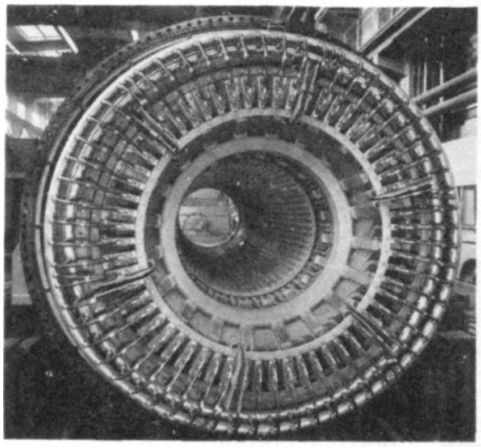
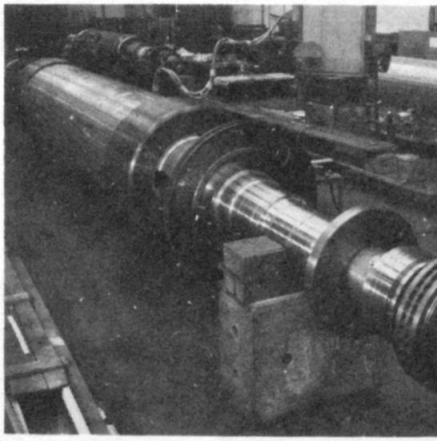
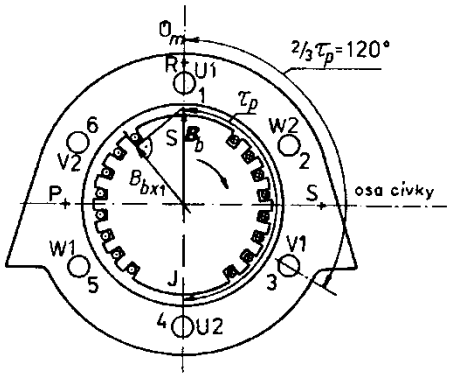
12. Alternators

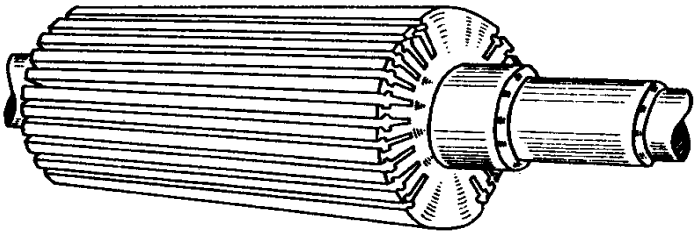
Large power alternators are synchronous machines (asynchronous only for small power). According to the turbine used, the machines are divided into:

- Turboalternators working with steam turbines - smooth rotor alternators usually two-pole for high power (over 1000 MVA) exceptionally four-pole (speed 3000, respectively 1500 rpm) (400 MVA in the picture)



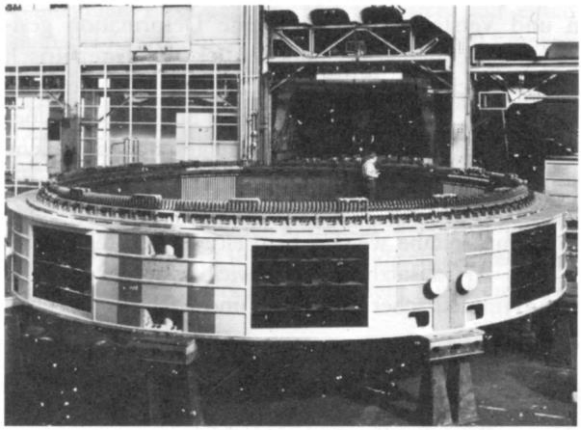


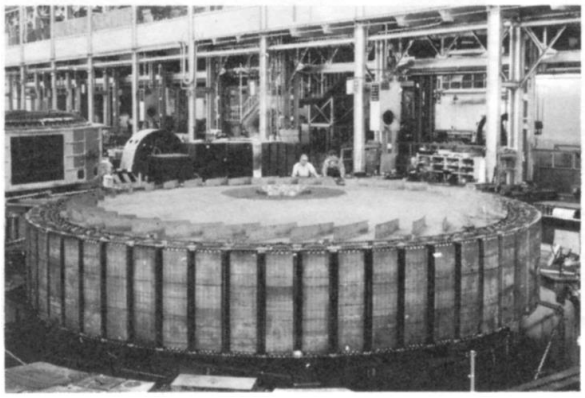


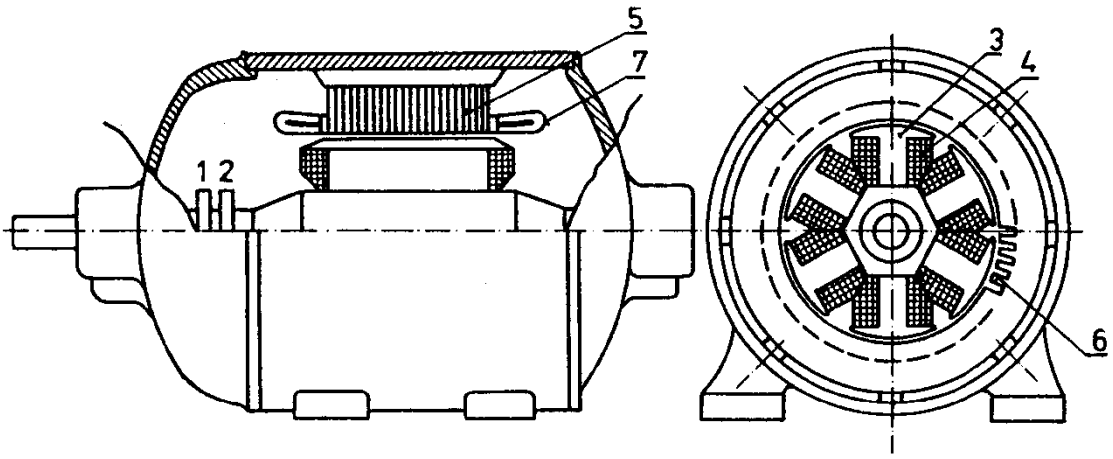


In the grooves is placed excitation winding secured by metal wedges (forming damping winding).

- Hydroalternators (Salient Poles Machines) working with water turbines - alternators and wye poles usually multi-pole (61 MVA, 100 rpm in the picture)







The damping winding (damper) is placed in the grooves of the pole extensions and connected by front couplings to the short

The number of poles is given by: $P_P = \frac{60 \cdot f}{n}$.

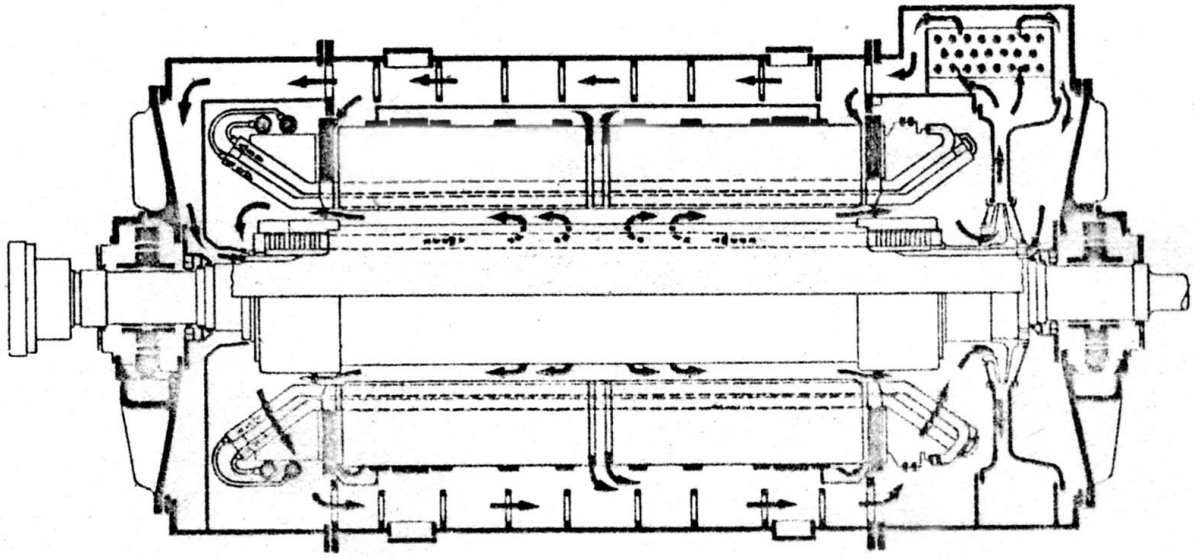
The power of the alternator is limited with respect to the development of heat losses by the size of its volume, which is determined by the external dimensions according to transport and handling possibilities. In addition, the rotor diameter is limited by centrifugal forces. Machines with smooth rotors of high power output are therefore rather elongated cylindrical in shape. In addition to this, the overall length of the shaft and the inherent oscillations of the machine must be taken into account. For higher outputs, the possibility of natural cooling becomes even more complicated with increasing voltage and increasing insulation required. Thus, for higher powers, the dimensions cannot be increased sufficiently and the heat loss per unit volume increases and active cooling is required:

- Air cooling supported by axial fans on the axis, air circulated through water cooling (for capacities up to 50 MW, in the world up to 200 MW due to its simplicity and cheapness despite lower efficiency)
- Direct hydrogen cooling of the rotor magnetic circuit and indirect hydrogen cooling of the stator
- Direct water cooling of the stator winding

The winding insulation is made with thermosetting or resin plastic RELANEX.

Direct rotor and indirect stator cooling with hydrogen

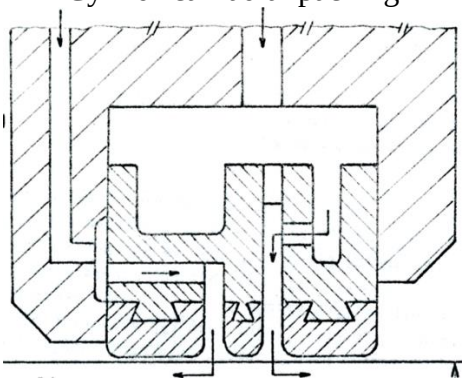
Hydrogen allows for increased cooling with lower ventilation losses. The design leads to higher volume utilization and machine efficiency. For outputs from 60 to 165 MW. Hydrogen pressure is 0.2 to 0.4 MPa. The rotor has hollow conductors through which the hydrogen is pressurized, the stator is cooled by axial channels in the magnetic circuit. Circulation is again supported by axial fans and water cooling.



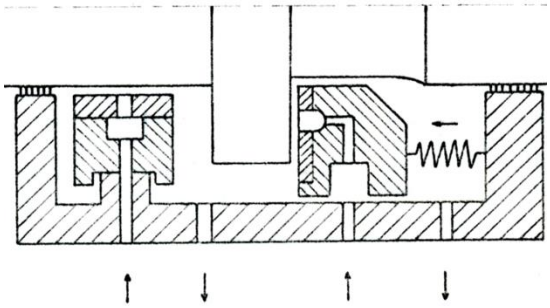
Hydrogen is friable at concentrations of 4 to 75% with air. Therefore, inert CO must be used for filling and emptying$_2$. During operation, the purity of H_2 is maintained at 98% with a critical low of 92%. Filling is with electrolytic hydrogen of 99.5% purity, cylinder pressure is reduced to 0.5 MPa. Often multiple units are designed with a common hydrogen farm and possible gas exchange between cylinders and alternators.

The sealing of the internal alternator compartment is made by gaskets:

Cylindrical radial packing

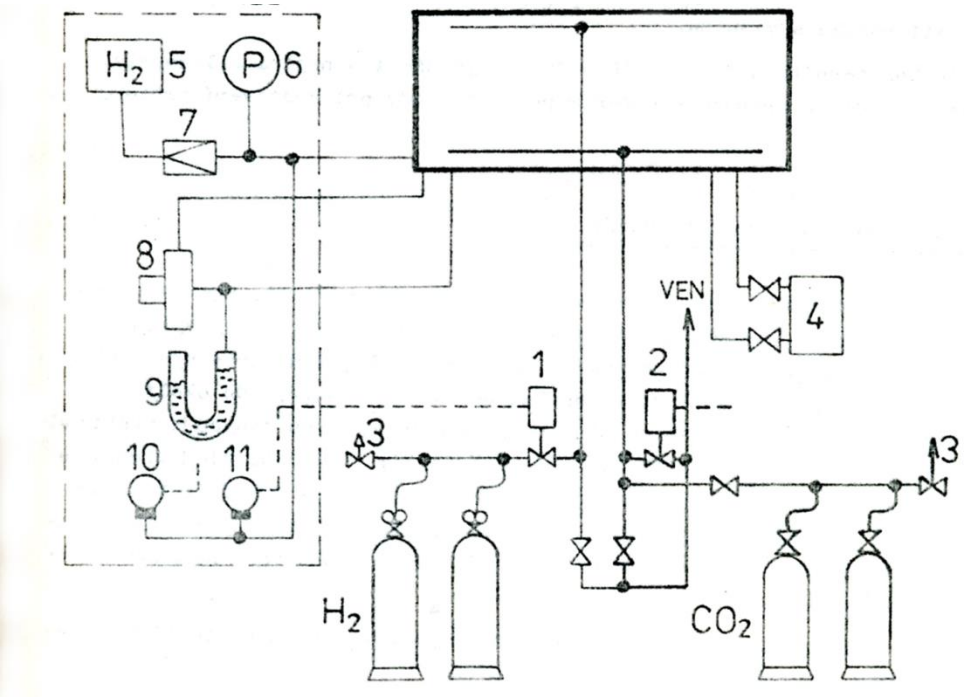


Frontal axial seal



A system of two sealing oils is used to prevent dissolved hydrogen from mixing with any dissolved air.

The gas management ensures the purity and pressure of the hydrogen and enables the filling of the machine:



1, 2 - relief valves3
- safety valve4
- hydrogen desiccant with silica gel
5 - hydrogen analyzer by pulse. conductivity
6 - pressure measurement
7 - constant flow regulator
8 - measuring fan
9 - measurement of gas purity during filling
10 - pressure signalling
11 - automatic hydrogen admittance

Direct water cooling of stator windings

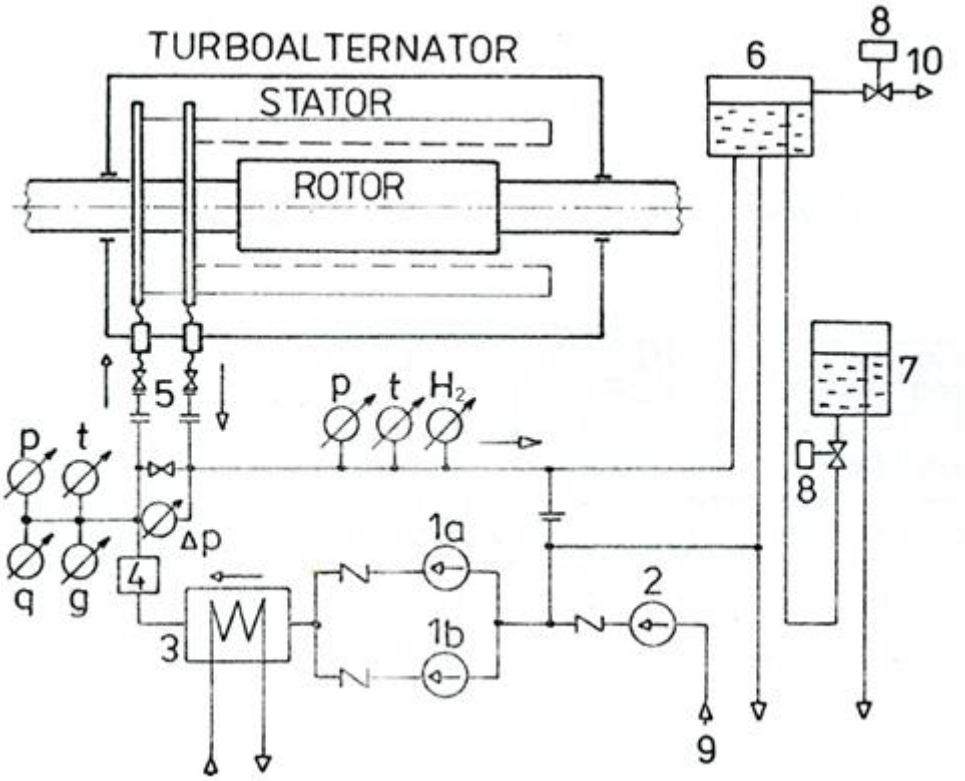
For alternators above and including 200 MW. It carries the problem of increasing losses, which are reduced by alternating solid and hollow conductors, using non-magnetic materials for machine faces. The hydrogen pressure must be higher than water so that its possible ingress can be easily detected and leakage of the water system can be eliminated. Water with a conductivity of 2 to 5 S/cm shall be used. The system is closed, the water is regenerated through chemical filters or by the admission of cleaner water:

Parameters of alternators in relation to the cooling system used:

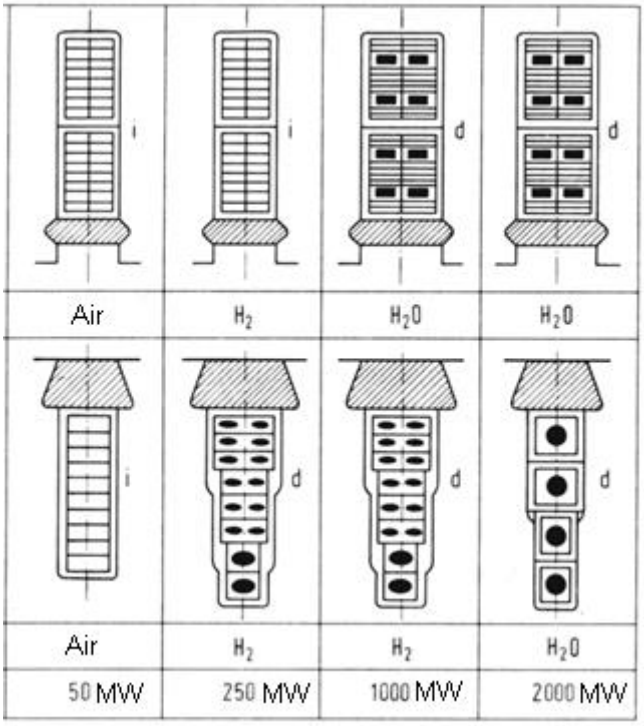
Rated active power P_N [MW]	165	235	500
Rated apparent power P_N [MW]	194	277	588
Cooling system	H_2 300 kPa	H_2 400 kPaH_2 O	H_2 500 kPaH_2 O
Current utilization [A/cm]	1522	1518	1965
Rated voltage U_N [kV]	15.00	15.75	20.00
Efficiency [%]	98.63	98.61	98.75
Specific gravity [kg/kVA]	0.857	0.860	0.630

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY



1 - working and backup pump
2 - feed pump
3 - radiator
4 - mechanical filter
5 - Removable inserts when measuring the insulation condition of the stator
6 - buffer vessel
7 - siphon (overflow)
8 - automatic closing
9 - clean water from the filter station
10 - outlet to degassing pump



Main parameters and characteristics of alternators

Nominal power - depends on the power of the turbomachine and the power of the thermodynamic energy source. For conventional thermal power plants, according to the rated series, we have 110, 200 and 500 MW (respectively 125, 235 and 588 MVA). For the NPPs according to the thermal output of the rector, two turbomachines of 220 MW (or 258 MVA) for VVER440 and one turbomachine for VVER1000 (or 1176 MVA).
The price of 1 kW and the magnitude of the losses decrease with the magnitude of the rated power of the alternator and the whole unit with the fourth root. The limiting factors are the fuel and water supply, or the possibility of off-take, discharge to the EC or the concentration of exhalations.

Alternator voltage

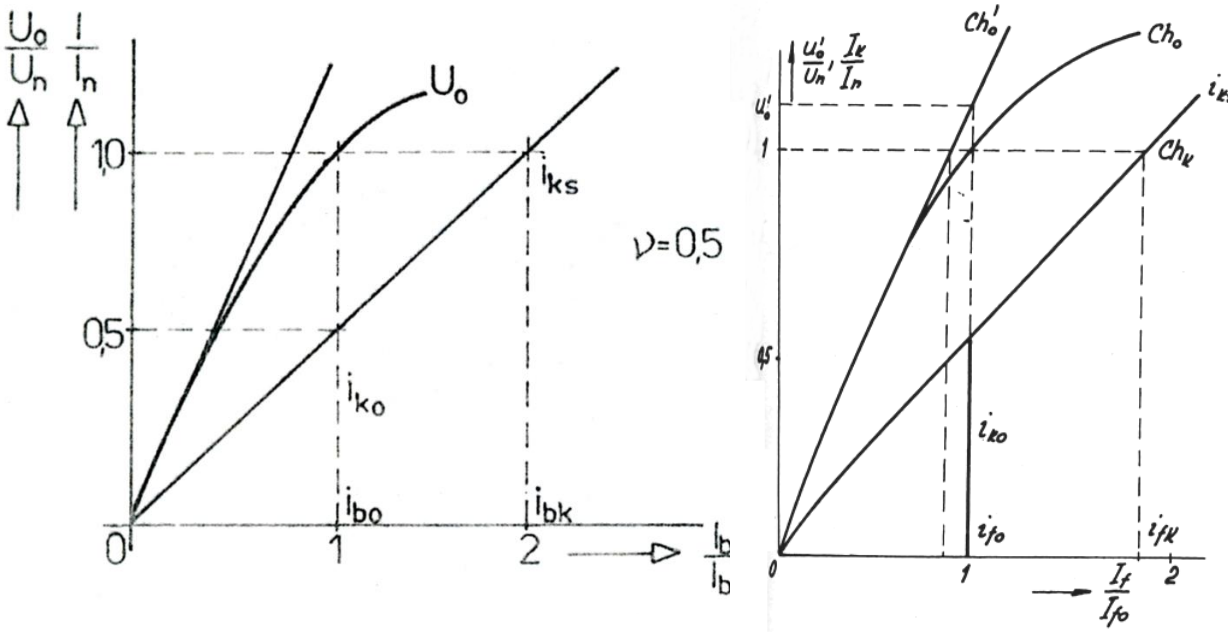
It is selected with regard to the size of the currents and the necessary insulation:

Rated power P_N [MW]	Rated voltage U_N [kV]	Rated power P_N [MW]	Rated voltage U_N [kV]
50	6.3	220	15.75
110	13.8	500	20.00
200	15.0	1000	25.00

Efficiency of $cos\varphi$ alternator

Determined by the role of the power plant in the EC (inclusion of the power plant in voltage magnitude control and reactive power distribution). The higher the requirements for the reactive (inductive) power supplied, the lower the power factor, which places increased demands on the excitation system and the rotor as such. For high power, a minimum $cos\ \varphi \geq$ of 0.8 (typically 0.85) is required, for low power, a $cos\varphi$ relatively smaller is chosen.

Characteristics of blank and short



For alternators of the same design type, this characteristic is similar. The so-called short-circuit ratio can be defined:

$$\nu = \frac{I_{K0}}{I_N} = i_{K0} = \frac{I_{b0}}{I_{bK}}$$

On the above specific characteristic is: $\nu = 0.5 \quad i_{K0} = 0.5$

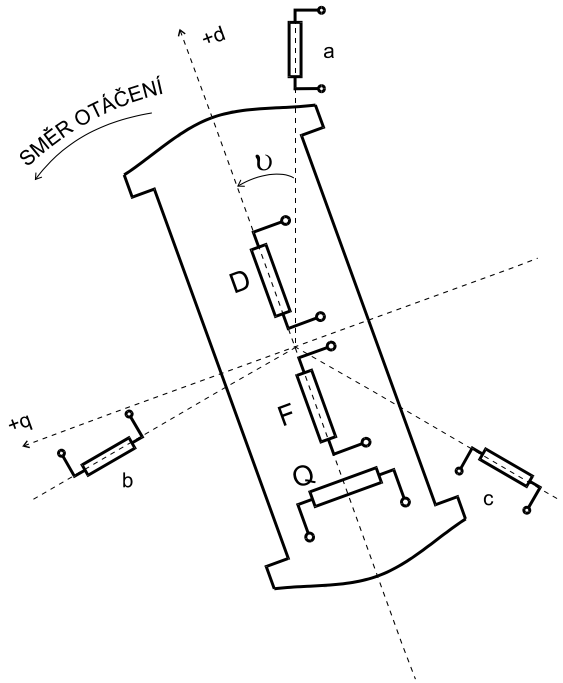
From the short-circuited state it can be determined: $x_{dS} = \frac{e}{i_{K0}} = \frac{e}{\nu} \approx \frac{1}{0.5} = 2$

The alternate reactance in the unsaturated state is analogous: $x_d = \frac{u_0^{/}}{i_{K0}} = \frac{i_{bK}}{i_{bO}^{/}} > x_{dS}$

For the operation of the alternator, a large value of ν is advantageous because of the increase in natural static stability and the reduction of the influence of the armature reaction and therefore the reduction of fault currents in the rotor during transients. However, decreasing x_d increases the design cost of the alternator (requiring an increase in the air gap and consequently a more massive excitation winding). Modern alternators have ν small (< 0.5) and x_d large (> 2). The reduced static stability is made up for by a fast exciter and regulator.

Alternator equations of operation

The relations are based on the Park transformation (assumption of complete linearity of the system):



$$U_k = -R_k I_k - \frac{d\Psi_k}{dt}$$

where *k* is *a*, *b*, *c*, *F*, *D*, *Q*

$$\begin{bmatrix} \Psi_a \\ \Psi_b \\ \Psi_c \\ \Psi_F \\ \Psi_D \\ \Psi_Q \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} & L_{aF} & L_{aD} & L_{aQ} \\ L_{ba} & L_{bb} & L_{bc} & L_{bF} & L_{bD} & L_{bQ} \\ L_{ca} & L_{cb} & L_{cc} & L_{cF} & L_{cD} & L_{cQ} \\ L_{Fa} & L_{Fb} & L_{Fc} & L_{FF} & L_{FD} & 0 \\ L_{Da} & L_{Db} & L_{Dc} & L_{DF} & L_{DD} & 0 \\ L_{Qa} & L_{Qb} & L_{Qc} & 0 & 0 & L_{QQ} \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_F \\ I_D \\ I_Q \end{bmatrix}$$

Where:

Stator inductance vs excitation:

$$L_{aF} = L_{Fa} = L_{aFm} \cos \vartheta$$

$$L_{bF} = L_{Fb} = L_{aFm} \cos\left(\vartheta - \frac{2}{3}\pi\right)$$

$$L_{cF} = L_{Fc} = L_{aFm} \cos\left(\vartheta + \frac{2}{3}\pi\right)$$

Inductance of stator vs damper in d-axis:

Inductance of stator vs damper in q-axis:

$$L_{aD} = L_{Da} = L_{aDm}\cos\vartheta$$

$$L_{bD} = L_{Db} = L_{aDm}\cos\left(\vartheta - \frac{2}{3}\pi\right)$$

$$L_{cD} = L_{Dc} = L_{aDm}\cos\left(\vartheta + \frac{2}{3}\pi\right)$$

$$L_{aQ} = L_{Qa} = L_{aQm}\cos\left(\vartheta + \frac{1}{2}\pi\right)$$

$$L_{bQ} = L_{Qb} = L_{aQm}\sin\left(\vartheta - \frac{2}{3}\pi + \frac{1}{2}\pi\right)$$

$$L_{cQ} = L_{Qc} = L_{aQm}\sin\left(\vartheta + \frac{2}{3}\pi + \frac{1}{2}\pi\right)$$

Inductance of the stator proper:

$$L_{aa} = L_{aO} + L_2\cos 2\vartheta$$

$$L_{bb} = L_{aO} + L_2\cos\left[2\left(\vartheta - \frac{2}{3}\pi\right)\right]$$

$$L_{cc} = L_{aO} + L_2\cos\left[2\left(\vartheta + \frac{2}{3}\pi\right)\right]$$

Stator mutual inductances:

$$L_{bc} = -L_{ab0} + L_2\cos 2\vartheta$$

$$L_{ca} = -L_{ab0} + L_2\cos\left[2\left(\vartheta - \frac{2}{3}\pi\right)\right]$$

$$L_{ab} = -L_{ab0} + L_2\cos\left[2\left(\vartheta + \frac{2}{3}\pi\right)\right]$$

After the introduction of the Park transformation in the stator (introduction of an inertial system connected to the rotor):

$$[P] = \frac{2}{3}\begin{bmatrix} \cos\vartheta & \cos(\vartheta - 2/3\pi) & \cos(\vartheta + 2/3\pi) \\ \sin\vartheta & \sin(\vartheta - 2/3\pi) & \sin(\vartheta + 2/3\pi) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

$$\lfloor u_{d,q,0} \rfloor = [P]\cdot\lfloor u_{a,b,c} \rfloor$$

$$\lfloor i_{d,q,0} \rfloor = [P]\cdot\lfloor i_{a,b,c} \rfloor$$

$$\lfloor \Psi_{d,q,0} \rfloor = [P]\cdot\lfloor \Psi_{a,b,c} \rfloor$$

instead of the first three voltage equations:

$$U_d = -RI_d - \frac{d\Psi_d}{dt} + \omega\Psi_q$$

$$U_q = -RI_q - \frac{d\Psi_q}{dt} - \omega\Psi_d$$

$$U_0 = -RI_0 - \frac{d\Psi_0}{dt}$$

and the magnetic fluxes are:

$$\Psi_d = L_dI_d + L_{dF}I_F + L_{dD}I_D$$

$$\Psi_q = L_qI_q + L_{qQ}I_Q$$

$$\Psi_0 = L_0I_0$$

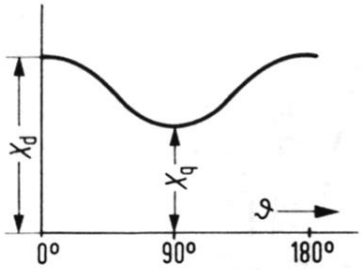
$$\Psi_F = L_{Fd}I_d + L_{FF}I_F + L_{FD}I_D$$

$$\Psi_D = L_{Dd}I_d + L_{DF}I_F + L_{DD}I_D$$

$$\Psi_Q = L_{Qq}I_q + L_{QQ}I_Q$$

L_d is the longitudinal synchronous inductance $L_d = L_{a0} + L_{ab0} + \frac{3}{2}L_2$

L_q is the transverse synchronous inductance $L_q = L_{a0} + L_{ab0} - \frac{3}{2}L_2$



L_0 is non-rotating inductance $L_0 = L_{a0} - 2L_{ab0}$
Machine performance:

$$P_i = U_a I_a + U_b I_b + U_c I_c \qquad P_i = \frac{3}{2} U_d I_d + \frac{3}{2} U_q I_q + \frac{3}{1} U_0 I_0$$

The machine moment equation for a two-pole machine is:

$$J_{mot} \frac{d\Omega}{dt} = M_{int} + M_Z \qquad M_{int} = \frac{P_i}{\Omega} = \frac{3}{2}\left(\Psi_d I_q - \Psi_q I_d\right)$$

where J_{mot} is the moment of inertia

Phasor diagram of a synchronous machine in steady synchronous operation
(all temporal changes of fluxes are zero, currents through the buffer are also zero)

Idle: $I_d = I_q = 0$ and $\Psi_q = 0$, thus $U_d = -\frac{d\Psi_d}{dt} = 0$ and $U_q = -\omega\Psi_d$, thus if it is steady state it must: $U_d = 0$ and $U_q = U_S = e_V$

Encumbered condition: $U_d = -RI_d + \omega\Psi_q = -RI_d + x_q I_q$

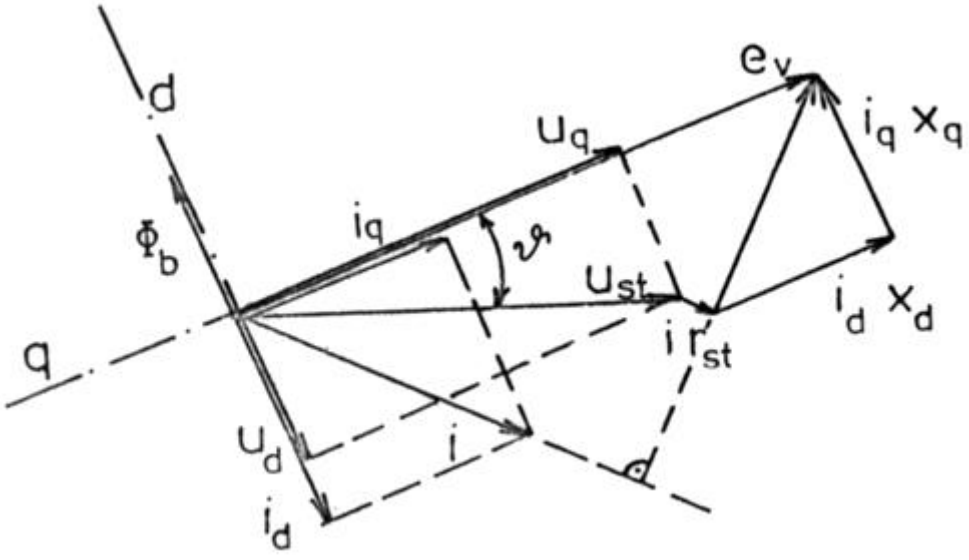
$$U_q = -RI_q - \omega\Psi_d = -RI_q - x_d I_d + e_V$$

We introduce a phase diagram for the magnitudes of these quantities:

$$\bar{e}_V = \left(\overline{U}_d + \overline{U}_q\right) + R \cdot \left(\bar{I}_d + \bar{I}_q\right) + j \cdot x_d \bar{I}_d + j \cdot x_q \bar{I}_q$$

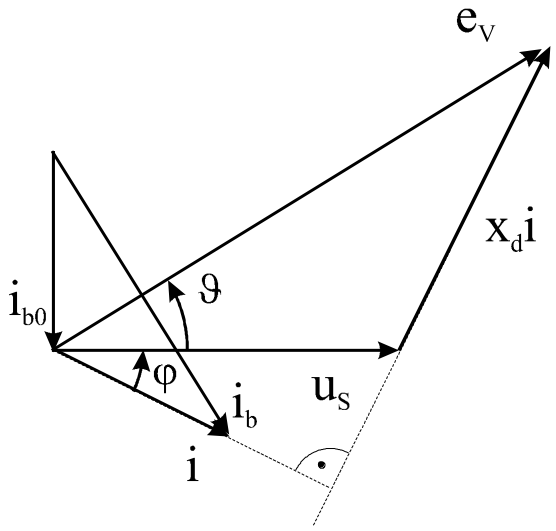
$$\bar{e}_V = \overline{U}_S + R \cdot \bar{I} + j \cdot x_d \bar{I}_d + j \cdot x_q \bar{I}_q$$

Where: $x_d = x_{ad} + x_\sigma$ a $x_q = x_{aq} + x_\sigma$ are the longitudinal and transverse synchronous reactances (x_d , x_q) and the anchor reaction reactance in the longitudinal and transverse axes (x_{ad} , x_{aq})

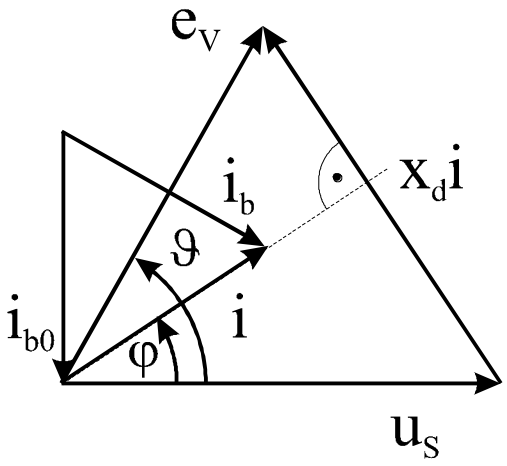


Phasor diagram of a synchronous machine with a smooth rotor (turboalternator):

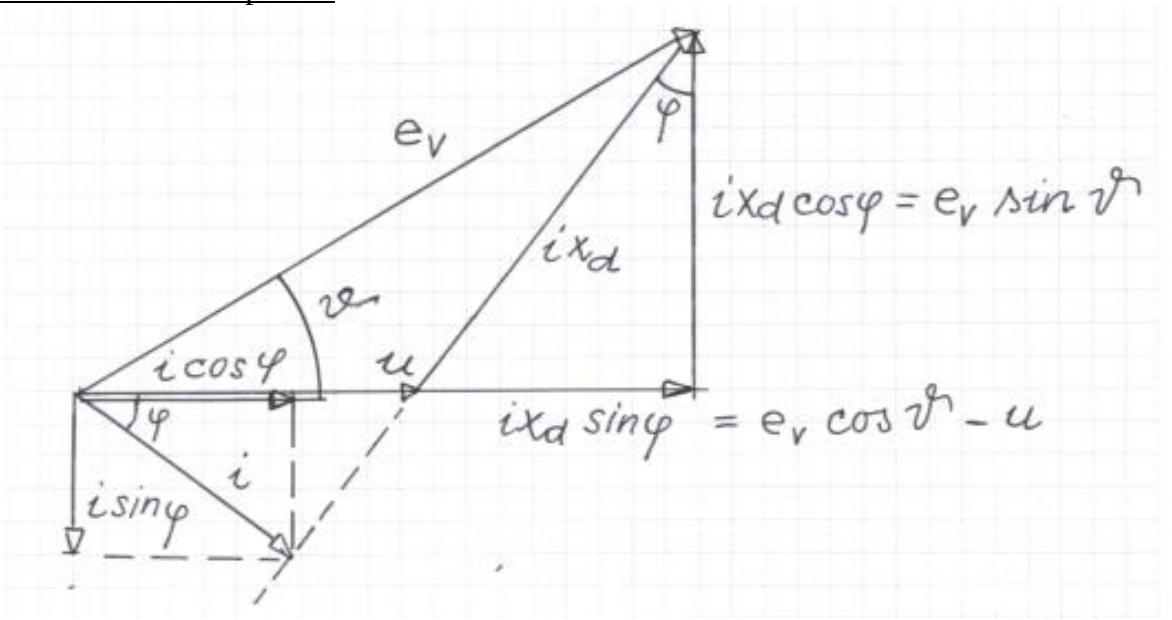
In an overexcited state



In an underexcited state.

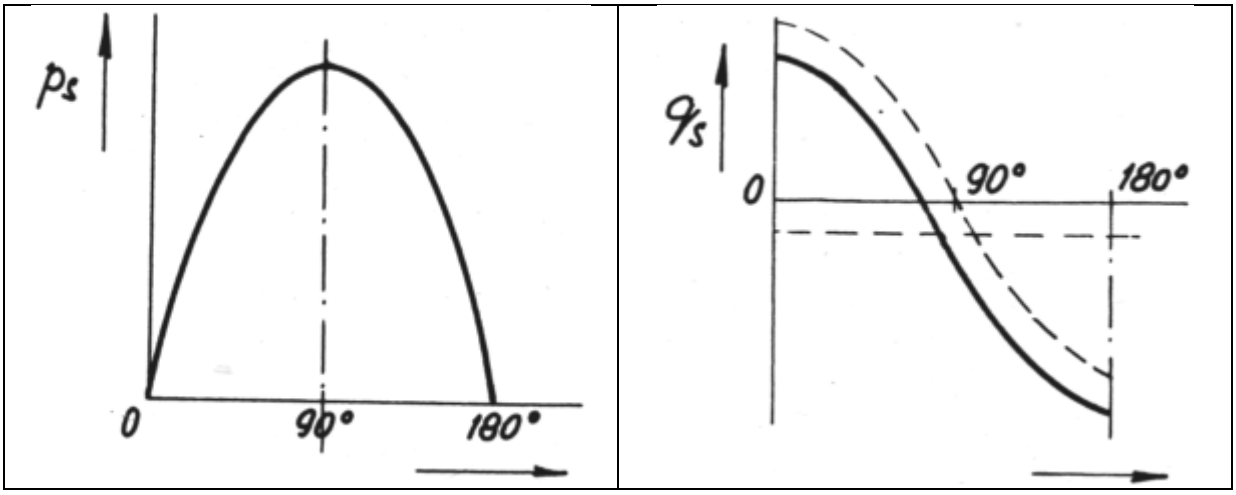


Alternator electrical power:



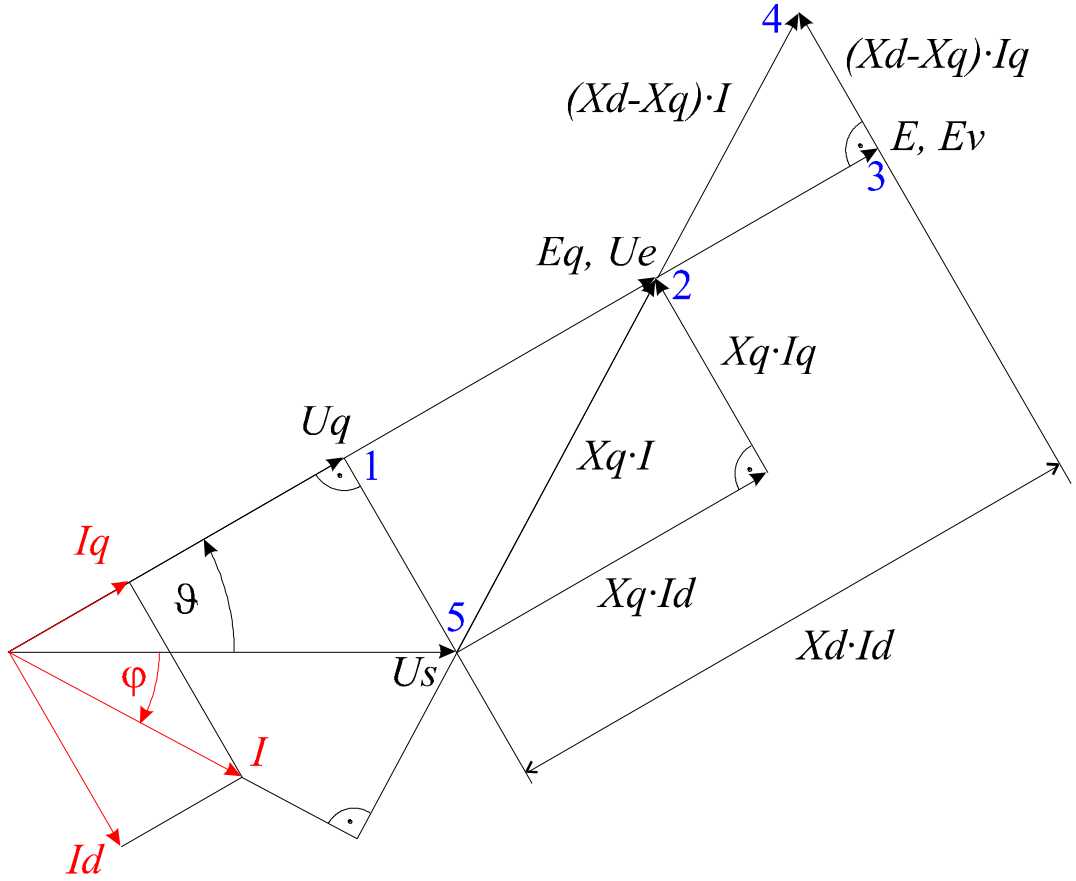
$$i \cdot \cos\varphi = \frac{e_V \cdot \sin\vartheta}{x_d} \qquad p_S = u \cdot i \cdot \cos\varphi = \frac{u_S \cdot e_V}{x_d} \sin\vartheta$$

$$i \cdot \sin\varphi = \frac{e_V \cdot \cos\vartheta - u}{x_d} \qquad q_S = u_S \cdot i \cdot \sin\varphi = \frac{u_S \cdot e_V}{x_d} \cos\vartheta - \frac{{u_S}^2}{x_d}$$



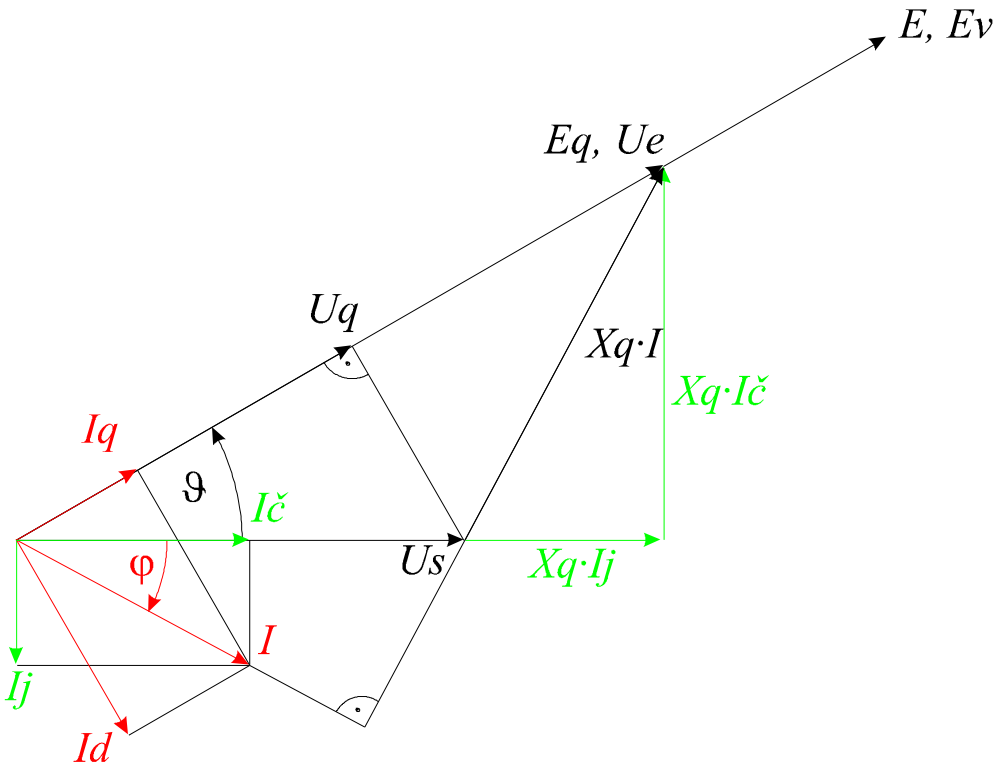
Three-phase apparent power: $s = 3\frac{u_S \cdot e_V}{x_d}\left(\sin\vartheta + j\left(\cos\vartheta - \frac{u_S}{e_V}\right)\right)$

Phasor diagram of a synchronous machine with salient poles (hydroalternator):



According to the similarity of the triangles:

$$\frac{1-2}{2-3} = \frac{5-2}{2-4} \qquad \frac{E_q - U_q}{E_V - E_q} = \frac{X_q \cdot I}{(X_d - X_q)\cdot I} \qquad E_q = E_V \frac{X_q}{X_d} + U_q \frac{X_d - X_q}{X_d}$$



$$P_S = U_S \cdot I \cdot \cos\varphi \qquad E_q \cdot \sin\vartheta = X_q \cdot I_{č} = X_q \cdot I \cdot \cos\varphi$$

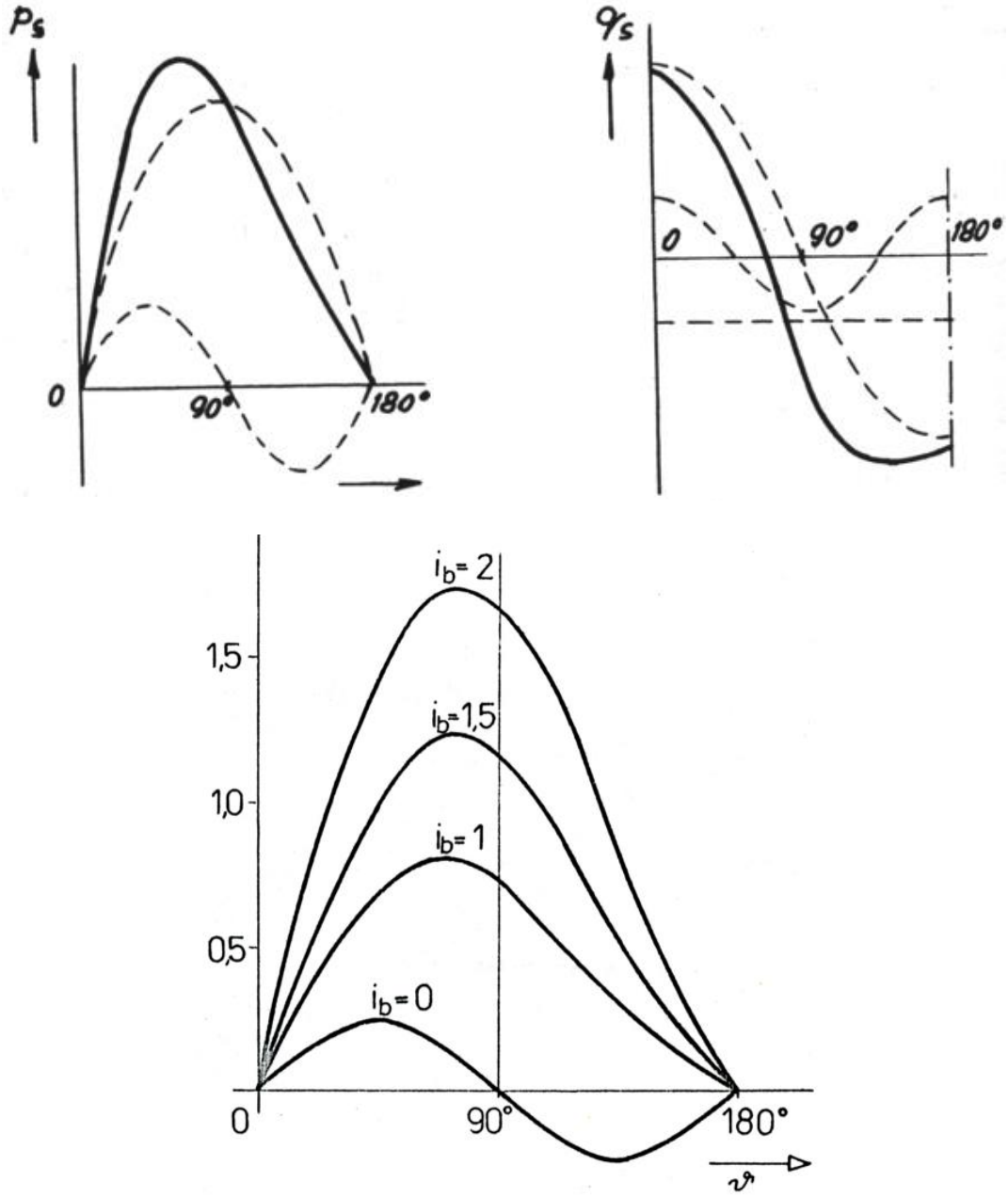
$$P_S = U_S \frac{E_q}{X_q} \sin\vartheta = \frac{U_S}{X_q}\left[E_V \frac{X_q}{X_d} + U_q \frac{X_d - X_q}{X_d} \right] \sin\vartheta =$$

$$= \frac{E \cdot U_S}{X_d} \sin\vartheta + \frac{U_S \cdot U_q}{X_q} \cdot \frac{X_d - X_q}{X_d} \sin\vartheta \qquad U_q = U_S \cos\vartheta$$

$$P_S = \frac{E \cdot U_S}{X_d} \sin\vartheta + \frac{{U_S}^2}{2} \cdot \frac{X_d - X_q}{X_d \cdot X_q} \sin(2\vartheta)$$

By analogy:

$$Q_S = \frac{E \cdot U_S}{X_d} \cos\vartheta + \frac{{U_S}^2}{2} \cdot \frac{X_d - X_q}{X_d \cdot X_q} \cos(2\vartheta) - \frac{{U_S}^2}{2} \cdot \frac{X_d + X_q}{X_d \cdot X_q}$$



Power supplied by a synchronous machine with exciting control:

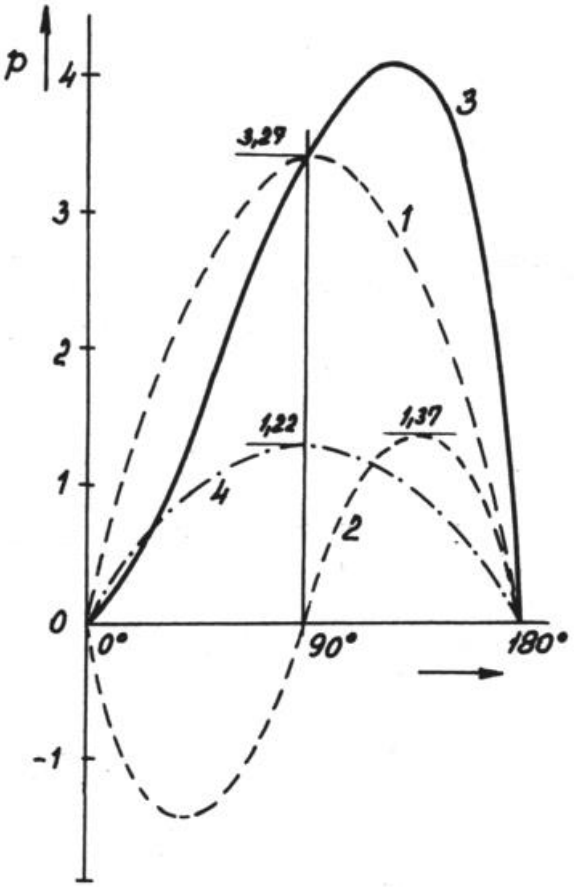
For regulation, the basic criterion is usually the constant magnitude of the alternator socket voltage. Then:

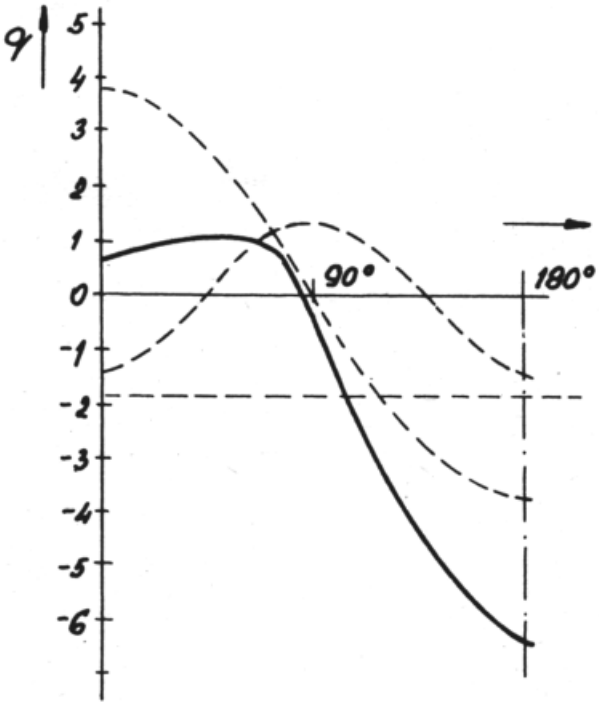
$$P_{S\,REG} = \frac{U_q \cdot U_S}{X_V} \sin\vartheta - \frac{{U_S}^2}{2} \cdot \frac{X_q}{\left(X_q + X_V\right) \cdot X_V} \sin\left(2\vartheta\right)$$

$$Q_{S\,REG} = \frac{U_q \cdot U_S}{X_V} \cos\vartheta - \frac{{U_S}^2}{2} \cdot \frac{X_q}{\left(X_q + X_V\right) \cdot X_q} \cos\left(2\vartheta\right) - \frac{{U_S}^2}{2} \cdot \frac{X_q + 2X_V}{\left(X_d + X_V\right) \cdot X_q}$$

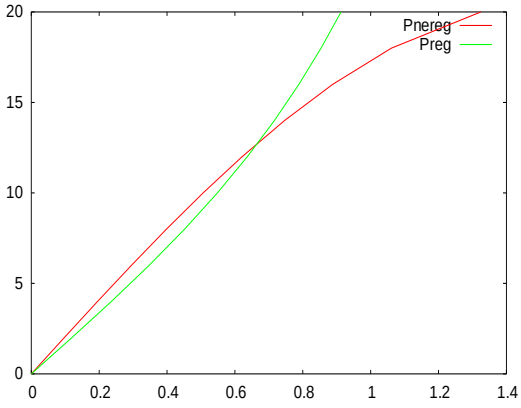
EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY



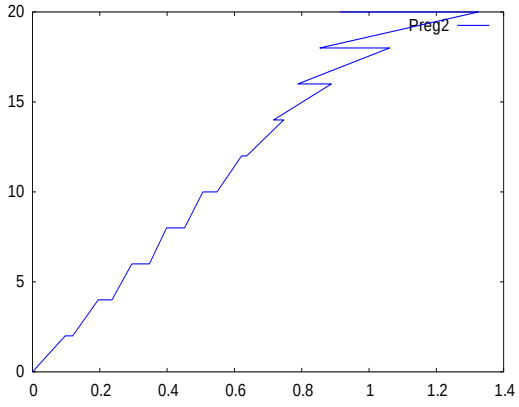


Zavislost vykonu dodavaneho do site na zateznem uhlu



ruzna zavislost s regulaci a bez regulace buzeni

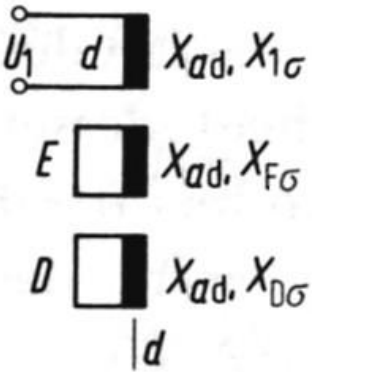
Zavislost vykonu dodavaneho do site na zateznem uhlu

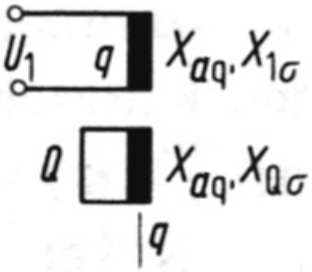


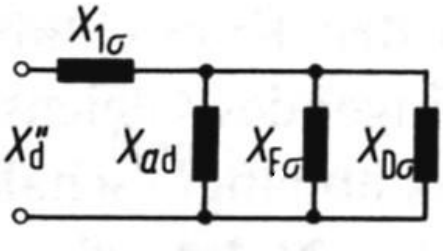
ruzne zavislosti s regulaci a bez regulace buzeni

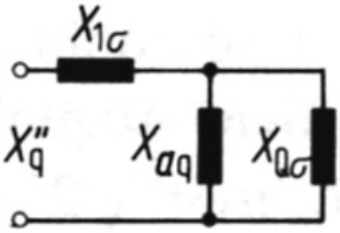
Other alternator parameters for steady states:

Reactance









$x_d^{/} = x_\sigma + \frac{x_{ad} x_{F\sigma}}{x_{ad} + x_{F\sigma}}$ - longitudinal transient reactance

x_q ' - transverse transient reactance

Determined mainly by the excitation time constant, therefore x_q '= x_q (because there is no excitation in the transverse axis). It is used in calculations of the magnitude of short-circuit currents after the first few strongly damped periods have passed.

$x_d^{//} = x_\sigma + \frac{x_{F\sigma} x_{ad} x_{D\sigma}}{x_{F\sigma} x_{ad} + x_{F\sigma} x_{D\sigma} + x_{ad} x_{D\sigma}}$

- longitudinal impact (subtransit) reactance

Determined mainly by the time constant of the damper (here the difference between x_d '' and x_q '' depends on the damper design). It is used in calculations of the magnitude of short-circuit currents immediately after they occur.

$x_q^{//} = x_\sigma + \frac{x_{aq} x_{Q\sigma}}{x_{aq} + x_{Q\sigma}}$ - transverse impact reactance

Time constants

T_{d0}' - transient time constant (of the excitation circuit) in the longitudinal axis during idle operation

T_{d0}'' - *shock* time constant (of the damping circuit) in the longitudinal axis during idling

T_{q0}'' - *shock* time constant (of the damping circuit) in the transverse axis at no-load operation

$T_d^{/} = \frac{x_d^{/}}{x_d} T_{d0}^{/}$ - transient time constant in the longitudinal axis when running short

$T_d^{//} = \frac{x_d^{//}}{x_d} T_{d0}^{//}$ - impact time constant in the longitudinal axis

$T_q^{//} = \frac{x_q^{//}}{x_q} T_{q0}^{//}$ - impact time constant in the transverse axis (value approx. as T_d'')

T_m - mechanical time constant (depending on the size of the alternator and its J_{mot})(e.g. 7 to 10 sec.).

T_F – exciting system constant (up to 1 sec.)

	Salient Poles Machine	machine with smooth rotor
x_d	0.9÷ 1.5 (1.2)	1.5÷ 2.5 (2)
x_q	0.5÷ 1.1 (0.2)	~ x_d (slightly smaller)
x_d'	0.3÷ 0.5 (0.4)	0.2÷ 0.35 (0.25)
x_d''	0.25÷ 0.35 (0.3)	0.15÷ 0.25 (0.2)
x_q''	~ x_d''	= x_d''
x_2	0.1÷ 0.25	0.1÷ 0.15
x_0	0.03÷ 0.2	0.02÷ 0.1
T_{d0}'	3÷ 8 (5)	8÷ 12 (10)
T_d''	0.02÷ 0.05 (0.04)	0.02÷ 0.05 (0.04)