15. Alternator working area and operating diagram

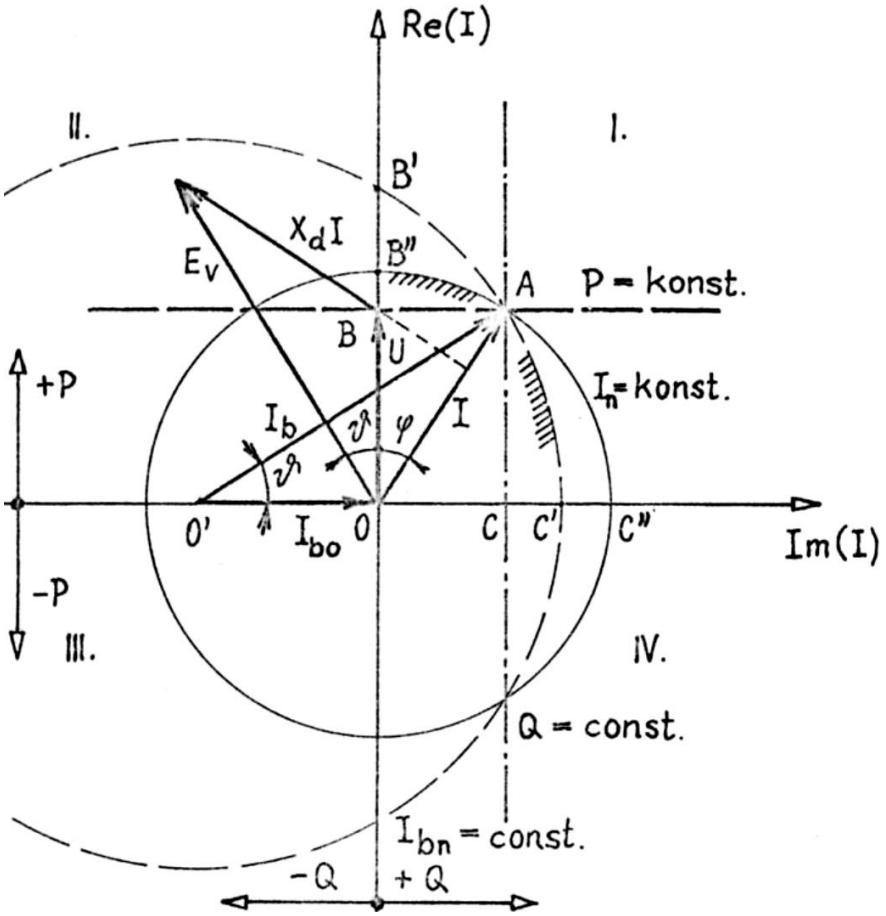
The permissible work area, limited by the maximum limit load, is determined by many factors, the most important of which are:

- Stator winding warming
- Warming of the stator magnetic yoke "iron"
- Warming of the rotor excitation winding
- Warming of the rotor body
- Static stability of the alternator

In addition, it is necessary to control the operation of the alternator according to the maximum active power supplied to the grid, which is mainly determined by the power of the turbine. More complicated is the choice of the magnitude of the reactive power supply, whose requirements vary more in the system and the reactive power transfer has to be optimised. In addition, each machine must have a certain power reserve to be able to maintain synchronism even in times of faults on the grid or on the excitation circuit. According to the resulting P-Q operating diagram, the control and protection elements are adjusted.

Operation of the alternator in an overloaded state

In the basic analysis, we limit the alternator operation for all states by thermal parameters corresponding to the nominal operation. In the rotor, this leads directly to a limitation by the nominal magnitude of the excitation current. Analogously, in the stator, it leads to a limitation by the nominal magnitude of the stator current:

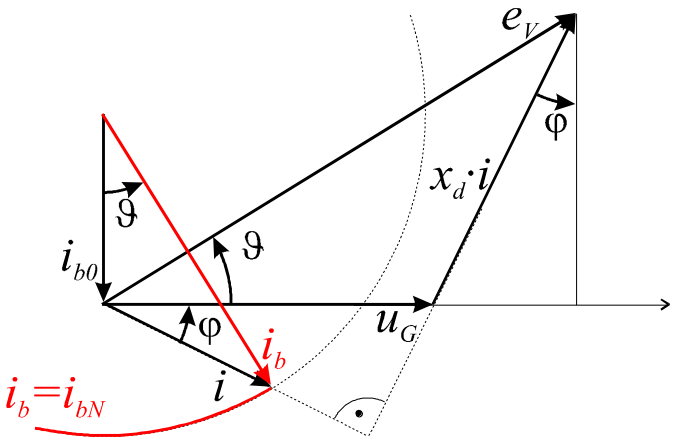


Where $|OA| \approx i_N$ $|O'A| \approx i_{bN}$ $|O'O| \approx i_{b0}$

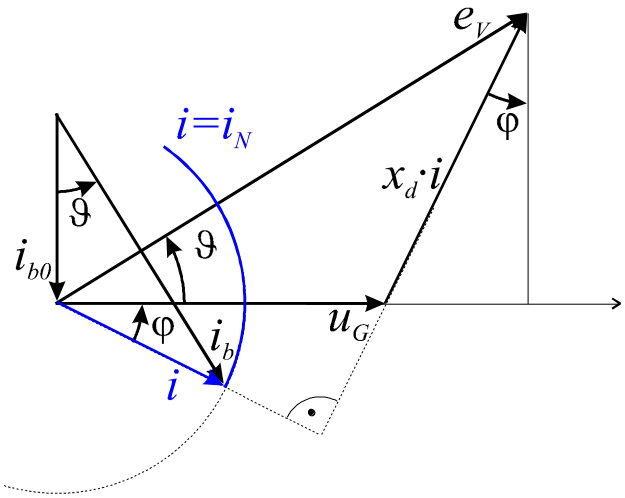
$|OB| \approx i_{ČINNÝ}$ $|OC| \approx i_{JALOVÝ}$

$|B''A|$ - stator current size limitation

$|AC'|$ - limitation of rotor excitation current



Limitation of rotor excitation current sizes



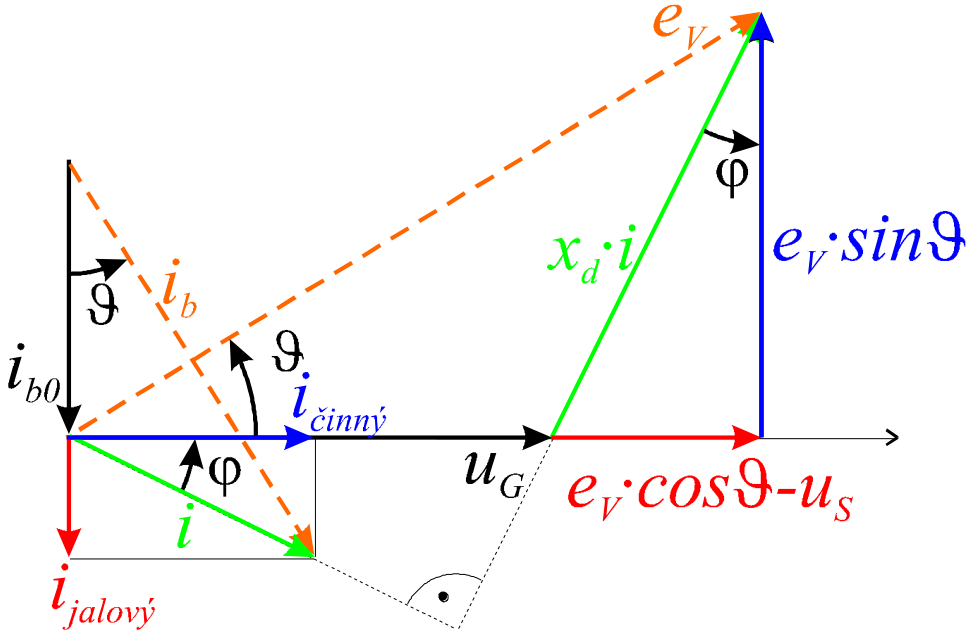
Stator current size limitation

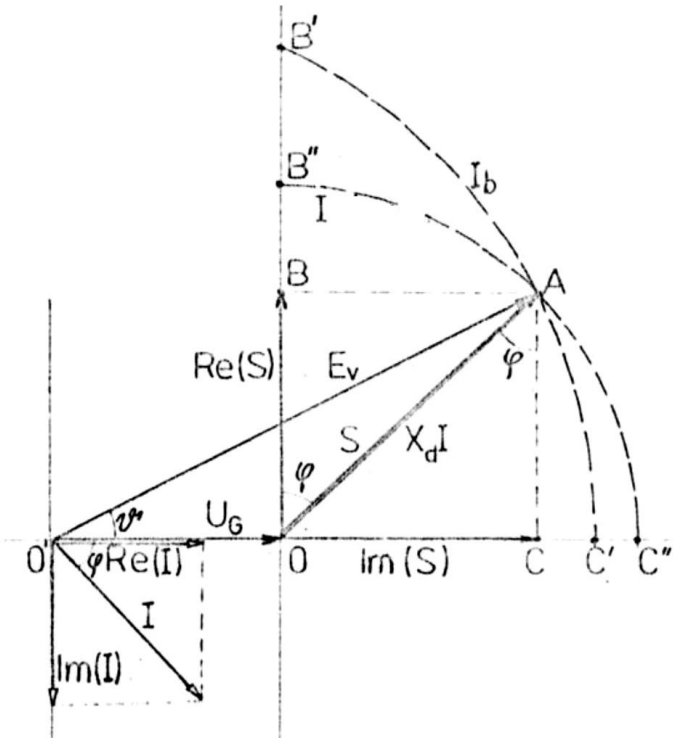
The same limitation in the voltage plane where:

$$e_V \approx i_b \qquad x_d \cdot i \approx i$$

$$p = \frac{e_V \cdot u_G}{x_d} \sin\vartheta \approx e_V \sin\vartheta = x_d \cdot i \cdot \cos\varphi \approx i_{ČINNÝ}$$

$$q = \frac{u_G \cdot e_V}{x_d} \cos\vartheta - \frac{u_G^{\,2}}{x_d} \approx e_V \cos\vartheta - u_G = x_d \cdot i \cdot \sin\varphi \approx i_{JALOVÝ}$$





After moving to the voltage plane and moving the origin to the peak of the grid voltage, active and reactive power can be displayed directly after scaling.

Here again, the sections of the restrictions are marked in the same way:

$\left|B^{//}A\right|$ - stator current size limitation

$\left|AC^{/}\right|$ - limitation of rotor excitation current

The scales of the quantities for i_N =1, S_N =1 and x_d =2 are:

$$k_U = \frac{i_N \cdot x_d}{|OA|} = \frac{1 \cdot 2}{|OA|}$$

$$k_S = \frac{s_N}{|OA|} = \frac{1}{|OA|}$$

The maximum active power is limited by the magnitude of the nominal apparent power of the alternator S_N . The maximum reactive power is limited by the magnitude of the excitation current and is given by $\left|OC^{/}\right| \approx q_{MAX}$ (approximately 80% of S_N). For the above values:

$$q_{MAX} = k_S \cdot \left|OC^{/}\right| = \frac{\left|OC^{/}\right|}{|OA|} \qquad k_U \cdot \left|OC^{/}\right| = e_V - u_G$$

$$q_{MAX} = \frac{1}{|OA|} \cdot \frac{e_V - u_G}{k_U} = \frac{e_V - u_G}{x_d} = i_{JALOVÝ\ MAX}$$

$$e_V = \sqrt{\left(u_G + i \cdot x_d \sin\varphi_N\right)^2 + \left(i \cdot x_d \cos\varphi_N\right)^2}$$

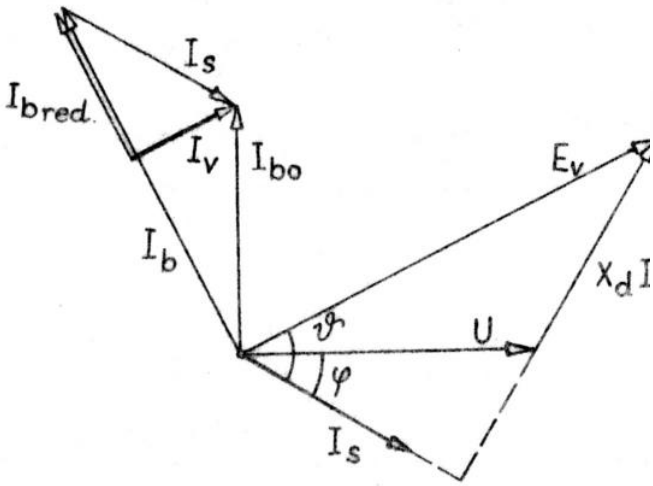
For nominal power factor $\cos\varphi_N = 0.8$:

$$e_V = \sqrt{\left(1 + 1 \cdot 2 \cdot 0.6\right)^2 + \left(1 \cdot 2 \cdot 0.8\right)^2} = 2.72 \qquad q_{MAX} = \frac{2.72 - 1}{2} = 0.86$$

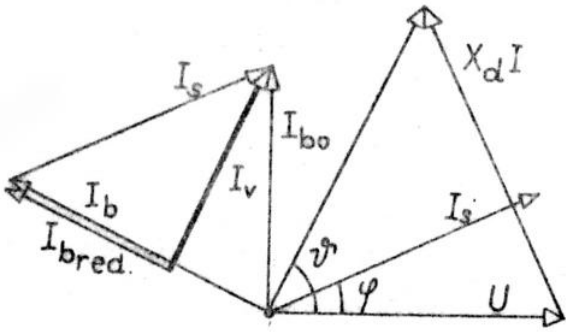
Operation of the alternator in an excited state

This mode of generator operation is common when the electricity system is relieved at night or on weekends. In this area, the limitation of operation is mainly due to the warming of the stator face and the static stability of the machine. The increased heating of the windings and the alternator structure is due to the change in the dissipative flux due to the different

spatial mutual distribution of the stator and rotor fields at low power factor, when the load angle is relatively large (the field does not close over the pole extensions and the direction of the stator and rotor fields is not so "opposite"), in addition, the excitation current is relatively small in this condition. The evaluation of the effect of warming must be investigated by appropriate practical measurements on a similar machine. However, the magnitude in the different modes can be inferred from the magnitude of the resulting vector sum I_V of the currents involved in generating the magnetic field in the rotor I_{bRED} and stator I_S .:

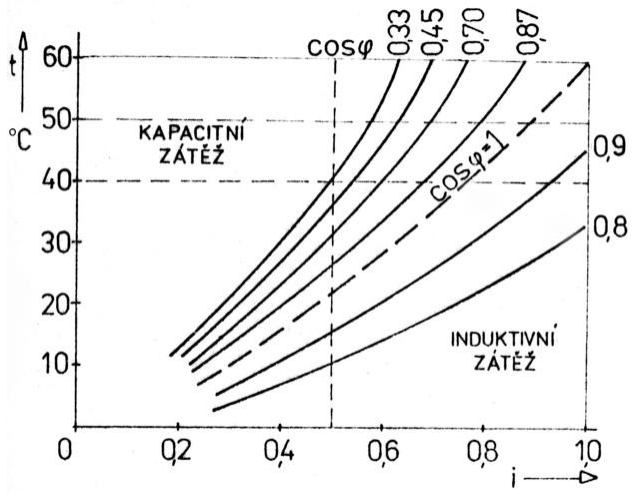


Overstimulated state

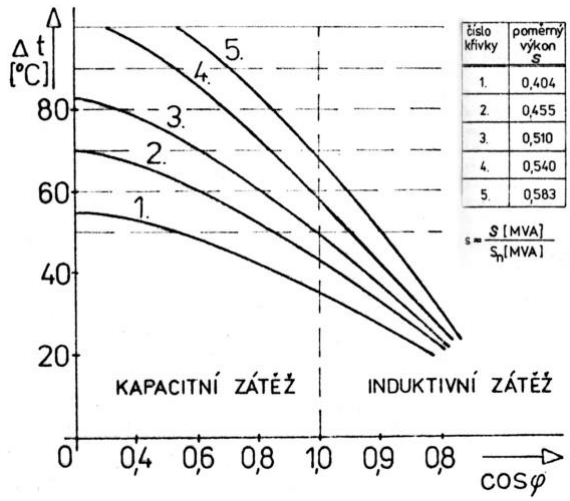


The stimulated state

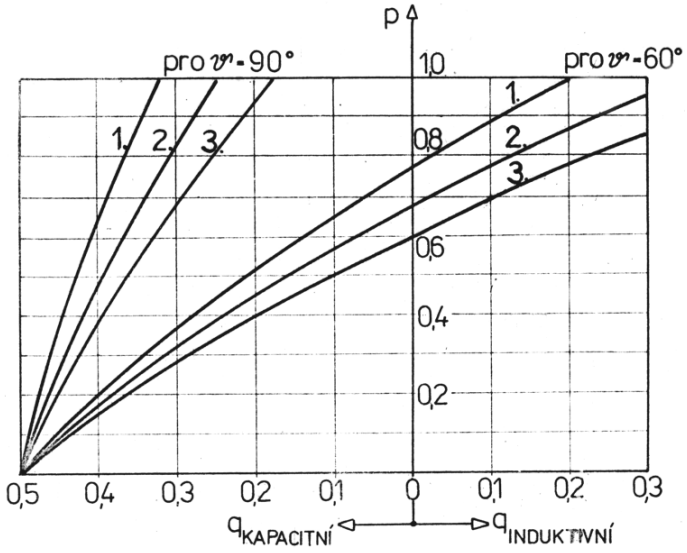
Resulting warming and allowable load depending on the alternator capacity load rate based on temperature measurements of the shielding and withdrawal plate of the machine face structure:



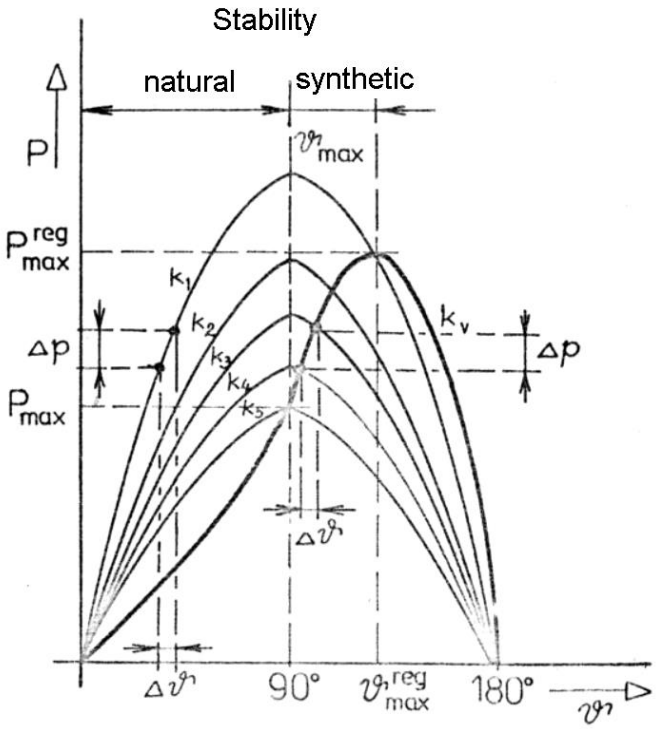
Warming of the stator faces as a function of current



Warming of the stator faces depending on the power factor



Allowable inductive load of the alternator for different external reactance:
1. - $x_V = 0.1$
2. - $x_V = 0.2$
3. - $x_V = 0.3$
and for different limit load angles ϑ at the maximum permissible machine face temperature up to 100° C.



Dependence of the active power on the load angle on excitation:

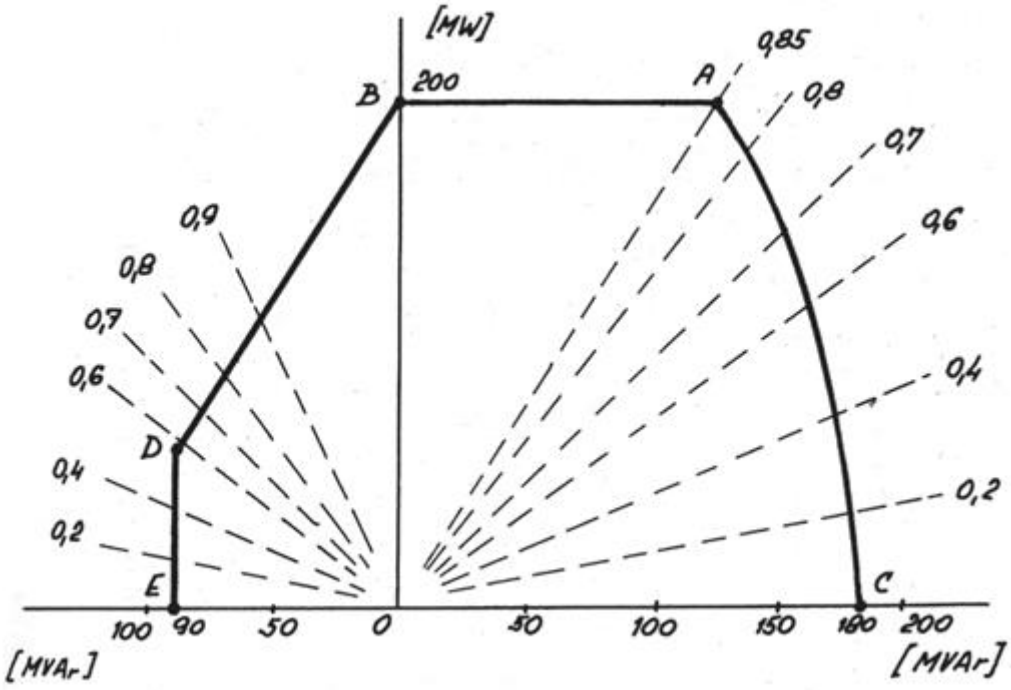
The static stability curve is determined by the block reserve requirement for the load angle, which is affected by the dynamics of the machine, excitation and controller. It is necessary to observe the condition:

$$\frac{dP}{d\vartheta} > 0$$

The maximum load angle is mainly determined by the wake regulation capabilities. For a machine without regulation, or with a significant controller insensitivity band, it is limited $\vartheta_{MAX} < 60°$. For a fast controller without an insensitivity band, it is possible to operate $\vartheta_{MAX} > 90°$. For hydroalternators, the limit is slightly lower due to the effect of the machine's reluctance torque.

Alternator operating P-Q diagram

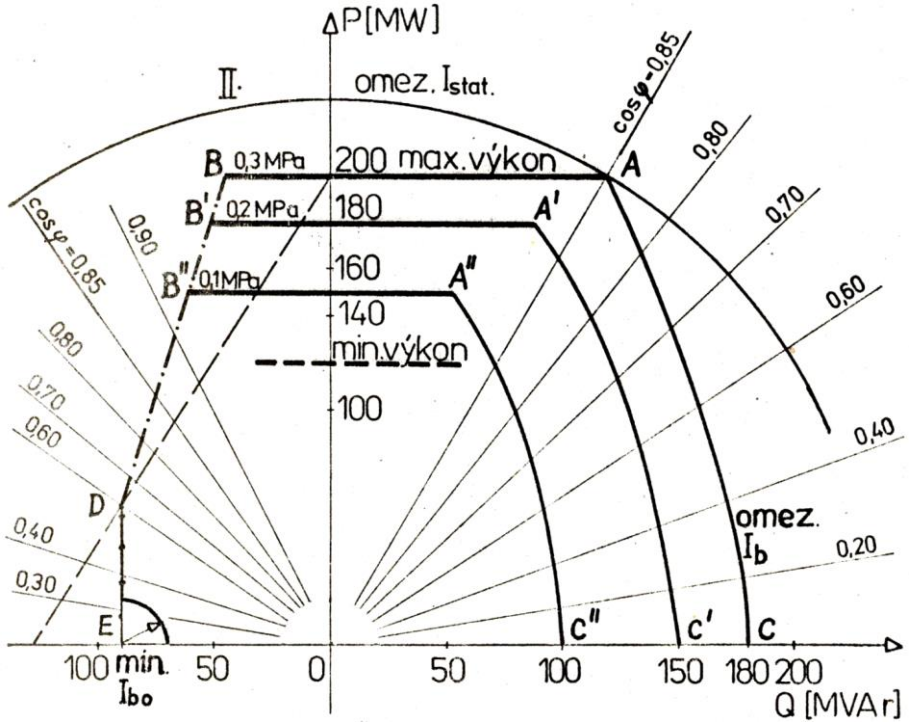
In addition to the above limitations, the final design of the P-Q diagram must also include the effect of the maximum delivered active power of the unit given by the ceiling of the mechanical power of the turbine, or, conversely, the effect of the minimum technological value of this power.



Operating P-Q diagram of the alternator of the 235 MVA power unit
Limitations are given:

AB - Turbine power limitation	BD - Insulation of front structures
AC - Warming of rotor excitation winding	DE - Restricted by static stability of the machine

In addition, the resulting P-Q diagram for the 235 MVA block is dependent on the cooling hydrogen pressure as a parameter:

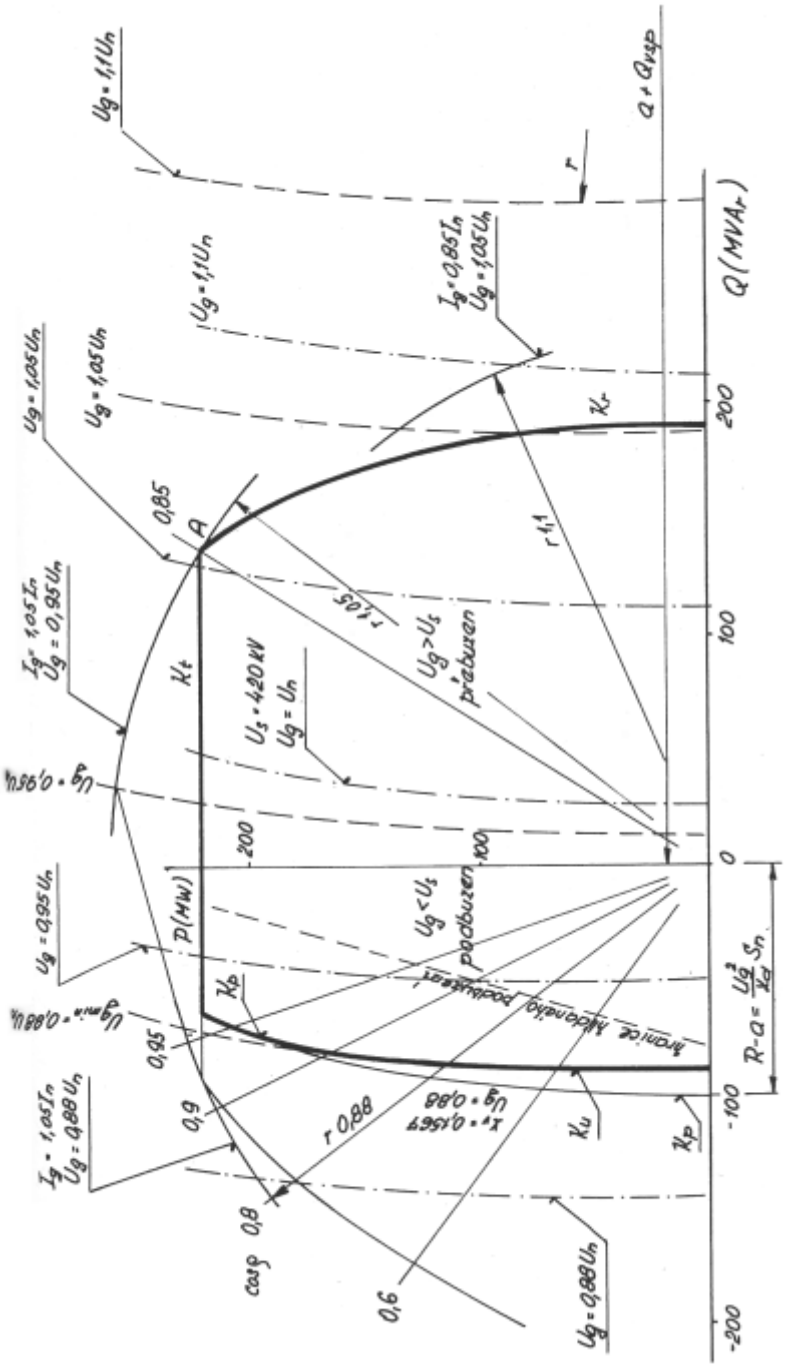


For the practical determination of the limits, the following refining parameters apply:

- For the clamp voltage $u_G \leq 1.05 \cdot u_N$ the stator current must not exceed $0.95 \cdot i_N$
- For the clamp voltage $u_G > 1.05 \cdot u_N$ the stator current must not exceed $0.85 \cdot i_N$
- The highest clamp voltage is $u_G = 1.1 \cdot u_N$ while the stator current must not exceed $0.85 \cdot i_N$, so the power must not exceed $u_G \cdot i_N = 1.1 \cdot 0.85 \cdot s_N = 0.935 \cdot s_N$
- The minimum voltage at the terminals is determined by static stability at a specific external reactance and the current must not exceed $1.05 \cdot i_N$ at $u_G < 0.95 \cdot u_N$. Voltages below the $u_G < 0.85 \cdot u_N$ limit are not recommended.
- The magnitude of the heating of the excitation winding must not exceed the permissible operating temperature

Other constraints arise from the operation of the block transformer, the self-consumption transformer and the network:

- The voltage on the mains side must not exceed the maximum permissible value
- At the alternator voltage $u_G = 1.1 \cdot u_N$, the block transformer and the self-consumption transformer are only allowed to operate at 90% of rated power $0.9 \cdot s_{NT}$
- On self-consuming appliances, the rated voltage must be within the permitted tolerance



Alternator operating p-Q diagram S_N =259 MVA, cosφ =0.85, U_N =15.75 kV, x_d =1.97 Operating with a block transformer with u_K =0.132, *p=15*.75 kV/420 kV to 400 kV network with x_V =0.1567.

Calculated curve for U_S = 420 kV

Calculated curve for U_S = 400 kV

Limiting curves:
K_r - limitation by excitation current
K_t - turbine power limitation
K_p - static stability limitation
K_u - minimum terminal voltage limitation

Alternator load limit in the impedance plane

From the alternator phase diagram it was derived:

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

$$s_S = p_S - j \cdot q_S = \frac{u_S \cdot e_V}{x_d} \sin\vartheta - j\frac{u_S \cdot e_V}{x_d} \cos\vartheta + j\frac{{u_S}^2}{x_d} =$$

$$s_S = \frac{u_S \cdot e_V}{x_d} \cos\left(\frac{\pi}{2} - \vartheta\right) - j\frac{u_S \cdot e_V}{x_d} \sin\left(\frac{\pi}{2} - \vartheta\right) + j\frac{{u_S}^2}{x_d} = \frac{u_S \cdot e_V}{x_d} e^{-j\left(\frac{\pi}{2} - \vartheta\right)} + j\frac{{u_S}^2}{x_d}$$

Limitation of excitation current sizes

$$|e_V| = |x_{dF} \cdot i_F| \quad => \quad e_{V\,MAX} = c \cdot i_{bMAX}$$

$$s_{MAX1} = \frac{c \cdot i_{bMAX} \cdot u_S}{x_d} e^{-j\left(\frac{\pi}{2} - \vartheta\right)} + j\frac{{u_S}^2}{x_d}$$

$$z_{MAX1} = \frac{{u_S}^2}{s_{MAX1}} = \frac{u_S \cdot x_d \cdot c \cdot i_{bMAX}}{c^2 \cdot {i_{bMAX}}^2 - {u_S}^2} e^{j\left(\frac{\pi}{2} - \vartheta\right)} + j\frac{x_d \cdot {u_S}^2}{c^2 \cdot {i_{bMAX}}^2 - {u_S}^2}$$

Stator current size limitation

$$s_{MAX2} = u_S \cdot i_{MAX} \cdot e^{-j\cdot\varphi} \qquad z_{MAX2} = \frac{{u_S}^2}{s_{MAX2}} = \frac{u_S}{i_{MAX}} e^{j\cdot\varphi}$$

Limitation by mechanical power of the turbine

$$s_{MAX3} = \frac{p_{MAX}}{\cos\varphi} \cdot e^{-j\cdot\varphi} \qquad z_{MAX3} = \frac{{u_S}^2}{s_{MAX3}} = \frac{{u_S}^2}{2 \cdot p_{MAX}} e^{j\cdot\varphi} + \frac{{u_S}^2}{2 \cdot p_{MAX}}$$

Limitation by active motor power (drawn from the grid)

$$s_{MAX4} = -\frac{\Delta p}{\cos\varphi} \cdot e^{-j\cdot\varphi} \qquad z_{MAX4} = \frac{{u_S}^2}{s_{MAX4}} = \frac{{u_S}^2}{2 \cdot \Delta p} e^{j\cdot\varphi} - \frac{{u_S}^2}{2 \cdot \Delta p}$$

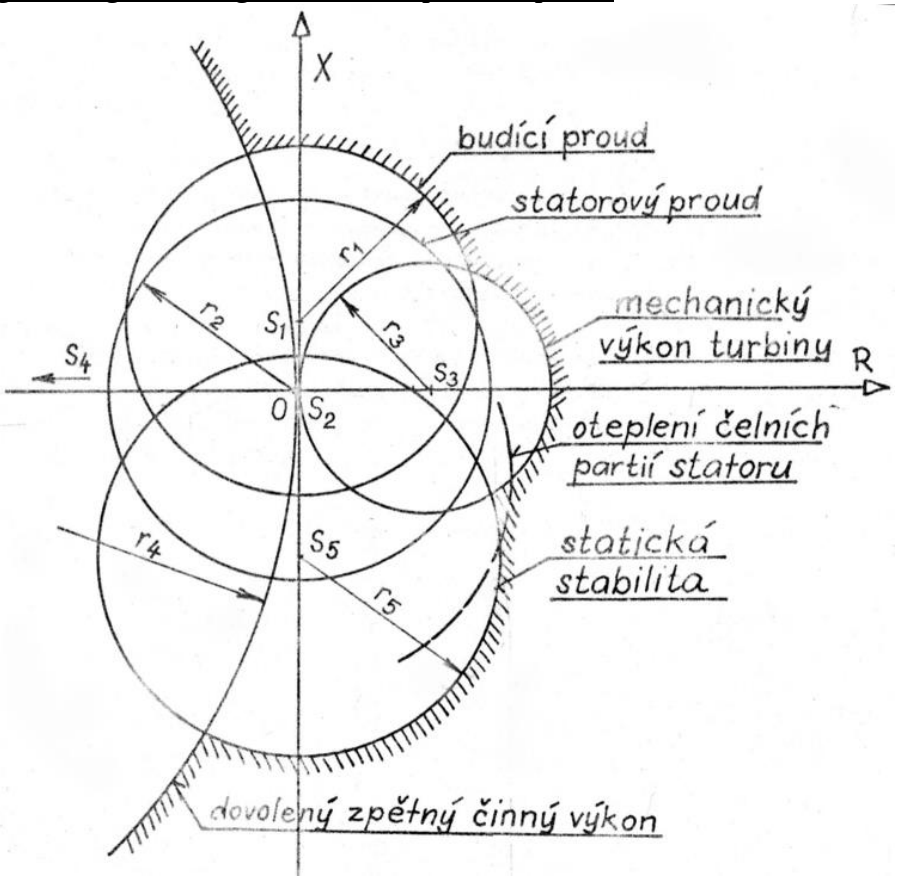
Limitation of stability limits

It is necessary to consider the load angle between the clamps and the net:

$$s_{MAX5} = {u_S}^2 \frac{x_d + x_S}{2 \cdot x_d \cdot x_S} e^{-j\left(2\vartheta_S - \frac{\pi}{2}\right)} - j \cdot {u_S}^2 \frac{x_d - x_S}{2 \cdot x_d \cdot x_S}$$

$$z_{MAX5} = \frac{x_d + x_S}{2} e^{-j\left(2\vartheta_S - \frac{\pi}{2}\right)} - j \cdot \frac{x_d - x_S}{2}$$

The resulting limiting state diagram in the impedance plane:



Transformation from the P-Q plane to the impedance plane using the inverse representation over the unit circle:

