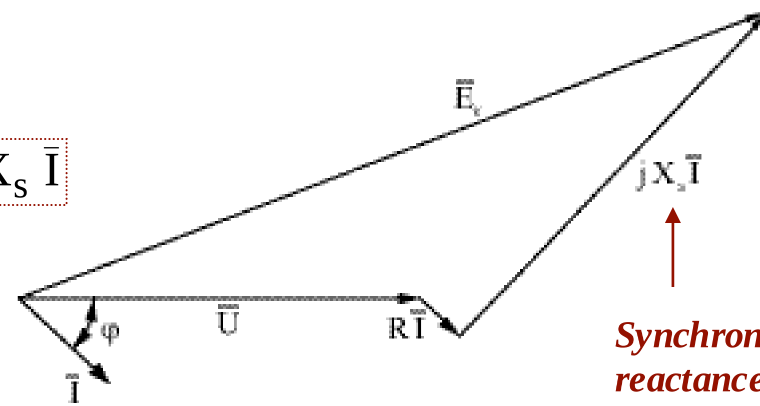
Equal angles OAB and OA'B'

Similar triangles OAB and OA'B'

A, B and C colinear



$$\bar{E}_V = \bar{U} + R\,\bar{I} + j\,X_s\,\bar{I}$$



Synchronous reactance

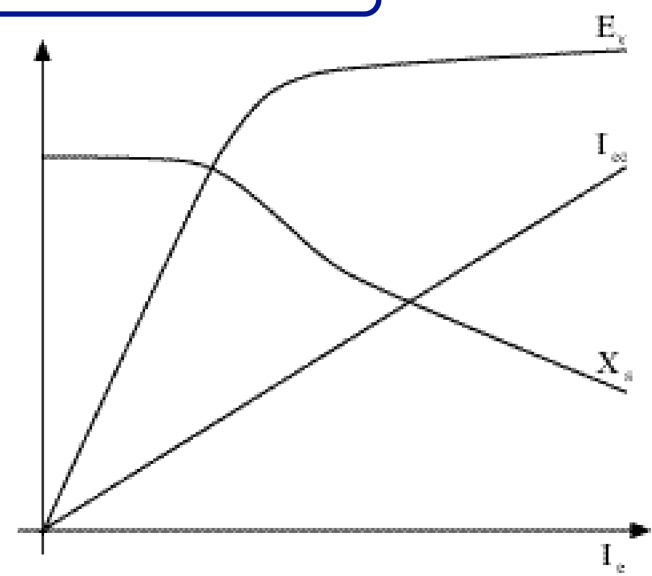
Experimental determination of X_s

Behn-Eschenburg's method – Synchronous reactance X_s

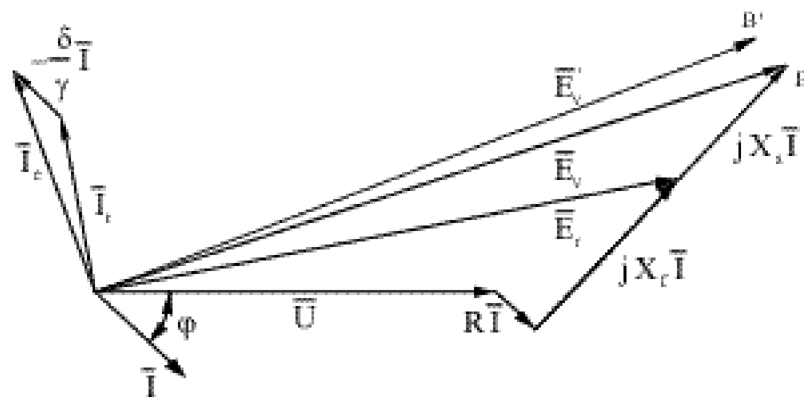
$\boxed{\overline{U} = 0} \quad \Rightarrow \quad \boxed{\overline{E}_V = \left(R + j\,X_S\right)\overline{I}_{CC}}$

$\Rightarrow \quad \boxed{R + j\,X_S = \dfrac{\overline{E}_V}{\overline{I}_{CC}}}$ *with* $\boxed{R << X_S}$

$\Rightarrow \quad \boxed{X_S \approx \dfrac{E_V(I_e)}{I_{CC}(I_e)}}$



Approximation when magnetic materials are saturated!

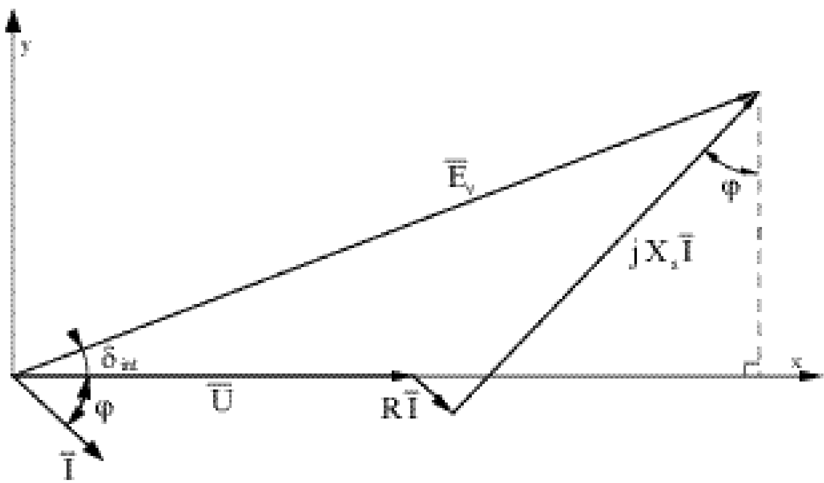


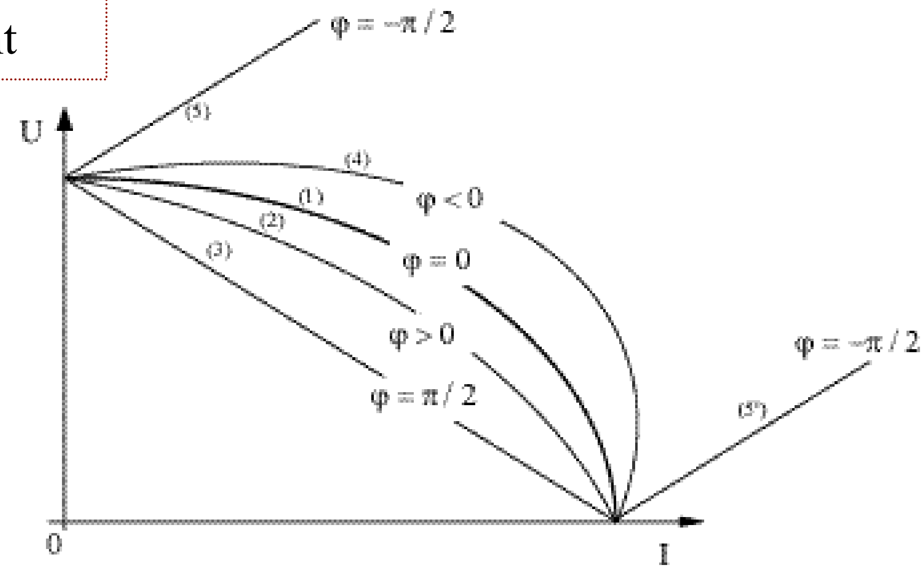
Exterior characteristic

Alternator exterior characteristic

Evolution of the voltage U on a given stator phase as a function of the current Iin this phase, when the alternator drives a load characterized by a constant power factor, at constant speed and excitation

$$U = f(I) \quad \text{with} \quad \begin{cases} \text{speed } \dot{\theta} = \text{constant} \\ I_e = \text{constant} \\ \cos\varphi = \text{constant} \end{cases}$$



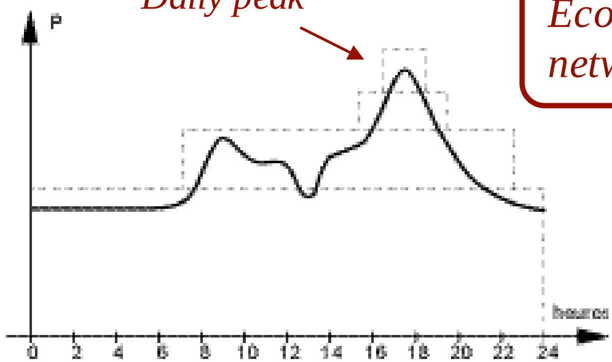


Network connection

Need for interconnection of electric power plants

Daily load

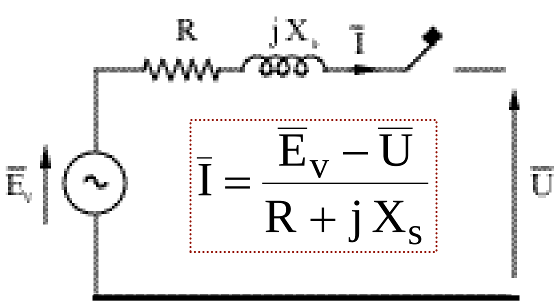
Daily peak



Economical organization of power production + Stability of the network despite local defects

Synchronization of an alternaltor on an ideal (infinitely powerful) AC network

Large number of production units in parallel
⇒ constant voltage and frequency



$$\bar{I} = \frac{\bar{E}_v - \bar{U}}{R + j X_s}$$

The current should be zero when the connection is made → 4 conditions

1. ***same pulsation*** ω ***(correct rotation speed)***
2. ***same amplitudes*** *for* E_v and U ***(adjusting*** I_e***)***
3. ***no phase shift between*** E_v and U
4. ***identical phase ordering*** *(in a 3-phase system)*

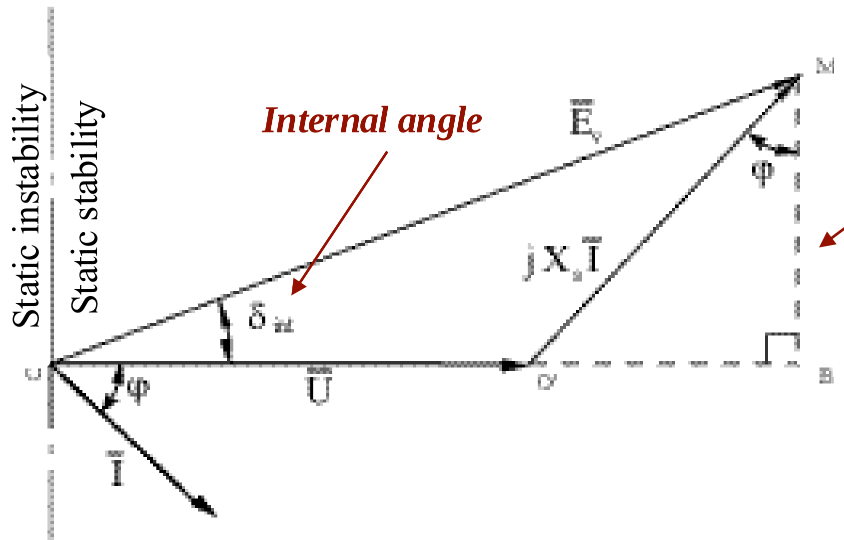
Behaviour with load

Active electric power

Electromagnetic power $P_{elm} \approx P = 3\,U\,I\cos\varphi$

Torque

$$C = \frac{P}{\omega / p} = \frac{3\,p}{\omega}\,U\,I\cos\varphi$$



$X_s\,I\cos\varphi = E_v\sin\delta_{int}$

$$C = \frac{3\,p}{\omega\,X_s}\,U\,E_v\sin\delta_{int}$$

Internal angle

The variations of the rotor mechanical angle $\Delta\delta_{mec}$ are proportional to the variations of the internal (electric) angle $\Delta\delta_{int}$

$$\Delta\delta_{mec} = \frac{\Delta\delta_{int}}{p}$$

After network synchronization, there is no exchanged current. Then :

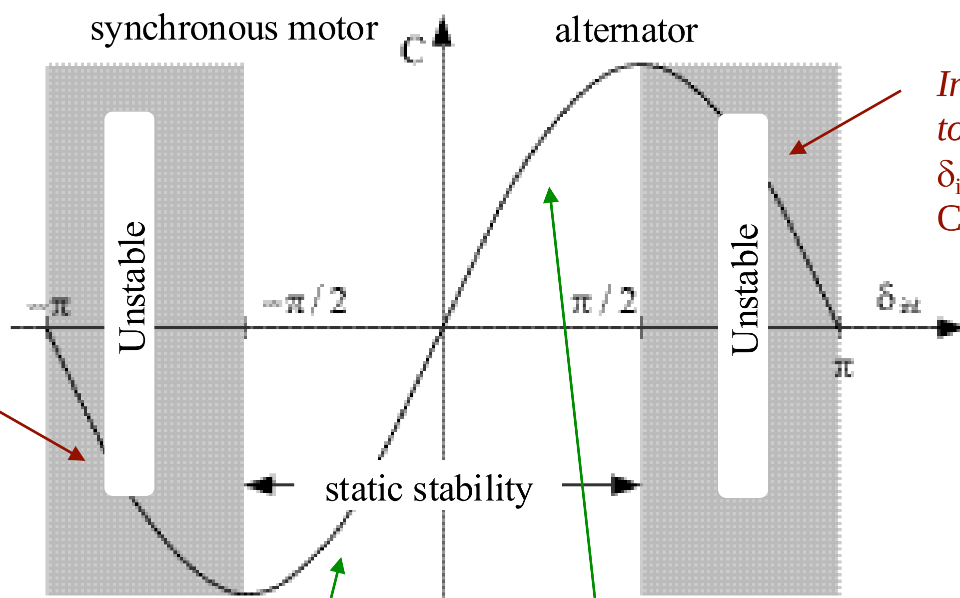
- *If mechanical power is provided to the alternator, E_v gets ahead of $U \Rightarrow \delta_{int}$ increases (until the equilibrium of the electromagnetic and mechanical torques)*
- *If a braking torque is applied to the alternator, E_v gets behind $U \Rightarrow \delta_{int}$ decreases (negative torque)*

Behaviour with load

Static stability

Internal angle

$\delta_{int} < 0$ $\delta_{int} > 0$



Increasing the mechanical (breaking) torque leads to an increase of the absolute value of δ_{int}, and thus to a decrease in the absolute value of C_{elm} $\Rightarrow$ ***unstable***

Increasing the mechanical torque leads to an increase of δ_{int}, and thus to a decrease of C_{elm} $\Rightarrow$ ***unstable***

Increasing the mechanical (breaking) torque leads to an increase of the absolute value of δ_{int} and thus of C_{elm} $\Rightarrow$ ***stable****.*
The equilibrium is reached when the two torques are equal.

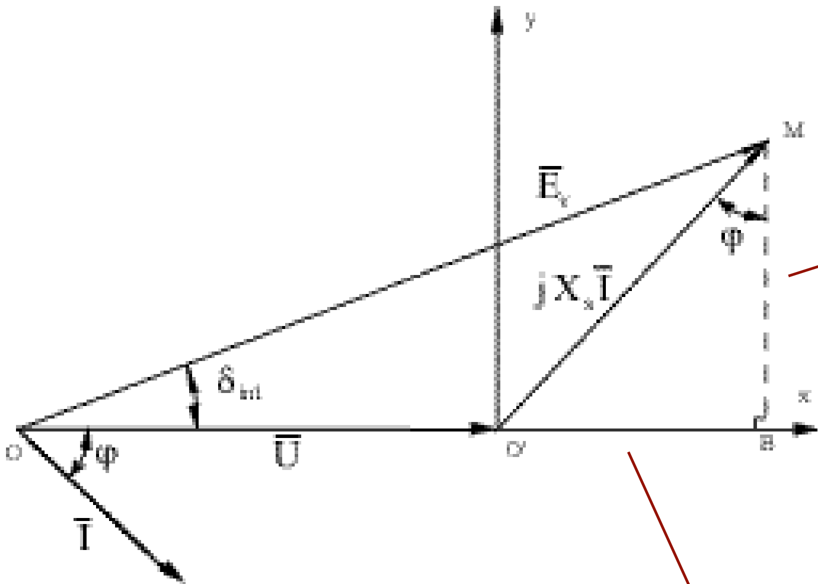
Increasing the mechanical torque leads to an increase of δ_{int} and thus of C_{elm} $\Rightarrow$ ***stable****.*
The equilibrium is reached when the two torques are equal.

Behaviour with load

Power diagram

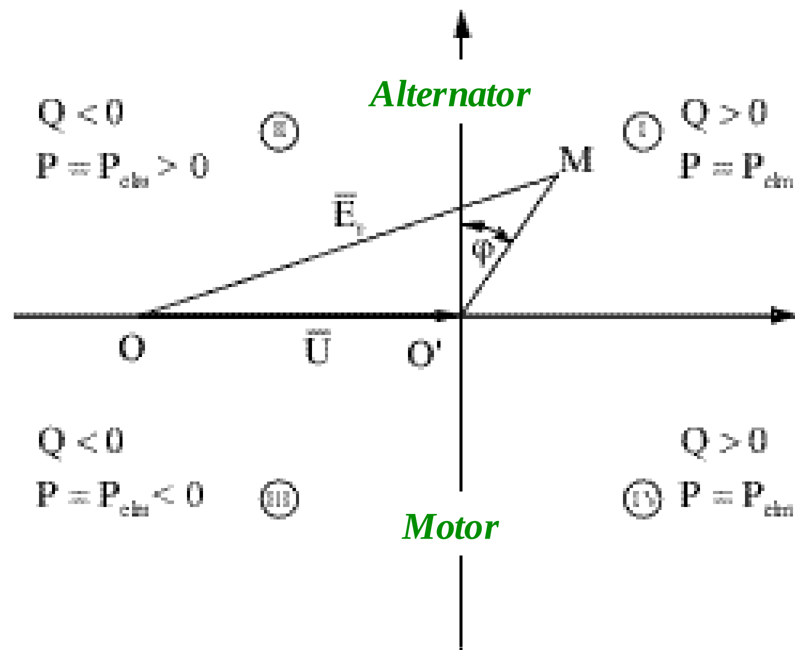
$$MB = X_s\, I \cos\varphi = \frac{X_s}{3\,U}\, 3\,U\, I \cos\varphi = \frac{X_s}{3\,U}\, P = \frac{X_s}{3\,U}\, P_{elm}$$

Active power P



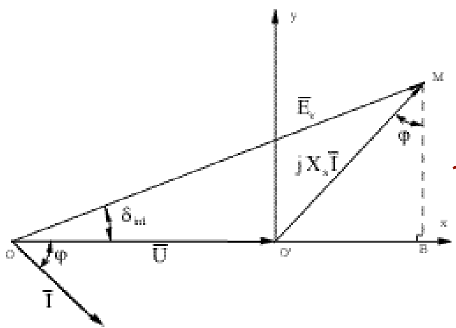
$$O'B = X_s\, I \sin\varphi = \frac{X_s}{3\,U}\, 3\,U\, I \sin\varphi = \frac{X_s}{3\,U}\, Q$$

Reactive power Q



V-curves (Mordey curves)

Evolution of the stator current I as a function of the excitation current I_e of a synchronous machine connected to an ideal network, at constant active power



Constant active power