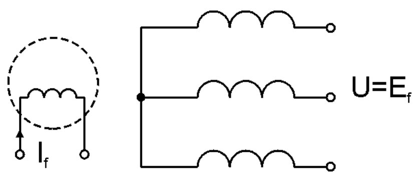
SYNCHRONOUS MACHINES OPERATION AND CHARACTERISTICS

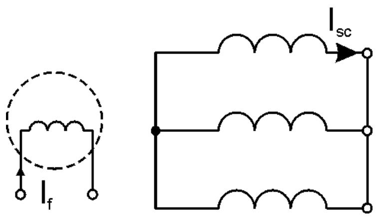
NO-LOAD AND SHORT-CIRCUIT CHARACTERISTICS



No-load state.

E_f = f(I_f) for n=n_N (const.)

open-circuit characteristic (occ)

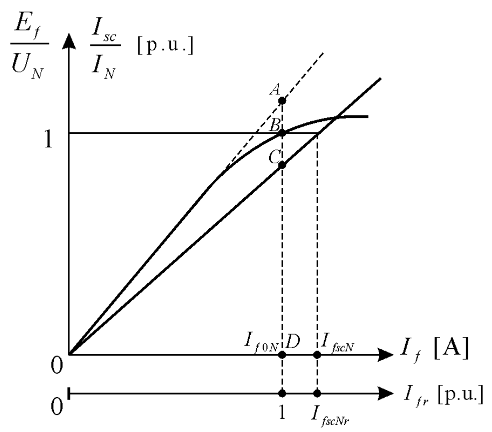


Short-circuit state.

I_{sc} = f(I_f) for n=n_N (const.)

short-circuit characteristic (scc)

Per-unit values: $I_r=I/I_N$ $U_r=U/U_N$ ($E_r=E/U_N$)



I_{foN} – nominal field current at no-load (E_f=U_N)

I_{fscN} – nominal field current at short circuit (I_{sc}=I_N)

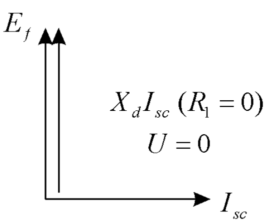
I_{foN} is usually applied as a base for relative values of field current

$$I_{fr} = I_f/I_{foN}$$

Short-circuit ratio is an important parameter of synchronous generator:

$$K_{sc} = \frac{I_{foN}}{I_{fscN}} = \frac{1}{I_{fscNr}} \begin{cases} \approx 0.3 - \text{for cylindrical mach. (turbogenerator)} \\ \approx 1.5 - \text{for salient-pole m. (hydrogenerator)} \end{cases}$$

Assume SM excited by I_{foN}. At no-load: E_f=U_N.
At short circuit: I_{sc}=CD and the state of machine can be shown by the following phasor diagram:



$$X_d = \frac{E_f}{I_{sc}} \Rightarrow \begin{cases} \frac{BD[\text{V}]}{CD[\text{A}]} = X_d[\Omega] \text{ for saturated machine} \\ \frac{AD[\text{V}]}{CD[\text{A}]} = X_{dun}[\Omega] \text{ for unsaturated machine} \end{cases}$$

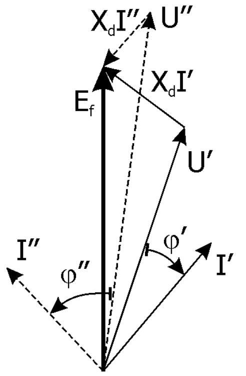
$$\frac{BD[\text{p.u.}]}{CD[\text{p.u.}]} = X_{dr}[\text{p.u.}] \qquad X_{dr} = \frac{X_d}{Z_N} = \frac{X_d}{U_N/I_N}$$

From the triangles:

$$\frac{BD[\text{p.u.}]}{CD[\text{p.u.}]} = \frac{I_{fscNr}}{1} \quad \Rightarrow \quad X_{dr} = \frac{1}{K_{sc}}$$

STEADY-STATE OPERATING CHARACTERISTICS OF GENERATOR

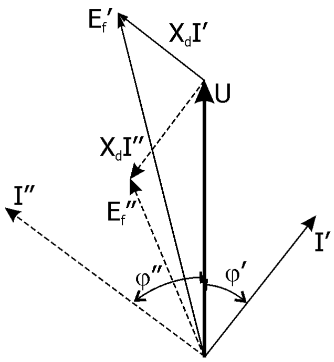
a) External characteristics; voltage-current characteristics; constant excitation characteristics



$U = f(I)$ for I_f = const
$\cos\varphi$ = const
n = const

‘ lagging character of load
‘’ leading character of load

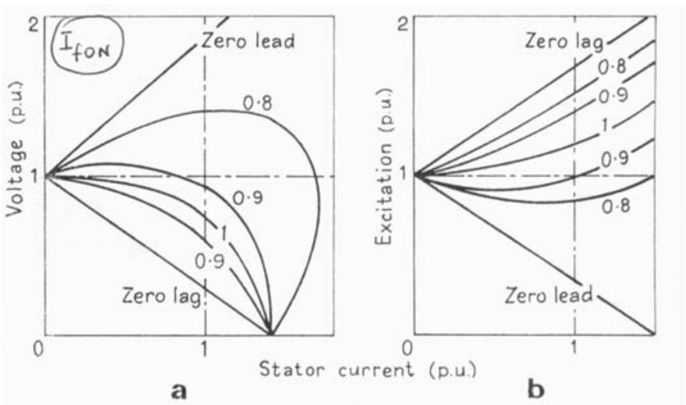
b) Regulation characteristics; constant voltage characteristics



$I_f = f(I)$ for U = const
$\cos\varphi$ = const
n = const

‘ lagging character of load; $E_f > U$; machine is overexcited
‘’ leading character of load; $E_f < U$; machine is underexcited

Characteristics for a) and b):



Voltage regulation

$$\Delta U_r = \frac{E_f - U}{U} \quad [\text{p.u.}]$$

for nominal load current, nominal excitation and nominal power factor

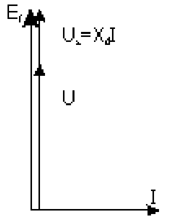
$$\Delta U_{rN} = \frac{E_{fN} - U_N}{U_N} \quad [\text{p.u.}]$$

ΔU_r for lagging power factor can be of significant value; it can be of zero value for leading power factor or even be negative.

Usually – in power stations – synchronous generators operate on lagging loads (p.f. = 0.8 – 0.9 lag) and have a large positive voltage regulation (voltage drop). To keep the voltage constant a wide range control of field current is required.

c) V-curves of synchronous generator (Mordey's curves)

$I = f(I_f)$ for P = const
U = const
n = const

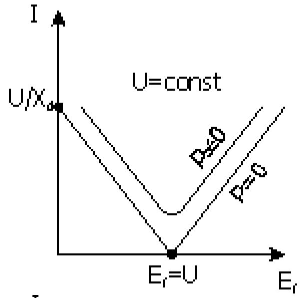


For example for $P = 0$

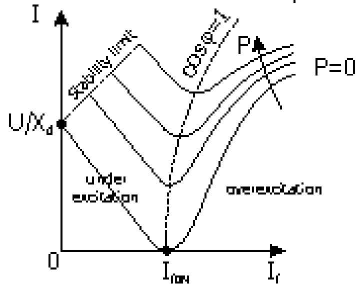
$$\underline{U}_s = jX_d \underline{I}$$

$$\underline{I} = -j\frac{\underline{U}_s}{X_d} = -j\frac{\underline{E}_f - \underline{U}}{X_d}$$

$$I = \left|\frac{U}{X_d} - \frac{E_f}{X_d}\right| \qquad \Rightarrow$$



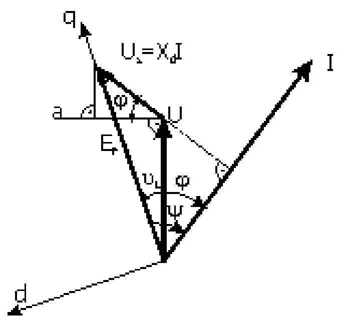
If we neglect saturation of magnetic core $E_f = cI_f$ and V-curves for $P = 0$ and other values of active power are shown ⇒



d) Active power – load angle characteristic $P = f(\vartheta_L)$ or $T_e = f(\vartheta_L)$

These characteristics are named "power angle characteristics" in US and "angle characteristics" in Poland.

In cylindrical generator ($X_d = X_q$) and with assumption $R_1 \cong 0$



$P = mUI\cos\varphi$ and due to phasor diagram

$$X_d I\cos\varphi = E_f \sin\vartheta_L$$

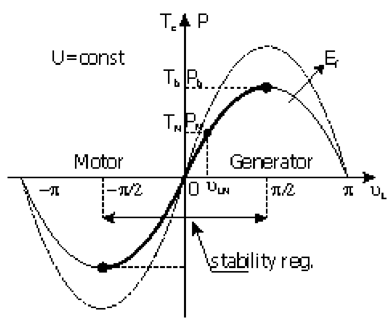
$$I\cos\varphi = \frac{E_f}{X_d}\sin\vartheta_L$$

hence

$$\boxed{P = m\frac{UE_f}{X_d}\sin\vartheta_L}$$

and due to the relation $T = \frac{1}{\Omega}P$ to so described active power corresponds electromagnetic torque

$$\boxed{T_e = \frac{1}{\Omega}m\frac{UE_f}{X_d}\sin\vartheta_L}$$



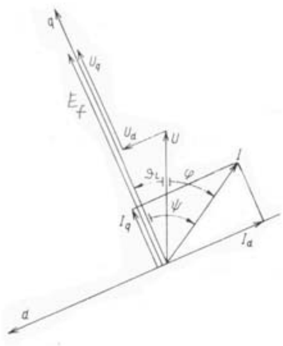
Both relations are sinusoidal functions.
T_b – breakdown torque (maximum torque) for given E_f (i.e. for given excitation); - it appears for $\vartheta_L = 90^o$.

$\frac{T_b}{T_N} = \frac{P_b}{P_N} \geq 2$ (stability margin);

therefore, usually $\vartheta_{LN} \leq 30^o$

For $\vartheta_L < 0$ $T_e < 0$ - negative value of torque means DRIVING TORQUE. MOTOR MODE OF OPERATION

<u>In salient-pole generator</u> ($X_d \neq X_q$) and with assumption $R_1 \cong 0$



I is resolved into *d*- and *q*-components.

Voltage drops corresponding to I_d & I_q currents are:

$$U_d = X_q I_q$$
$$U_q = X_d I_d$$

From the diagram

$E_f = U\cos\vartheta_L + X_d I_d$ from where

$I_d = \dfrac{E_f}{X_d} - \dfrac{U}{X_d}\cos\vartheta_L$ and

$U\sin\vartheta_L = X_q I_q \Rightarrow$ $\quad I_q = \dfrac{U}{X_q}\cos\vartheta_L$

This phasor diagram is an example of Blondel's diagram.

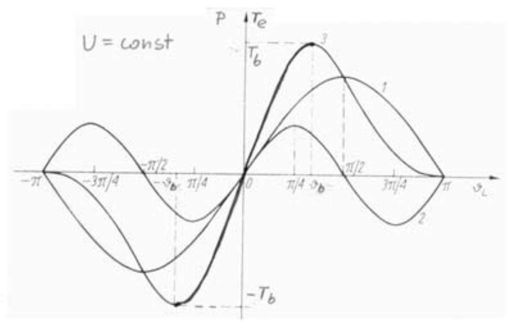
Substituting these relations (for I_d and I_q) to the following expression for power

$$P = mUI\cos\varphi = mU\left(I_d\sin\vartheta_L + I_q\cos\vartheta_L\right)$$

yields

$$\boxed{P = \underbrace{m\frac{UE_f}{X_d}\sin\vartheta_L}_{1} + \underbrace{m\frac{U^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\vartheta_L}_{2}}$$

($T=P/\Omega$)

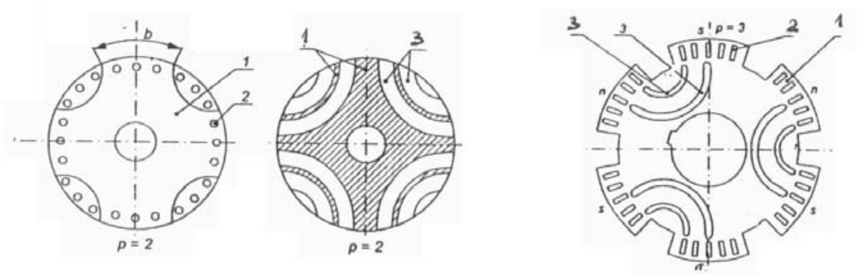


1 – power (torque) due to field excitation (<u>synchronous torque</u>)

2 – power (torque) due to saliency ($X_d \neq X_q$); it doesn't depend on E_f (or I_f) **!**
<u>RELUCTANCE TORQUE</u> !
RELUCTANCE MACHINES (with no excitation)

3 – total power (torque).

Rotors of synchronous reluctance motors

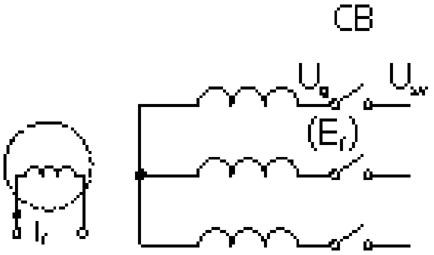


$\dfrac{X_d}{X_q} = 1.5 \div 2$ $\quad \dfrac{X_d}{X_q} = 2.5 \div 3$ $\quad \dfrac{X_d}{X_q} = 5$

1 – ferromagnetic core
2 – starting & damping cage
3 – magnetic flux barriers

OPERATION OF SYNCHRONOUS GENERATOR WITH A POWER SYSTEM

SYNCHRONIZATION OF GENERATOR – connection of synchronous generator on to the system busbars.



CB – circuit-breaker

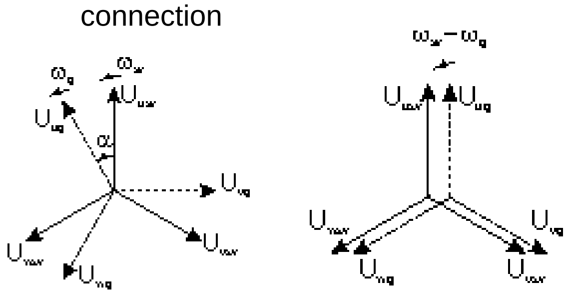
Condition of correct synchronization:
To avoid heavy currents flow after switching on, the voltages (potentials) of generator terminals and system terminals should be of equal value before and after connection – equal potentials at CB terminals:

$u_{ug} = u_{usy}$
$u_{vg} = u_{vsy}$ instantaneous values for t_{o+}^{-} must be the same.
$u_{wg} = u_{wsy}$

t_o – time of CB closing

Practically this one general conditions is satisfied when the following "more practical" conditions are fulfilled:

1. rms values $U_g = U_{sy}$ (≈5% difference allowed);
2. frequencies $f_g = f_{sy}$ (0.2 – 0.4 Hz difference allowed);
3. phase sequences are the same (of generator & system)
4. instantaneous values are practically equal at the moment of connection



$\alpha < 5^o$

co-phasal position of generator & system voltage stars;

5. voltage curves (waveforms) of generator & system are sinusoidal.

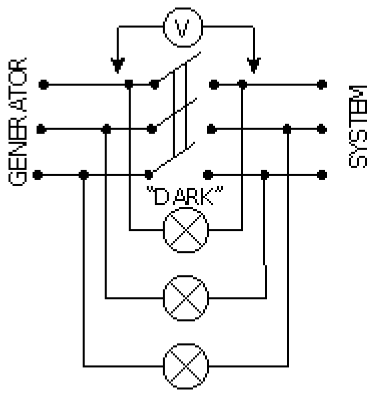
In power stations – synchronization by means of synchroscope or automatic.

In laboratory: voltmeter + lamps connected in so called "rotating light arrangement with one dark bulb":

Three bulbs are located symmetrically at circumference of a circle.

In case of the same phase sequences of GEN and SYS an effect of rotating light appears. The speed of rotation is proportional to the difference of frequencies.

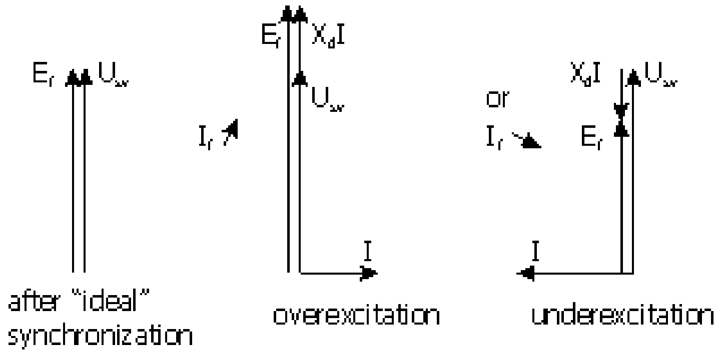
In case of different sequences all bulbs pulsate simultaneously.



OPERATION OF GENERATOR AT SYSTEM BUSBARS
(infinite busbars)

After synchronization with infinite busbars: $U_g = U_{sy}$ = const; f = const

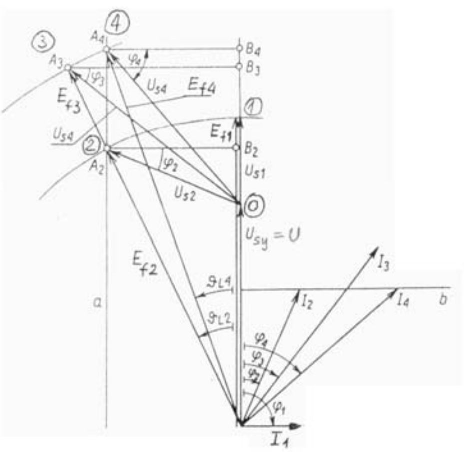
a) Field current regulation (= reactive power regulation)



$\vartheta_L = 0$ $P = 0$ By means of excitation regulation we can control <u>ONLY REACTIVE POWER:</u>

when $I_f > I_{foN}$ – reactive (inductive) power is delivered to the system;
when $I_f < I_{foN}$ – reactive (capacitive) power is delivered to the system or reactive (inductive) power is absorbed from the system and delivered to generator.

b) Torque (mechanical power, active power) regulation



point **0** – after "ideal" synchronization $E_{fo} = U_{s1}$ and $I = 0$

point **1** – $I_f \uparrow$; $E_f \uparrow$ and $E_{f1} > U \Rightarrow U_{s1} \Rightarrow I_1$ (overexcitation)

$P_1 = mUI_1 \cos\varphi_1 = 0$

$Q_1 = mUI_1 \sin\varphi_1 = mU_1 I_1$

point **2** – driving torque $T \uparrow$ (mechanical power $\uparrow$)
$E_{f2} = E_{f1}$ but rotor accelerates and $\vartheta_L = \vartheta_{L2} \Rightarrow U_{s2} \Rightarrow I_2$

$P_2 = mUI_2 \cos\varphi_2$ (*b*)

$Q_2 = mUI_2 \sin\varphi_2$

$$T_{e2} = cmUI_2 \cos\varphi_2 = m\frac{UE_{f2}}{X_d}\sin\vartheta_{L2} = T$$

steady-state operation, active power P_2 delivered to the system.

Point **3** - $I_f \uparrow$; $E_f \uparrow E_{f3} \Rightarrow U_{s3} \Rightarrow I_3$ only transiently! It is not steady state because

$P_3 = mUI_3 \cos\varphi_3$

$T_{e3} = cmUI_3 \cos\varphi_3 \succ T$ and generator is slowing down to point 4

Point **4** – due to $T_{e3} > T$ angle $\vartheta_L \downarrow \vartheta_{L4} \Rightarrow U_{s3} \Rightarrow I_4$

$P_4 = mUI_4 \cos\varphi_4 = P_2$ (*b*) $T_{e4} = T$

$Q_4 = mUI_4 \sin\varphi_4 \succ Q_2$

steady-state operation with the same *P* but with *Q* increased. Lines *a* and *b* are hodographs of constant active power (torque), active currents.

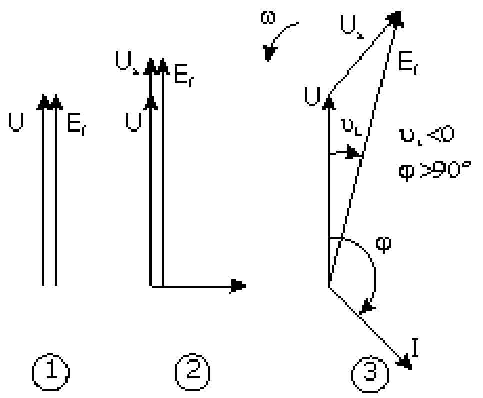
Conclusion: During operation of synchronous generator with U = const (connection to infinite busbars):

1. By means of field current the control of only reactive power is possible;
2. Control of active power delivered to the system is possible only by means of mechanical power driving the generator (regulation of prime mover – turbine);
3. Both above regulations practically don't affect each other (are independent).

SYNCHRONOUS MOTOR

Consider 3 steps of synchronous machine (generator) operation:

1. synchronization,
2. overexcitation,
3. application of breaking torque (mechanical load) to the machine's shaft:



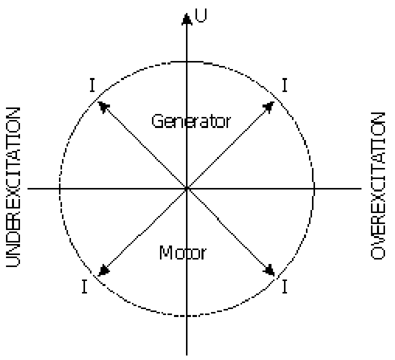
What is the result?

$$T_e = \frac{1}{\Omega}\frac{UE_f}{X_d}\cos\varphi < 0 \quad (!)$$

For the machine considered as generator the negative torque (electromagnetic torque produced in the machine) means driving character of this torque (not breaking as it is in generator).
The machine becomes a motor. Active power delivered to the system

$P = mUI\cos\varphi < 0$ i.e. the active power is delivered to the machine (to the motor) from the mains.

All possible positions of armature current phasor:



Overexcited synchronous machine can operate as synchronous motor (converting electrical active power into mechanical) and simultaneously can deliver reactive inductive power to the supply (to the system).

Compare this situation to induction motor. Induction motor always absorbs reactive inductive power from the mains. Synchronous motor seems to be much better from this point of view.

How to start such a motor?