Power Plants
A1M15ENY

Lecture No. 6

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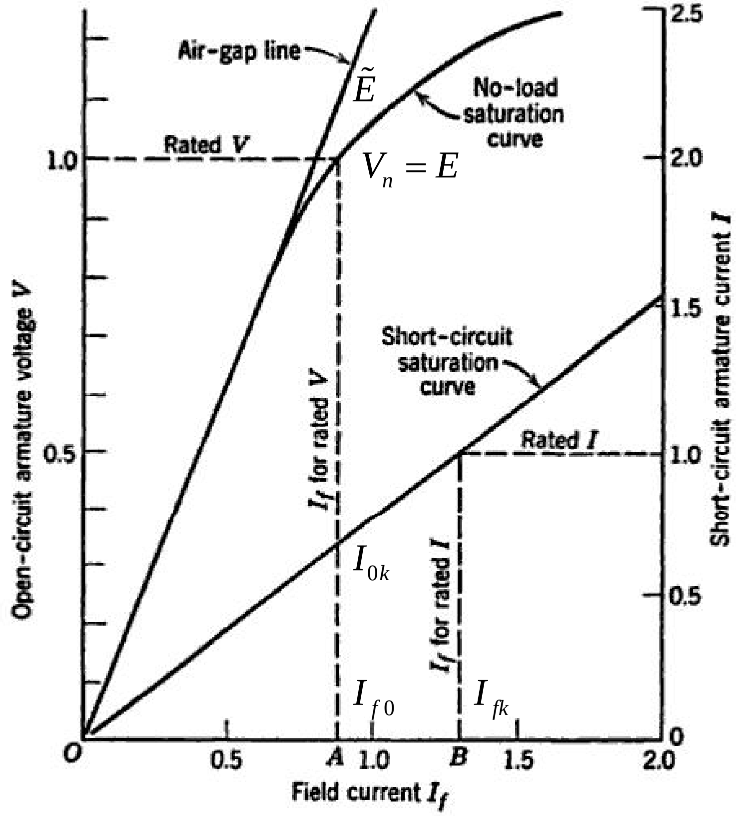
No-load, Short Circuit Characteristics



Influence of iron core characteristics of synchronous machine:

No-load characteristics:

$$U = E = f\left(I_f\right) \qquad u = e = f\left(i_f\right)$$

Short circuit characteristics:

$$I_k = f\left(I_f\right) \qquad i_k = f\left(i_f\right)$$

At point of filed current I_{f0} of open circuited machine reaches voltage at terminals its rated value value V_n (point A)

At point of filed current I_{fk} of short circuited machine reaches armature current its rated value I_n (point B)

No-load, Short Circuit Characteristics

Taking into consideration that position of point A I_{f0} corresponds to a stator current I_{0k} in a scc. characteristics $i_k = f\left(i_f\right)$ and definig a terminal voltage of unsatureted mechine as $\tilde{e}$

We define *short circuit ratio* as:

$$\nu = \frac{I_{f0}}{I_{fk}} = \frac{i_{f0}}{i_{fk}}$$

and then *saturated reactance* xdS from no-load characteristics as:

$$x_{d(S)} = \frac{e}{i_{0k}} = \frac{1}{i_{0k}} = \frac{1}{\frac{i_{fk}}{i_{f0}}.1} = \frac{1}{\nu}$$

and *unsaturated reactance* xd from scc. characteristics as:

$$x_d = \frac{\tilde{e}}{i_{0k}}$$

No-load, Short Circuit Characteristics

From hereinabove, always must be: $x_d > x_{d(S)}$

High value of ν is improving static stability of a machine in the network

However, this leads to larger, heavier and finally more expensive machine

Typical values are $\nu = 0,5 - 1,1$ some hydroalternators up to $\nu = 2$

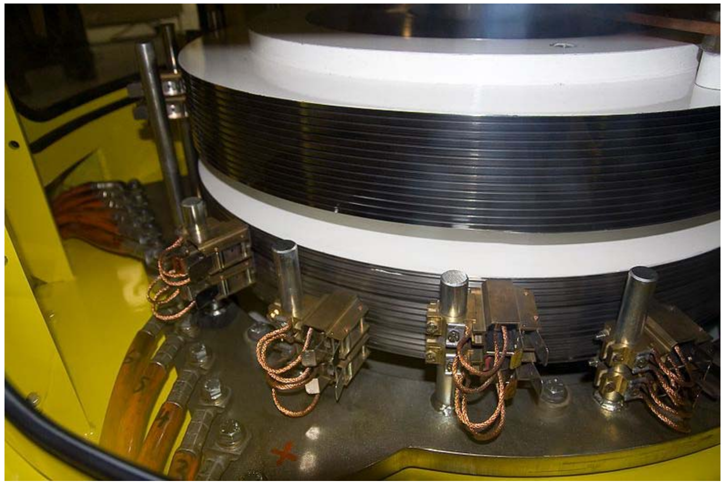
Excitation Systems

Consisting of:

- Field current sources
- Excitation regulation systems (Automatic Voltage Regulator - AVR)
- De-excitation systems

Requirements:

- High reliability
- Smooth and wide regulation of field currents and voltages (up to $2.V_{fn}$)
- Corresponding speed of field voltage response
- Corresponding speed of de-excitation



Detail of DC excitation supply (brushes)

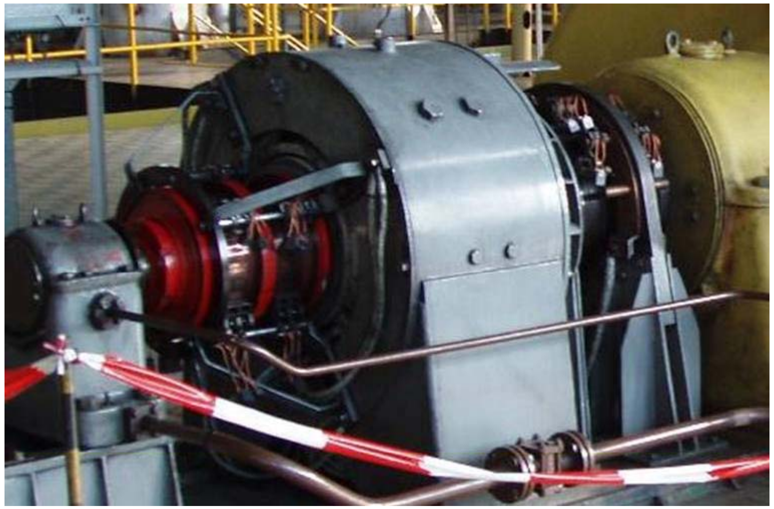
Excitation Current Sources

Main techniques of excitations:

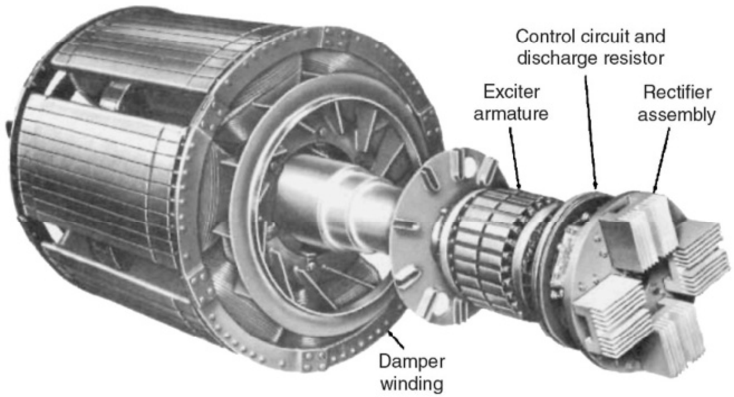
- Rotating exciter (dynamo)
- Static system outlet to slip rings
- Static system inside a rotor
- Permanent magnet system (PMSM, only small applications)

Ways of supply:

- Thyristor DC source supplied by transfromer from generator terminals
- Independent source (i.e. pilot exciter)



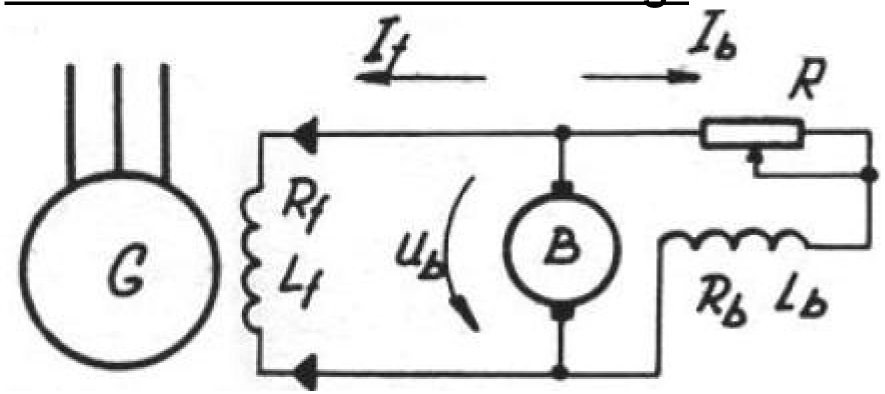
Rotating exciter (with a pilot exciter)



Brushless thyristor system integrated in a rotor

Excitation Current Sources

Exciter with a shunt winding:

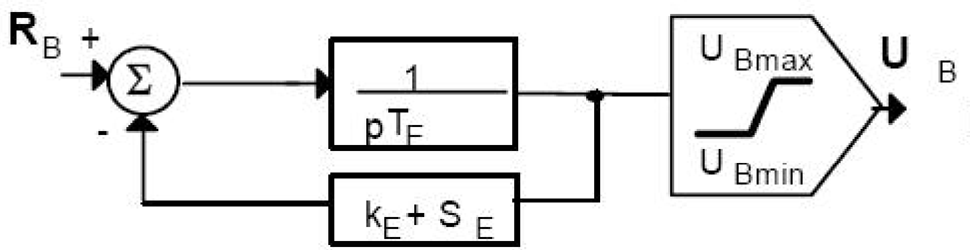


$$u_b = R_b.i_b - \frac{d\psi}{dt} = R_b.i_b - \frac{L_b}{R_b}\frac{du_b}{dt}$$

$$T_b = \frac{L_b}{R_b} \qquad U_b = \frac{R_b}{1+s.T_b}.I_b$$

$$s.T_E.U_b = \mathbf{R}_B - k_E.U_b$$

Model respecting saturation:



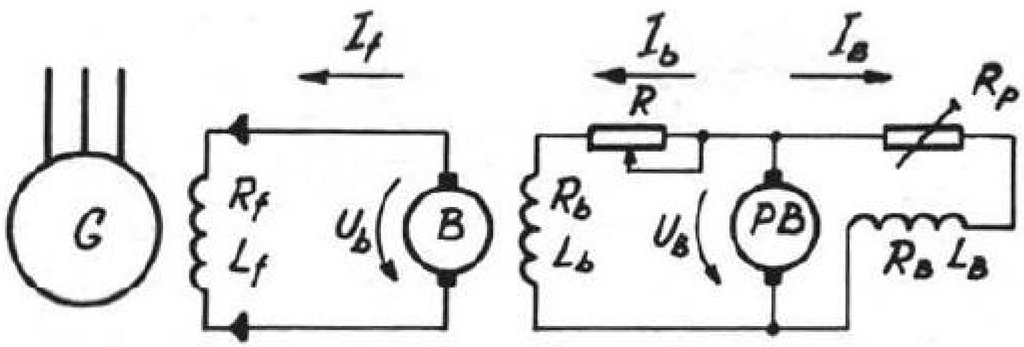
$S_E = A*\exp(B*\mathbf{U}_B/U_{Bn})$

Funkce sycení

Transfer fcn.:

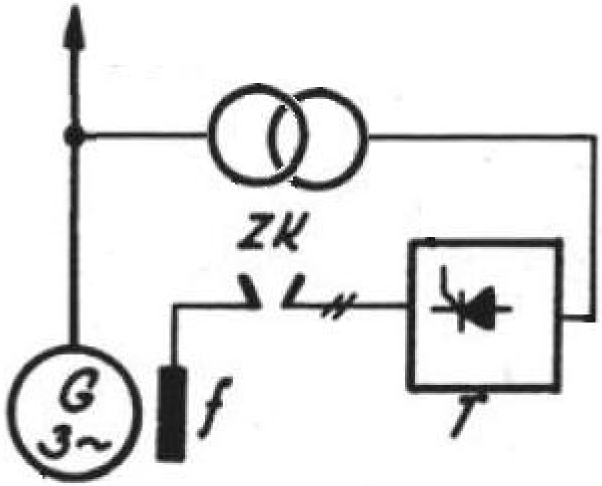
$$U_B = \frac{1}{k_E + s_E + s.T_E}.R_B$$

Exciter with a pilot excitation:



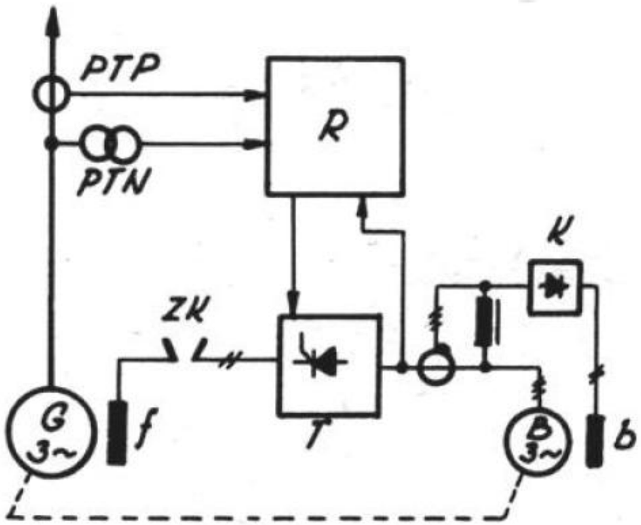
Excitation Current Sources

<u>Static exciter with controlled rectifier supplied from gen. terminals:</u>



The source is dependent on terminal voltage of generator. This solution is affecting regulation speed within sudden changes of u_S (i.e. distant short circuit)

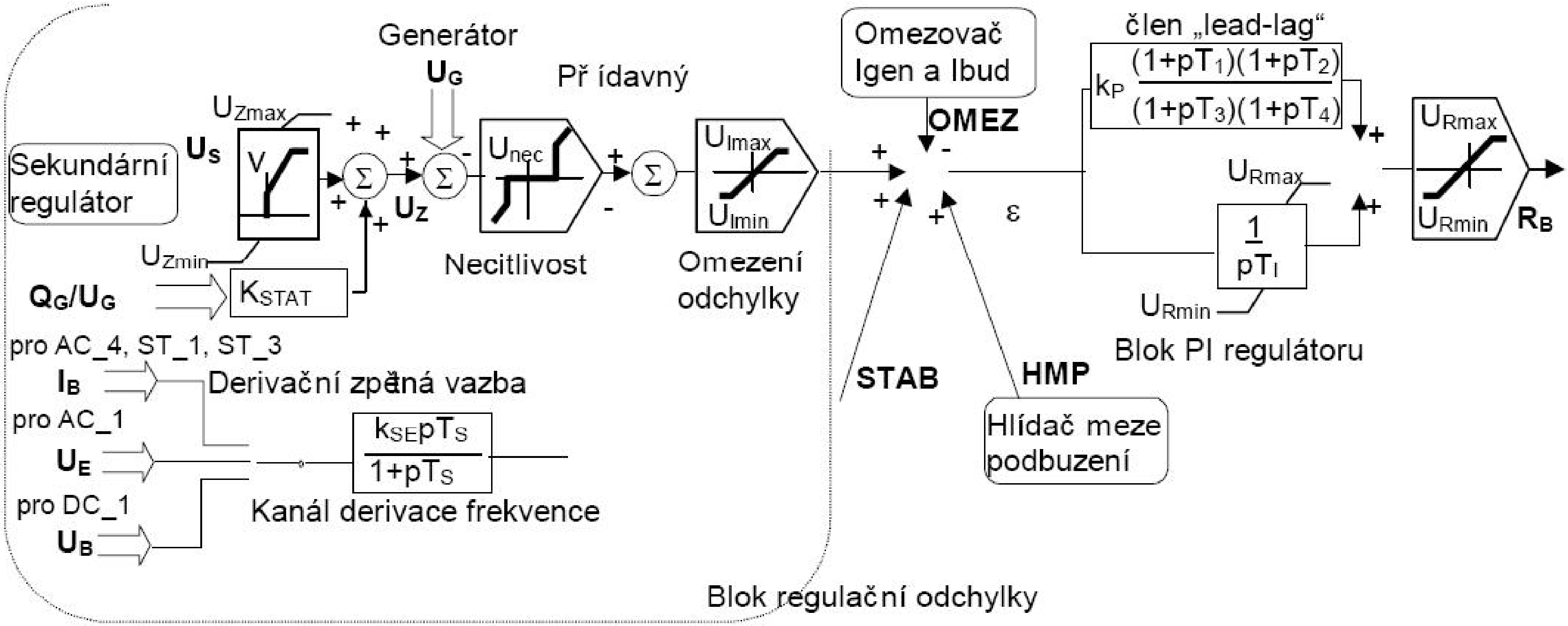
<u>Static exciter with controlled rectifier supplied from a special generator:</u>



An example of independent exciter

Voltage Regulation

General scheme of voltage regulation:



Source: www.ceps.cz

Reference voltage (Uz) is constructed from: Secondary regulation and droop
Difference signal is continuing through dead zone (Unec), low/high limitter (Umax,Umin), limitters Ig and If, underexcitation limitter (HMP) and system stabilizer (STAB)
Corrected signal is finally entering to PI controller, output R_B is an input signal for an exciter

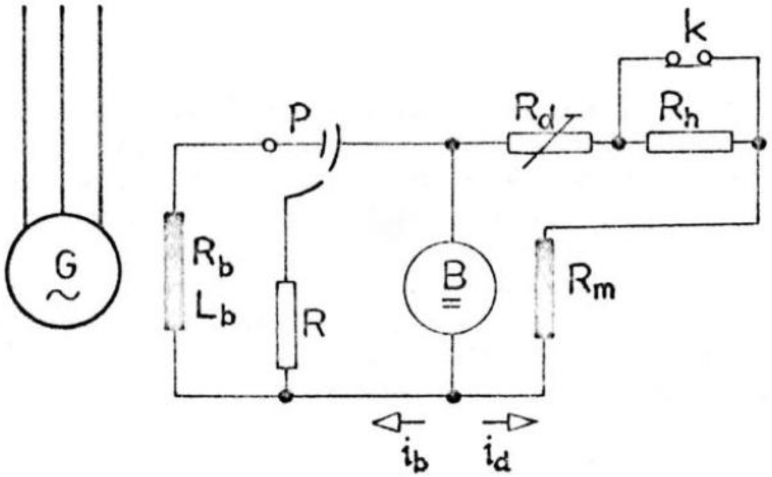
De-excitation

Ways of de-excitation:

- with parallel discharge resistor
- with field breaker (arc extinguishing chamber)
- inverter regime of excitation winding

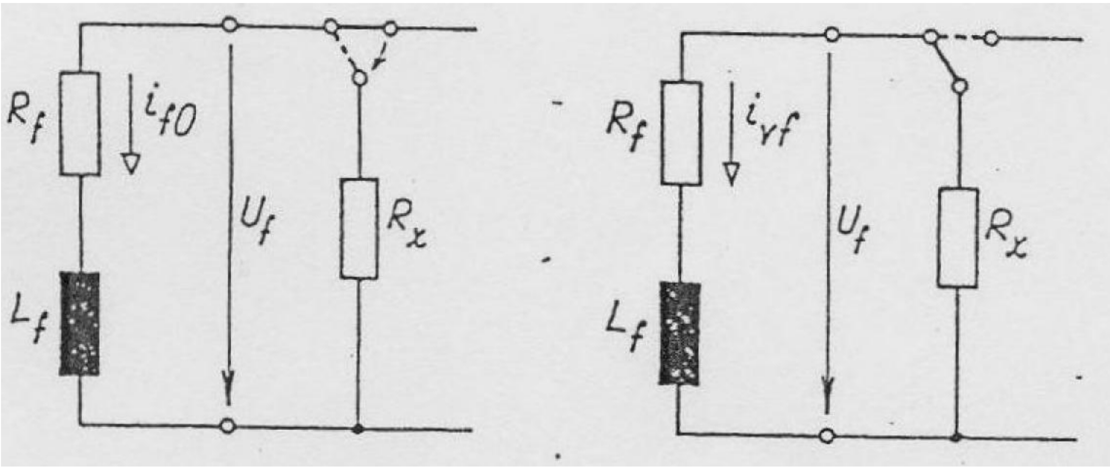
De-excitation with Resistor

Scheme:



Resistor R is inserted into a field circuit by switching P and at the same time the contactor k is disconnected inserting Rh to an excitation circuit of dynamo. A choice of resistance R must ensure a quick de-excitation. However, contemporarily it must avoid overvoltage on slip rings.

Simplified model (without damper winding):



Equation:

$$u_f = L_f.\frac{di_{vf}}{dt} + R_f.i_{vf} = -R_x.i_{vf}$$

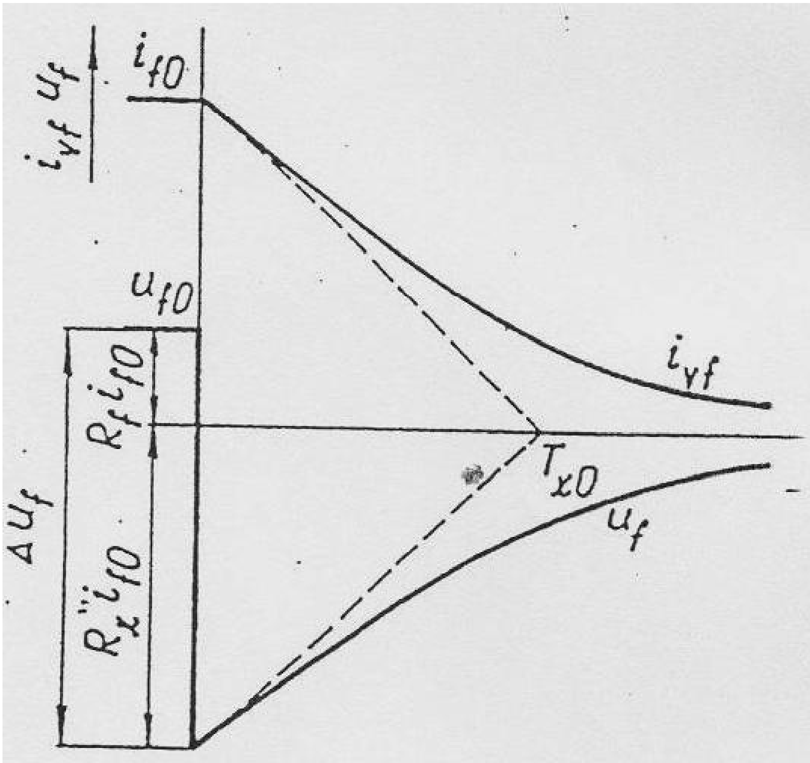
De-excitation with Resistor

Solution:

$$i_{vf} = i_{f0}.e^{-\frac{t}{T_x}} \qquad u_f = -R_x.i_{f0}.e^{-\frac{t}{T_x}}$$

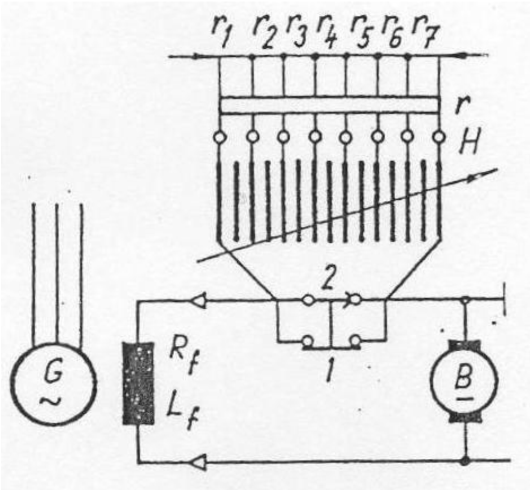
If the initial filed current is at maximum i_{fn} and requirement is $u_f < 7.u_{fn}$

$$7.u_{fn} = 7.R_f.i_{fn} = R_x.i_{fn} \Rightarrow R_x = 7.R_f$$



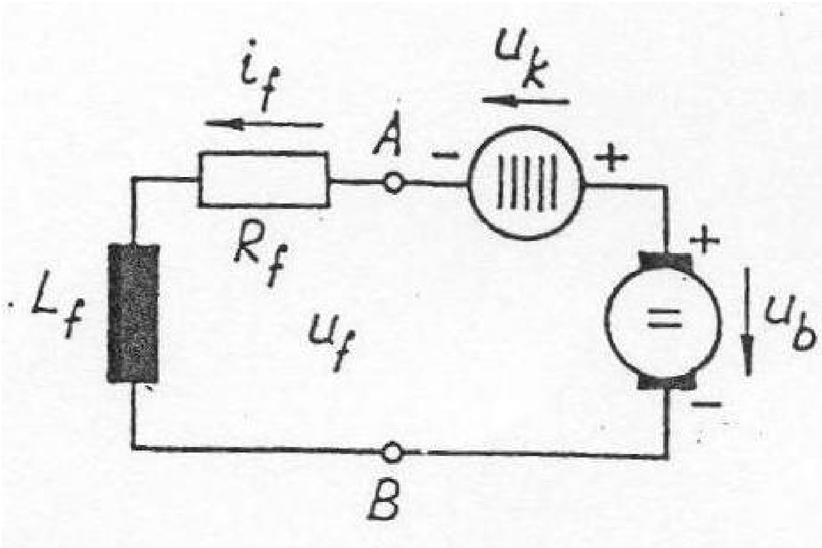
De-excitation with Field Breaker

Scheme:



For generators of greater power output.
After disconnection of contacts No. 1 the field current is flowing through main contacts No. 2 with inductances, which are redirecting the current flow to the chamber after disconnection. Thanks to a combination of r1-r7 and an arrangement of the chamber, the voltage uk is held practically constant within discharging

Simplified model (without damper winding):

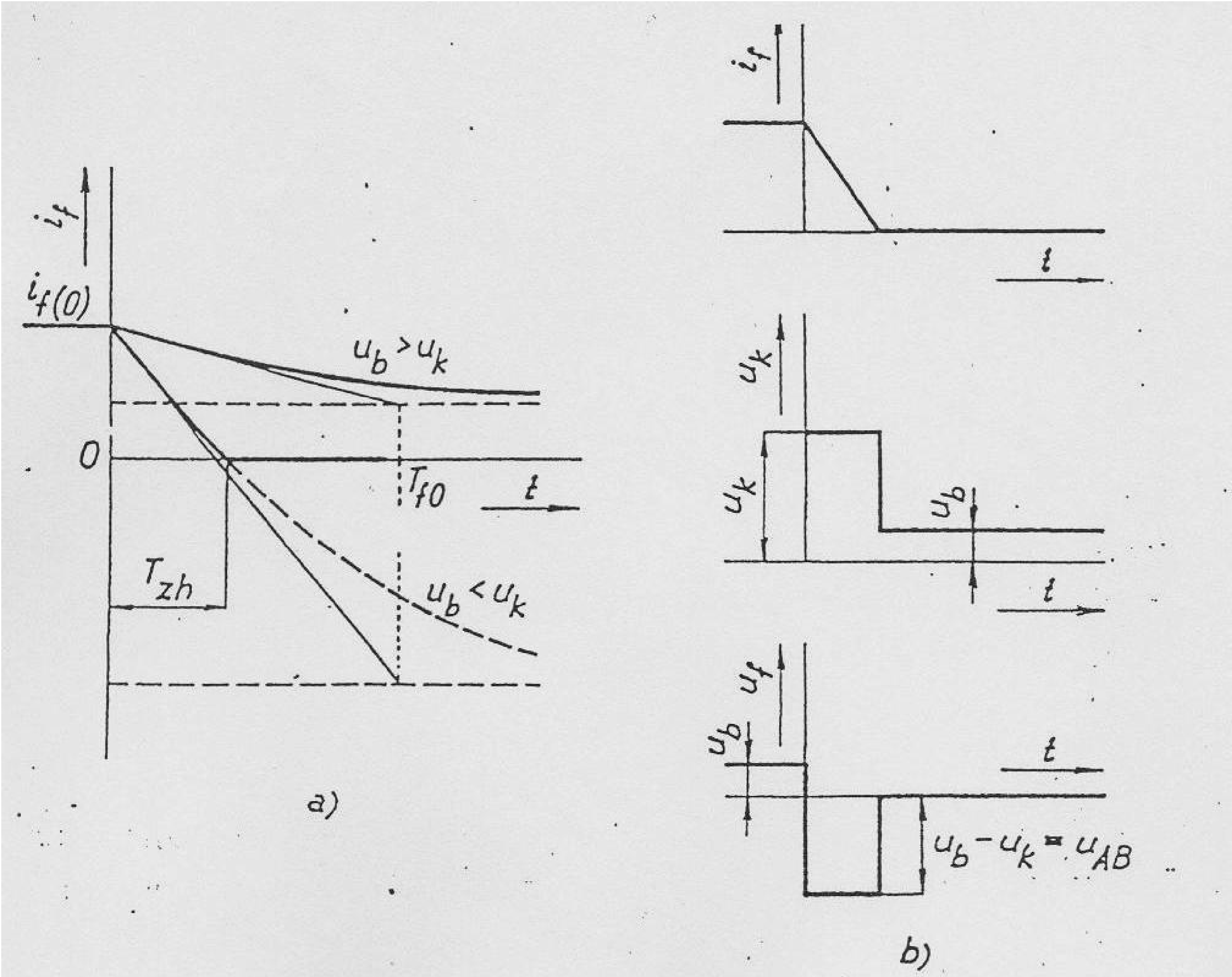


Equation:

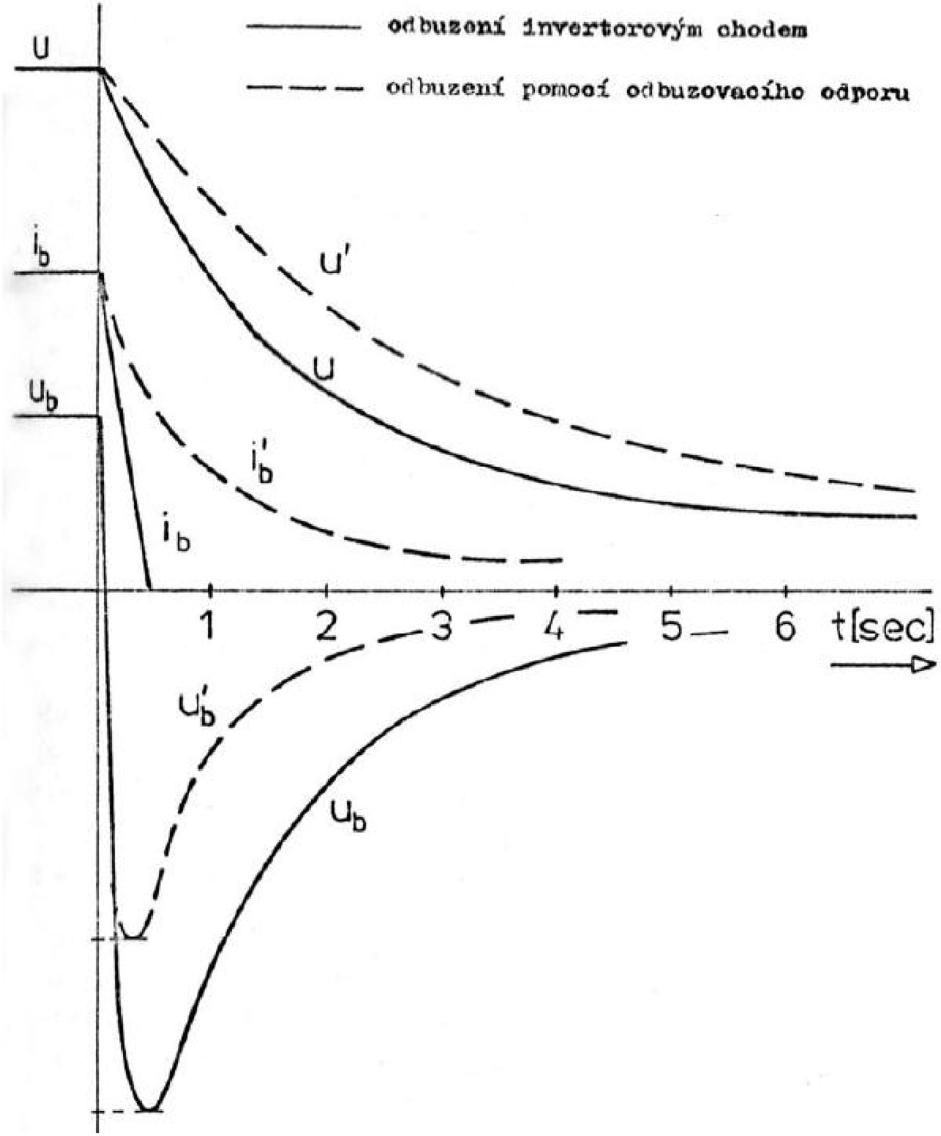
$$i_f = \frac{1}{R_f}\left(u_b - u_k + u_k.e^{-\frac{t}{T_{f0}}}\right)$$

$$T_{f0} = \frac{L_f}{R_f}$$

De-excitation with Field Breaker



De-excitation with Thyristor Converter



Instead of the chamber it is possible to use a thyristor controlled converter. Equipped for a planned de-excitation. However, conventional solutions are still used in case of emergency fast discharge need (faults).

Generator Synchronizing

Connection a generator to grid:

As first, a turbo-generator set is driven to its nominal speed, in a next step is excited to its nominal voltage, and finally synchronized to the network. After connection, the generator is loaded to required values of P and Q. Generator synchronizing must be performed with minimum current and torque transients, which are influenced by:

- Different phase order of generator/network
- Different voltage of generator/network
- Different voltage phase angle of generator/network
- Different frequency of generator/network

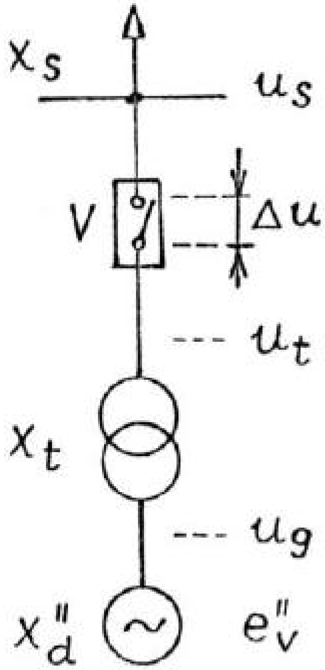
These requirements cannot be met absolutely, tolerances are as follows:

Phase order:

Necessary, today phase order check is a part of every common unit multifunctional digital protection

Generator Synchronizing

<u>Voltage level difference:</u>



If we assume a voltage difference Δu
and zero phase difference before synchronization

Current transient after a connection will be:

$$i''_k = \frac{e'' - u_s}{x_t + x''_d} = \frac{\Delta u}{x_t + x''_d}$$

If the tolerance has to be at most: $i''_k = i_n$

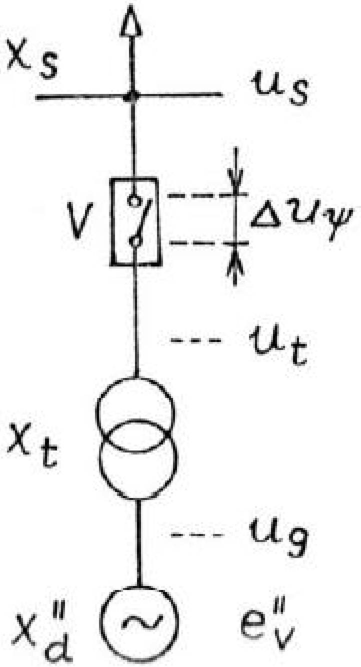
$$\Delta u_{\max} = i''_k . x''_d = i_n . x''_d \simeq 1.0{,}15 = 15\ \%$$

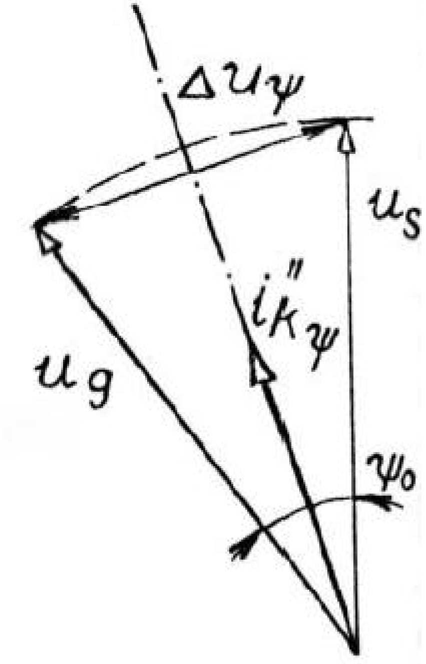
If $u_s < e''$ a reactive power is flowing from the generator to the network and operating in overexcited (inductive) regime. If $u_s > e''$ the generator is operating in underexcited (capacitive) regime

Generator should be slightly overexcited to avoid the second case.

Generator Synchronizing

Phase angle difference:





$$i''_k = \frac{e'' - u_s}{x_t + x''_d} = \frac{2u.\sin\frac{\psi}{2}}{x_t + x''_d}$$

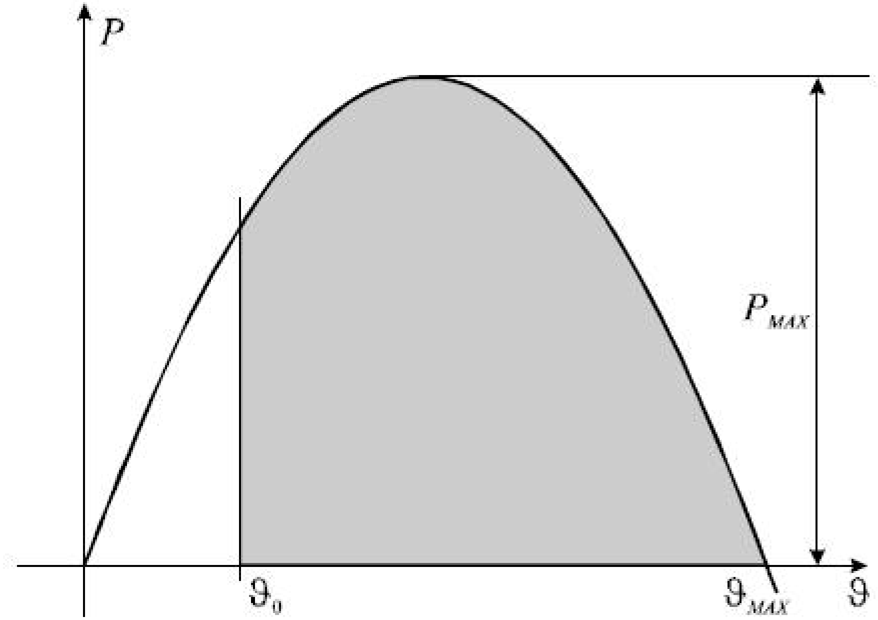
Analogically:

$$i''_k = i_n = \frac{2u.\sin\frac{\psi_{\max}}{2}}{x''_d} \qquad \psi_{\max} = 2.\arcsin\frac{i_n.x''_d}{2u} = 2.\arcsin\frac{1.0,15}{2.1} = 8,6°$$

=> Generator is more sensitive to a phase angle difference, if synchronized at counter phase current transient can reach up to 2x of three pole short circuit

Generator Synchronizing

Frequency:



Equality of damping and accelerating energy:

$$\frac{1}{2}J\Delta\Omega^2=\int_{t_0}^{t_{\max}}P_e\left(t\right).dt=$$

$$\cong\int_{\vartheta_0}^{\pi}P_e\left(\vartheta\right).\frac{dt}{d\vartheta}d\vartheta\cong$$

$$\cong\int_{\vartheta_0}^{\pi}p_{\max}.\sin\vartheta.\frac{M_n.\Omega_n}{\Omega_n}d\vartheta$$

$$\frac{1}{2}\frac{J.\Omega_n^2}{M_n}\Delta\omega^2=\frac{1}{2}T_m\Delta\omega^2=\int_{\vartheta_0}^{\pi}p_{\max}.\sin\vartheta.d\vartheta$$

and thus

$$\Delta\omega_{\max}=\sqrt{\frac{2}{T_m}\int_{\vartheta_0}^{\pi}p_{\max}.\sin\vartheta.d\vartheta}=\sqrt{\frac{2}{T_m}p_{\max}.\left(1+\cos\vartheta_0\right)}$$

Self-synchronizing

An unexcited machine at nominal speed is connected to grid,

A field winding is short circuited

Current transient is then:

$$i_k'' \cong \frac{u}{x_t + x_d''}$$

Similar to an induction machine start up with shorter period of a current transient (so called “asynchronous start up”)

For emergency uses only

Generator Operating Limits

<u>Limitations:</u>

- Turbine (prime mover) power rating
- Underexcitation limit (loss of stability)
- Rotor winding temperature rise
- Stator winding temperature rise
- Stator face side temperature rise
- Rotor body temperature rise

Parametric expression with load angle / phase shift:

<u>Prime mover limitation:</u>

$$p = n_t = s.\cos\varphi \qquad q = s.\sin\varphi$$

In a complex function form:

$$\hat{s} = \frac{n_t}{\cos\varphi}\left(\cos\varphi - j.\sin\varphi\right) = \frac{n_t}{\cos\varphi}.e^{-j.\varphi}$$

Generator Operating Limits

Field current limitation:

$$e = x_{ad}.i_f = K.i_f \qquad p = \frac{K.i_{f\max}.u_s}{x_d}.\sin\vartheta \qquad q = \frac{K.i_{f\max}.u_s}{x_d}.\cos\vartheta - \frac{u_s^2}{x_d}$$

In a complex function form:

$$\hat{s} = \frac{K.i_{f\max}.u_s}{x_d}.\sin\vartheta - j.\frac{K.i_{f\max}.u_s}{x_d}.\cos\vartheta + j.\frac{u_s^2}{x_d} =$$

$$= \frac{K.i_{f\max}.u_s}{x_d}.\cos\left(\frac{\pi}{2} - \vartheta\right) + j.\frac{K.i_{f\max}.u_s}{x_d}.\sin\left(\frac{\pi}{2} - \vartheta\right) + j.\frac{u_s^2}{x_d} =$$

$$= \frac{K.i_{f\max}.u_s}{x_d}.e^{j.\left(\frac{\pi}{2} - \vartheta\right)} + j.\frac{u_s^2}{x_d}$$

Stator current limitation:

$$\hat{s} = u_s.i_{\max}.e^{-j.\varphi}$$

Generator Operating Limits

Stability:

For a stable solution of mechanical differential equation, it must be met:

$$\frac{\partial p}{\partial \vartheta} > 0$$

From this condition, we obtain an angle limit $\vartheta_{\max}$. Taking into account Infinity Bus – Machine System (IBMS)

$$\hat{s} = \frac{e.u_s}{x_d}.\sin\vartheta_{\max} - j.\frac{e.u_s}{x_d}.\cos\vartheta_{\max} + j.\frac{u_s^2}{x_d}$$ (a line with parameter e)

Taking into account a network impedance xv, for an angle difference between generator terminals and network voltage ϑ_s :

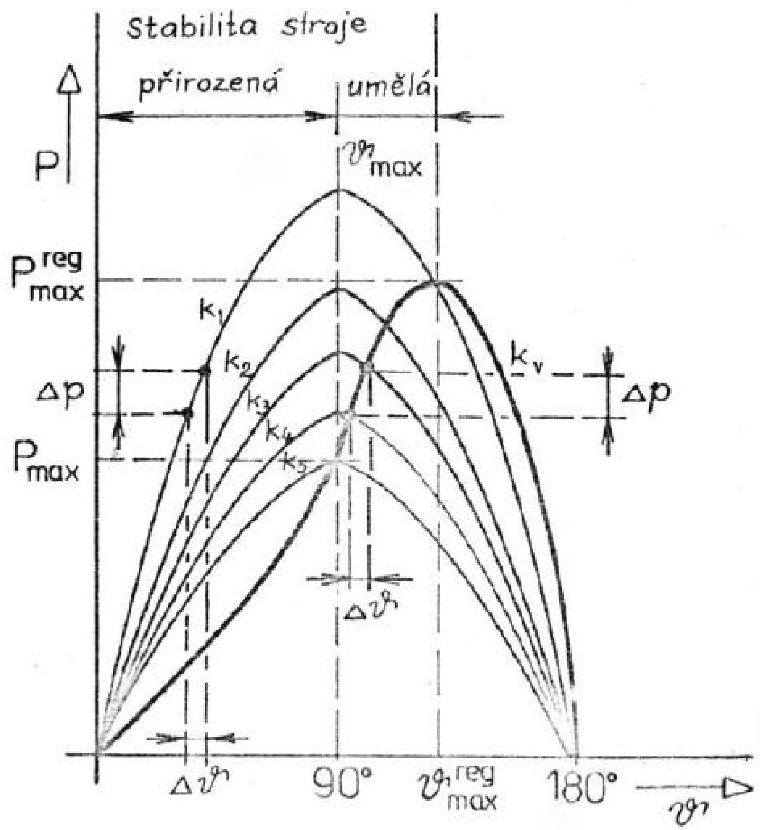
$$\hat{s} = u_s^2 \frac{x_d + x_v}{2.x_d.x_v}.e^{j.\left(\frac{\pi}{2} - 2.\vartheta_s\right)} - j.u_s^2 \frac{x_d - x_v}{2.x_d.x_v}$$ (a circle with parameter ϑ_s)

Generator Operating Limits

Artificial stability:

For emergency manual operation, lower angle limit, circa $\vartheta_{max} = 60°$

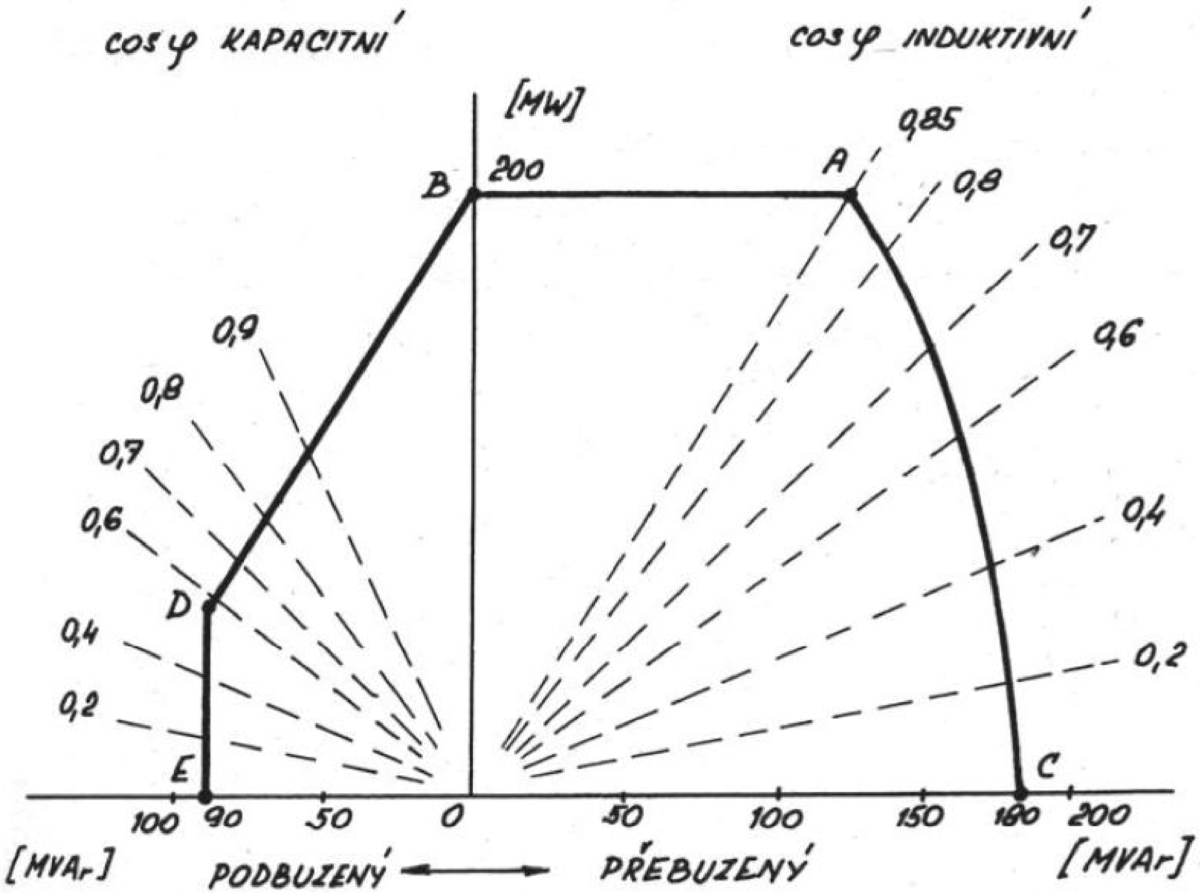
In the other hand, fast controller can shift the limit beyond 90°: $\vartheta_{max} > 90°$



Characteristics $p(\vartheta)$ considering controller influence

Generator PQ Chart

PQ chart:



AB - Omezení výkonem turbíny

AC - Oteplení rotorového budícího vinutí

BD - Oteplení čelních konstrukcí

DE - Omezeni statickou stabilitou stroje