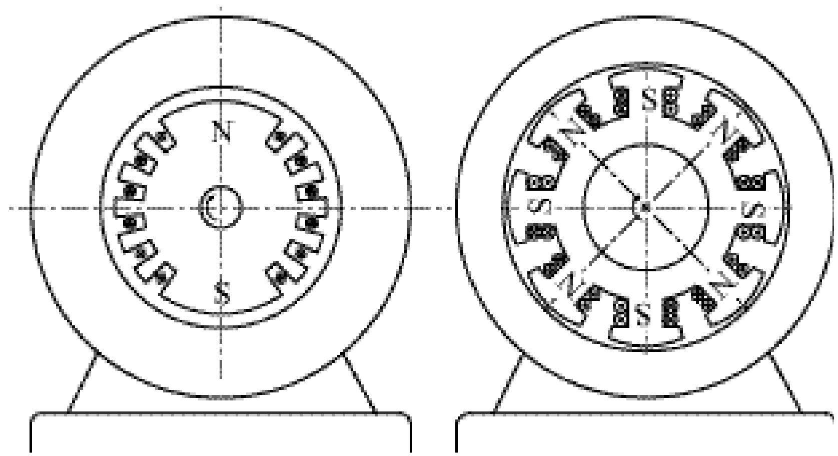
Synchronous machines

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*

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

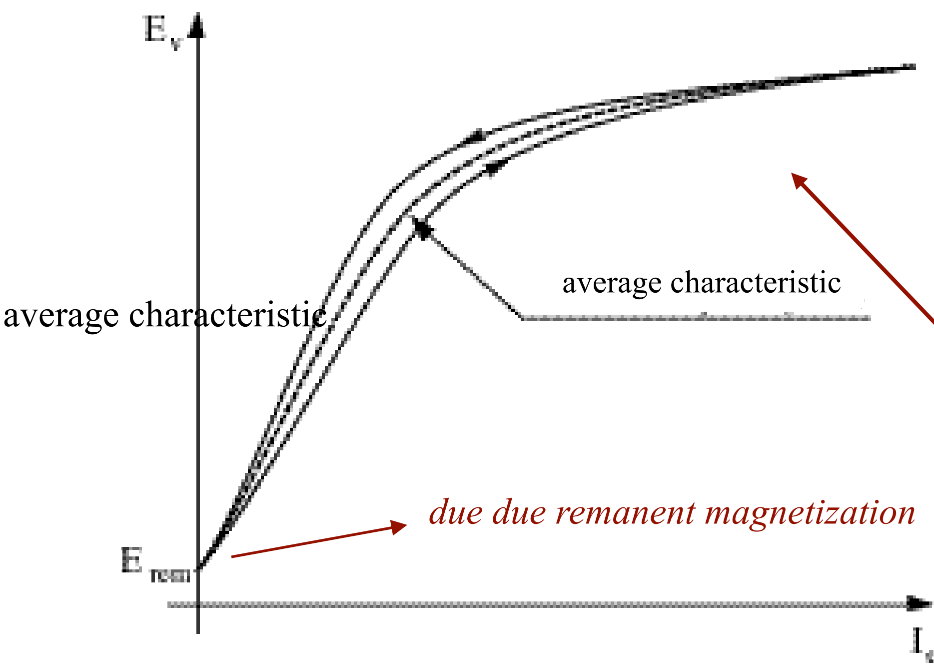
…

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 $\pi/2$.*



due due remanent magnetization

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

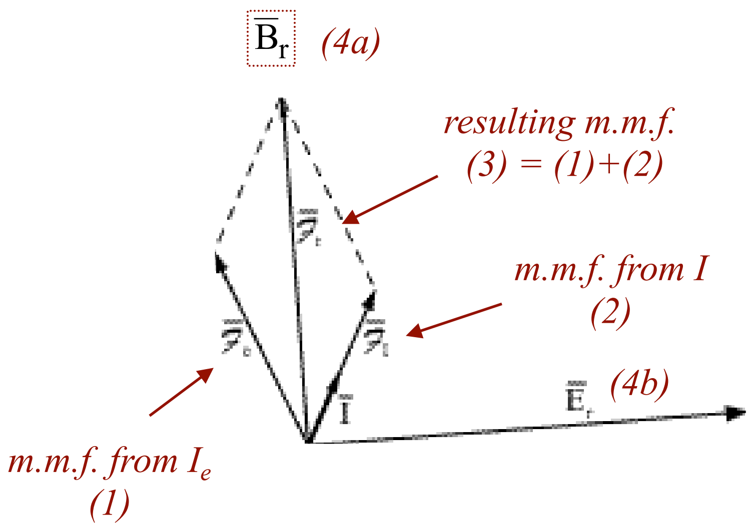
$$E_v = k_E \, \dot{\theta} \, \Phi_v(I_e)$$

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



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

(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 $\overline{F}_r = \overline{F}_e + \overline{F}_I$.*

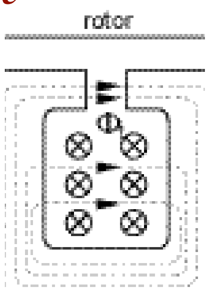
(4) *$\overline{F}_r$ generates a magnetic flux density $\overline{B}_r$ (with the same phase) in the airgap,, which induces sinusoidal e.m.f.s in the stator windings, with a phase lag of $\pi/2$.*

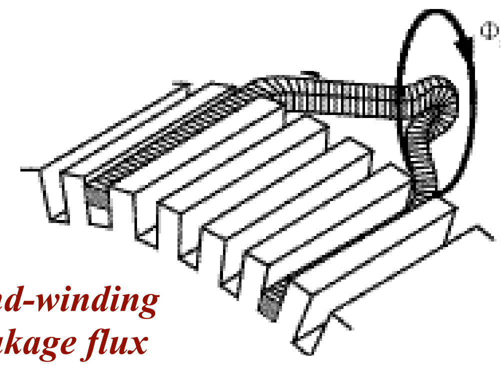
Vector diagram with load

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

$$e_\lambda(t) = -\lambda\,\partial_t i_1 - \lambda_m\,\partial_t i_2 - \lambda_m\,\partial_t i_3$$
$$= -(\lambda - \lambda_m)\,\partial_t i_1$$

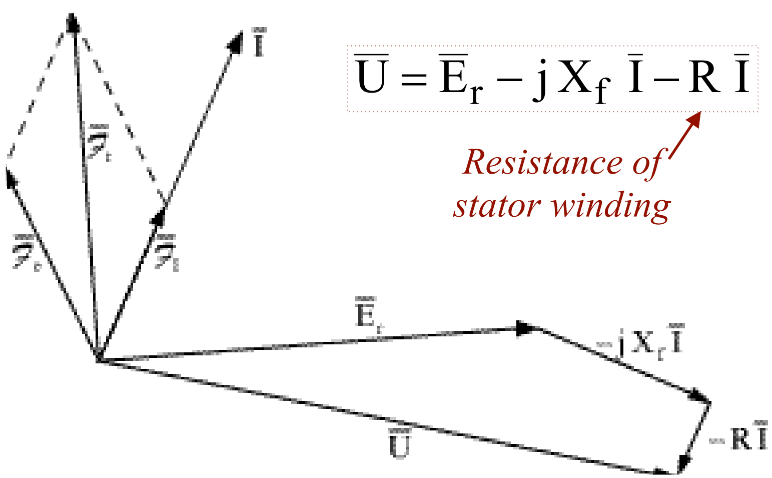
because $i_1 + i_2 + i_3 = 0$

$\overline{E}_\lambda = -j\,X_f\,\overline{I}$ *with* $X_f = \omega\,(\lambda - \lambda_m)$

Stator leakage reactance

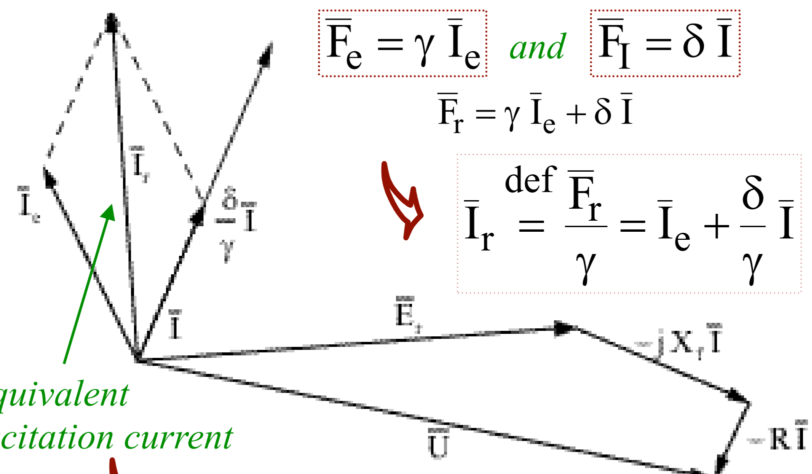
$\overline{E}_t = \overline{E}_r - j\,X_f\,\overline{I}$ *total e.m.f.*

Diagrams



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

Resistance of stator winding



Equivalent excitation current

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

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

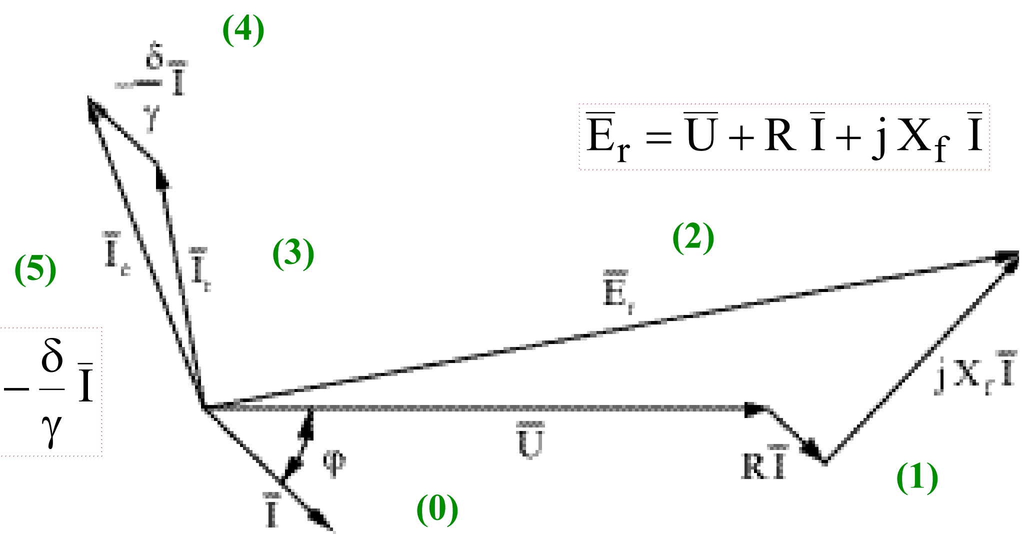
$$\overline{I}_r \overset{\text{def}}{=} \frac{\overline{F}_r}{\gamma} = \overline{I}_e + \frac{\delta}{\gamma}\,\overline{I}$$

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

Potier diagram

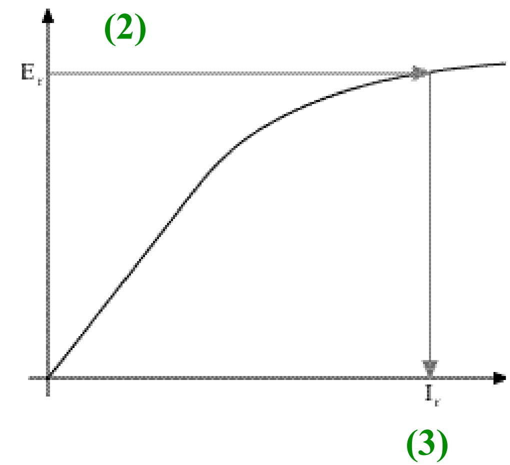
'Which excitation current I_e *should one impose in the synchronous machine to reach the operating point corresponding to a given voltage* U *and current* I in the stator, *with a phase shift of* φ *between* U *and* I*?'*

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



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

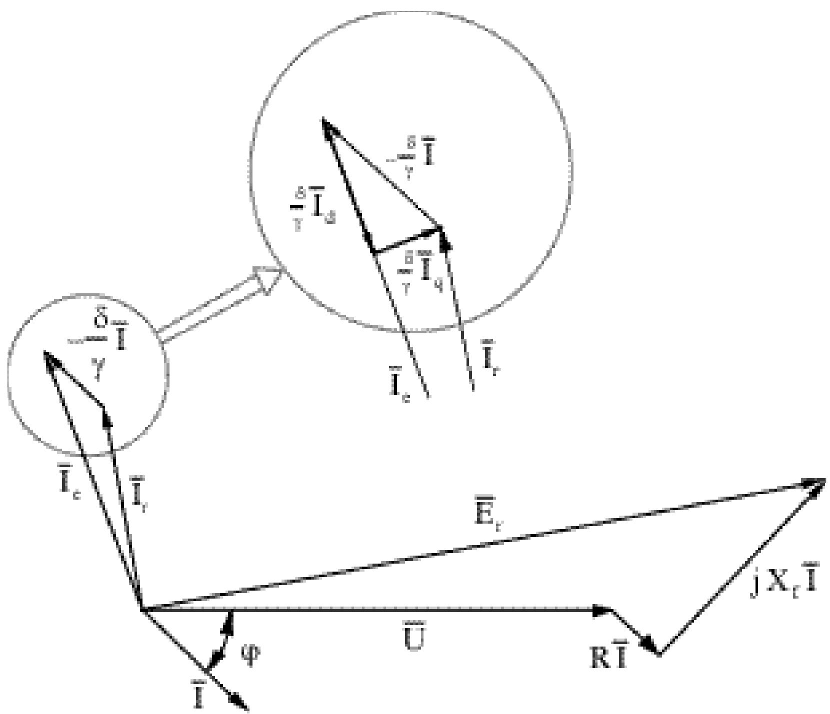
$$\bar{I}_e = \bar{I}_r - \frac{\delta}{\gamma}\bar{I}$$



Reaction

Demagnetizing reaction

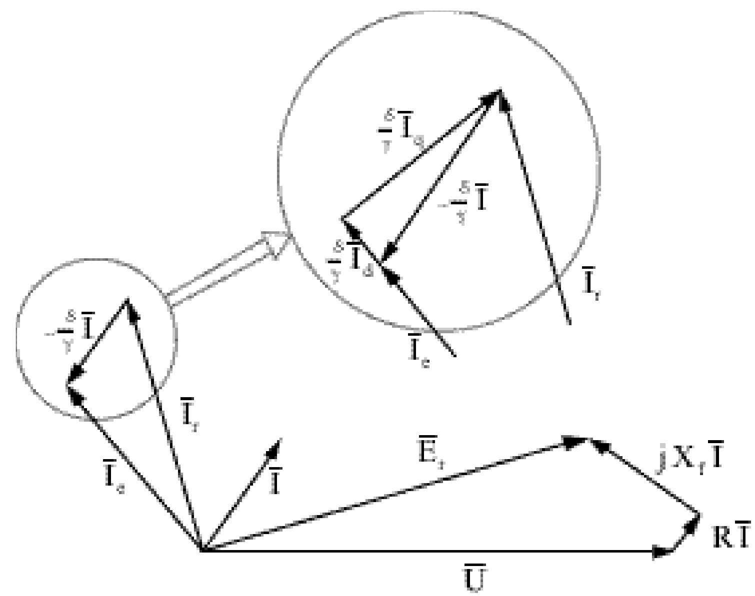
The m.m.f. is smaller than the no-load m.m.f. ($I_r < I_e$)



Inductive behaviour of the load
(I lagging behind U)

Magnetizing reaction

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

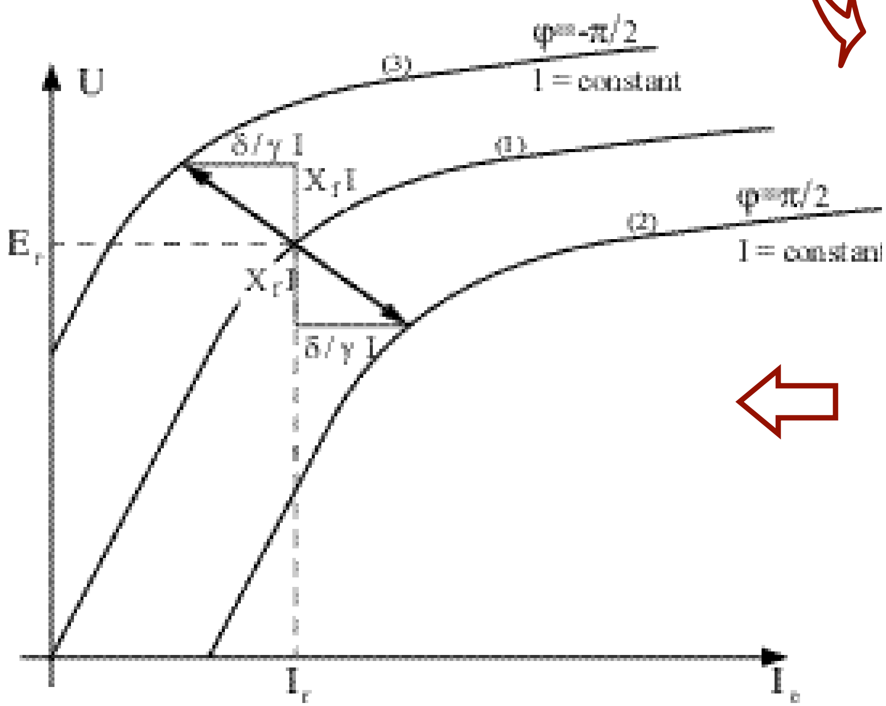


Capacitive behaviour of the load
(I in front of U)

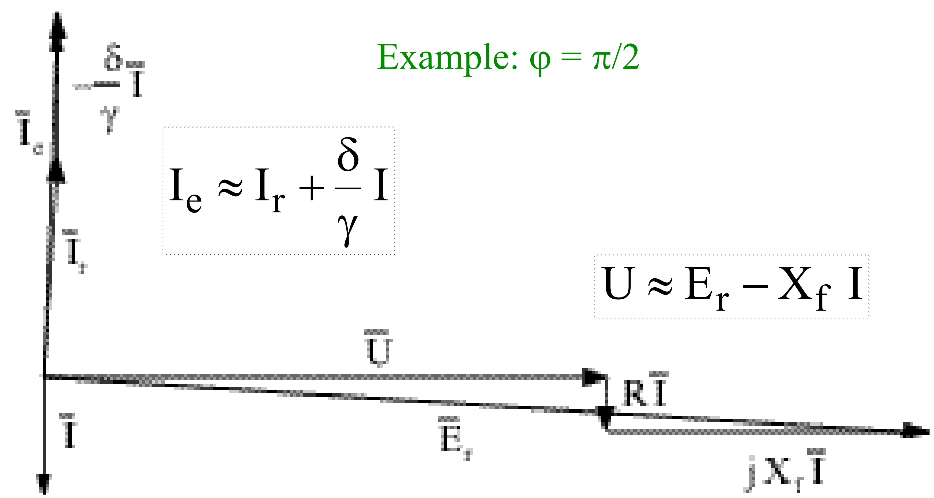
Zero power factor characteristic

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: $\varphi = \pi/2$



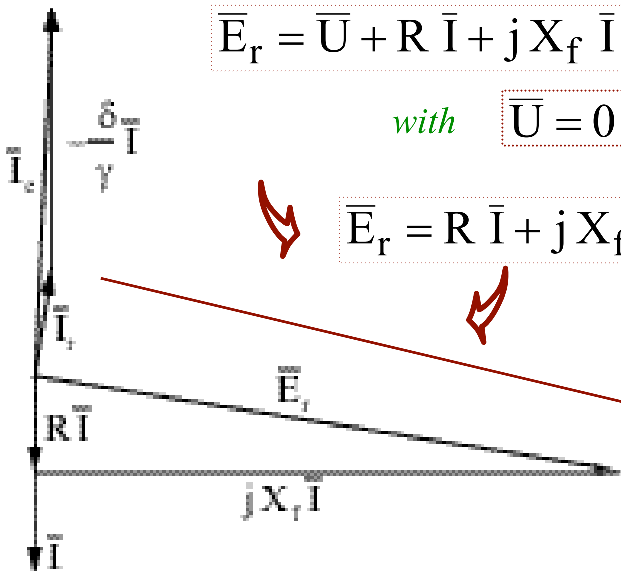
$$I_e \approx I_r + \frac{\delta}{\gamma} I$$

$$U \approx E_r - X_f I$$

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 $\bar{U} = 0$

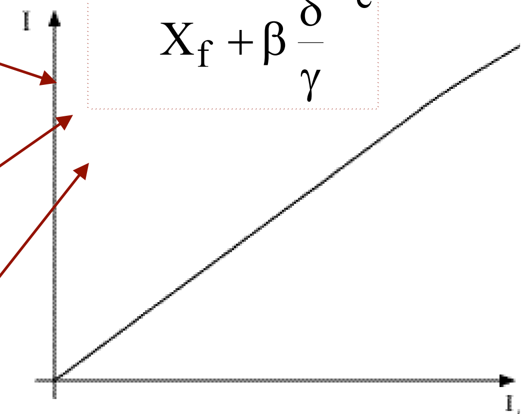
$$\bar{E}_r = R\,\bar{I} + j\,X_f\,\bar{I}$$

$$E_r \approx X_f\,I$$

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

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

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

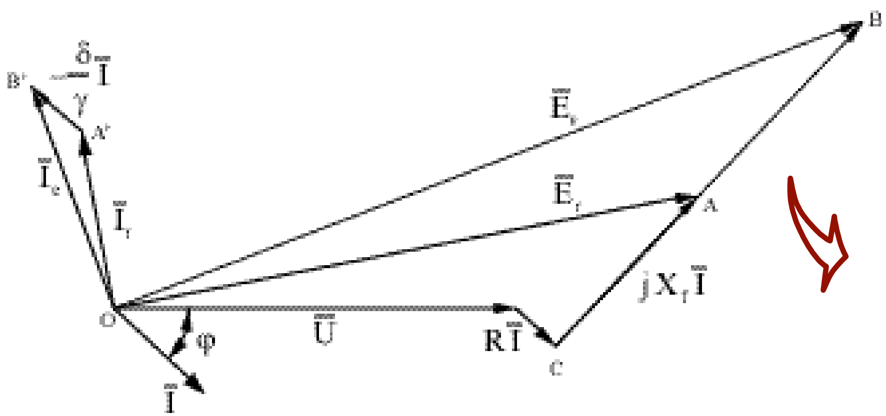


Simplified vector diagram

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

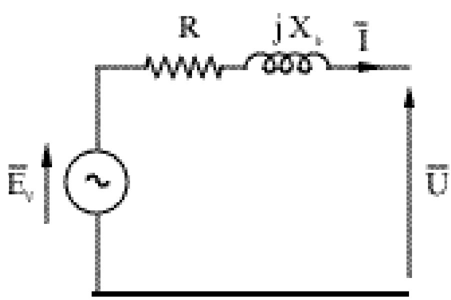
$$\frac{E_v}{I_e} = \frac{E_r}{I_r} = \text{constant}$$



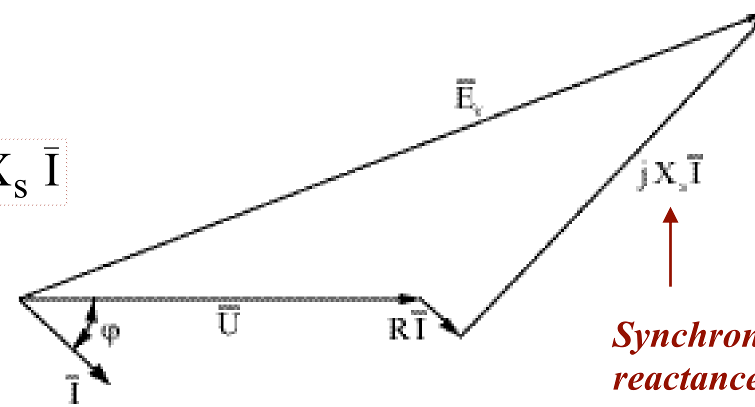
Equal angles OAB and A'OB'

Similar triangles OAB and OA'B'

A, B and C colinear



$$\overline{E}_V = \overline{U} + R\,\overline{I} + j\,X_S\,\overline{I}$$



Synchronous reactance

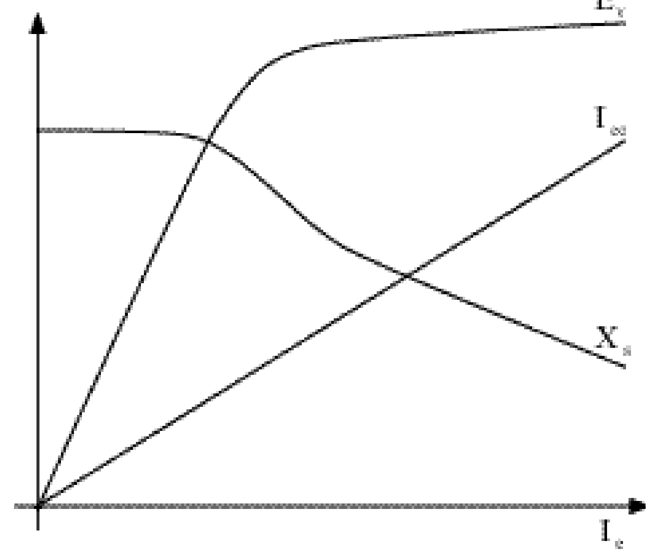
Experimental determination of X_s

Behn-Eschenburg's method – Synchronous reactance X_s

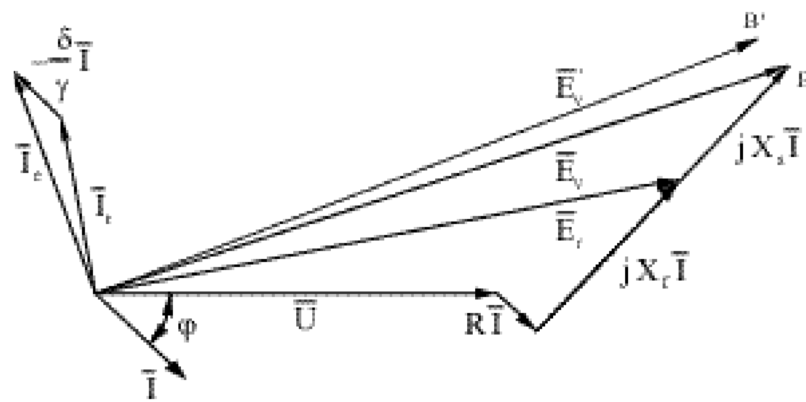
$\overline{U} = 0 \Rightarrow \overline{E}_V = (R + jX_s)\,\overline{I}_{cc}$

$\Rightarrow R + jX_s = \dfrac{\overline{E}_V}{\overline{I}_{cc}}$ *with* $R \ll X_s$

$\Rightarrow X_s \approx \dfrac{E_V(I_e)}{I_{cc}(I_e)}$



Approximation when magnetic materials are saturated!

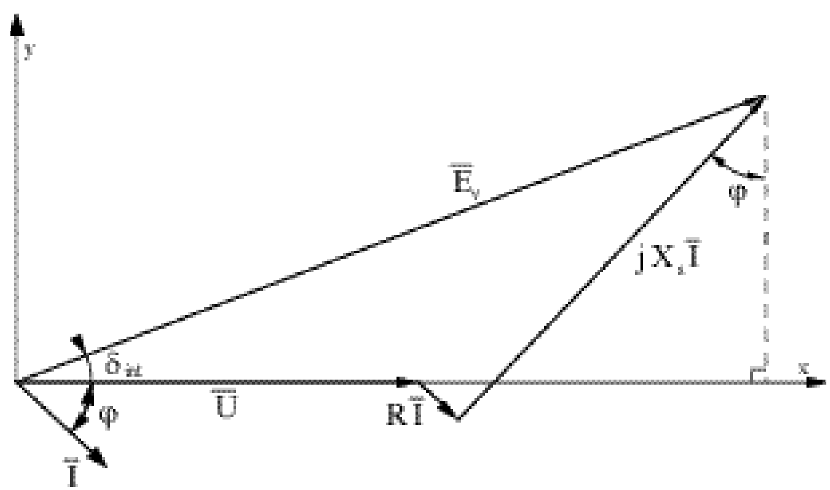


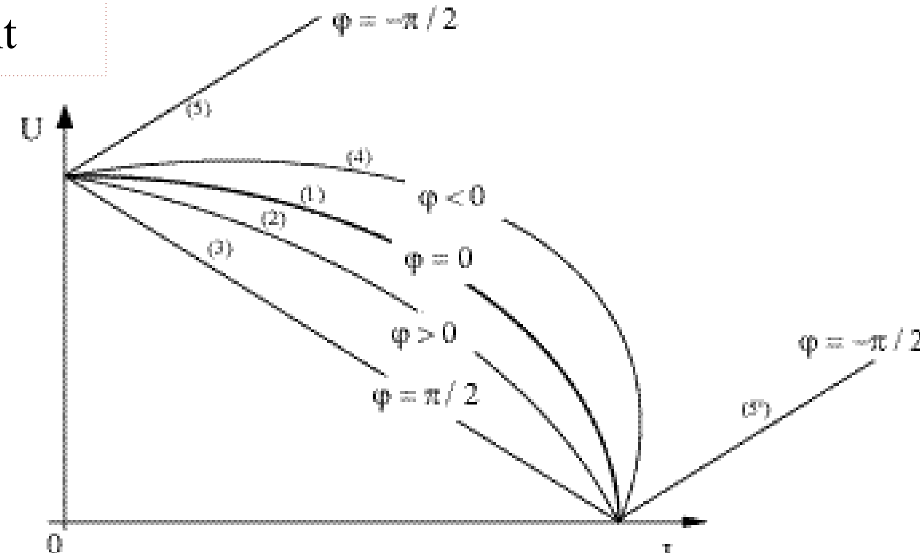
Exterior characteristic

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

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



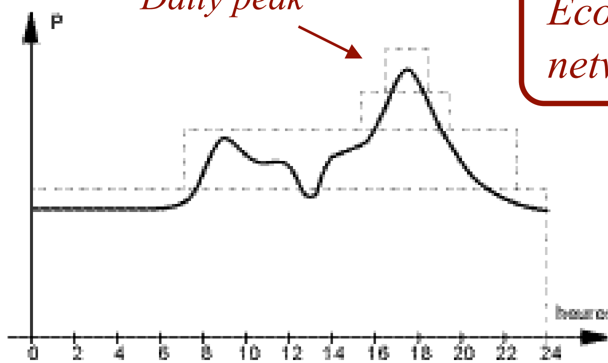


Network connection

Need for interconnection of electric power plants

Daily peak

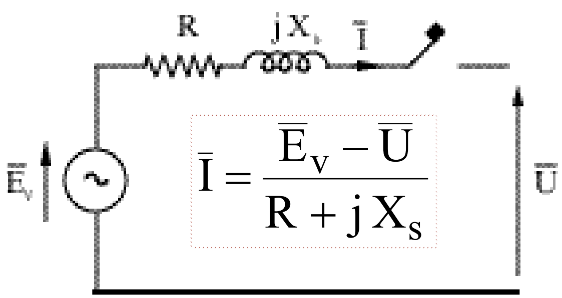
Daily load



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



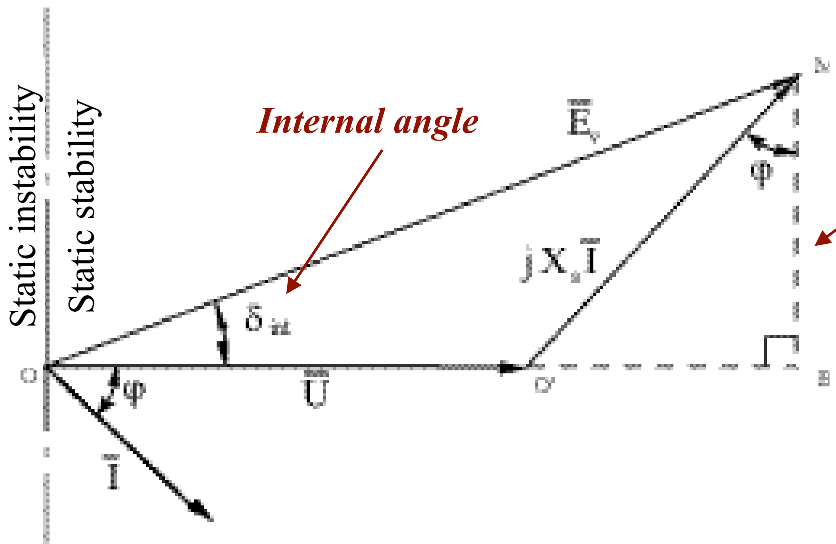
The current should be zero when the connection is made → 4 conditions

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 — *Torque*

Electromagnetic power $P_{elm} \approx P = 3\,U\,I\cos\varphi$ ⇒ $C = \frac{P}{\omega/p} = \frac{3\,p}{\omega} U\,I\cos\varphi$



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

⇓

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

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 :

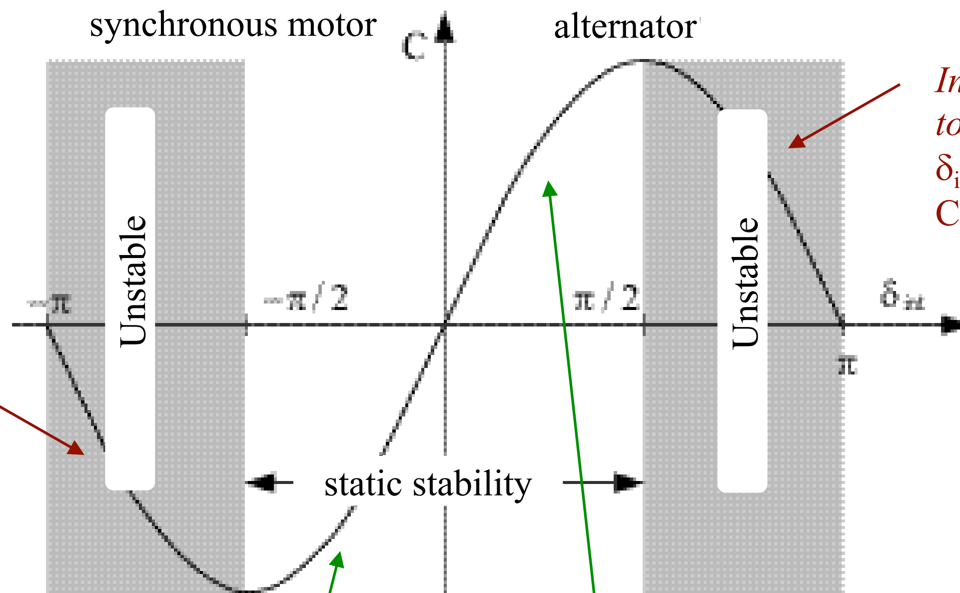
- *If mechanical power is provided to the alternator,* E_v *gets ahead of* $U \Rightarrow \delta_{int}$ *increases (until the equilibrium of the electromagnetic and mechanical torques)*
- *If a braking torque is applied to the alternator,* E_v *gets behind* $U \Rightarrow \delta_{int}$ *decreases (negative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

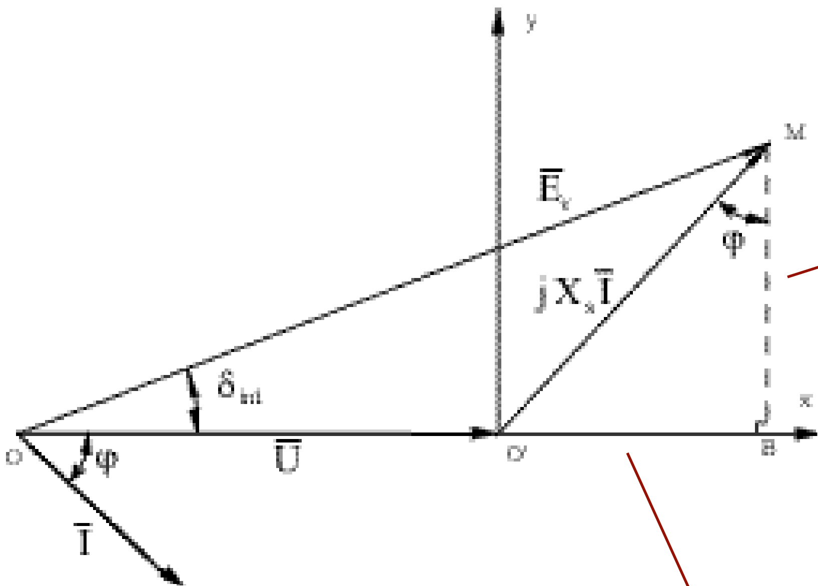
Increasing the mechanical torque leads to an increase of δ_{int} and thus of C_{elm} $\Rightarrow$ ***stable****.*
The equilibrium is reached when the two torques are equal.

Behaviour with load

Power diagram

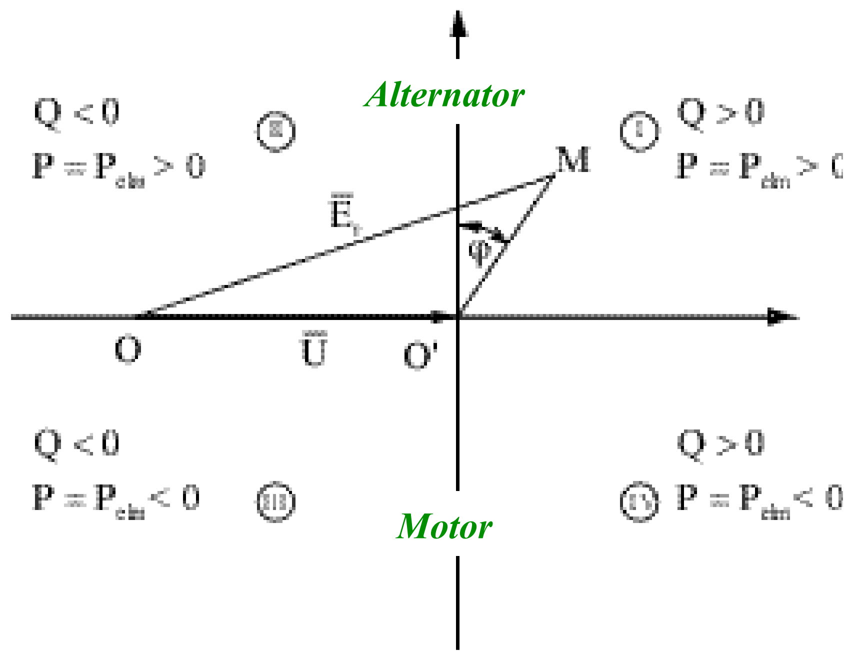
$$MB = X_s\ I \cos\varphi = \frac{X_s}{3\,U}\ 3\,U\,I\cos\varphi = \frac{X_s}{3\,U}\ P = \frac{X_s}{3\,U}\ P_{elm}$$

***Active power* P**



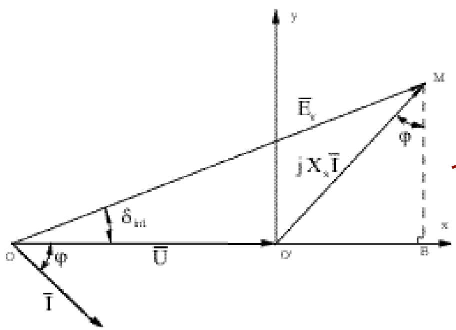
$$O'B = X_s\ I \sin\varphi = \frac{X_s}{3\,U}\ 3\,U\,I\sin\varphi = \frac{X_s}{3\,U}\ Q$$

***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