Technical University of Cluj-Napoca
Faculty of Automation and Computer Science
Department of Automation

Semester Project

discipline

Industrial Plant Control

Analysis and control of a boiler – turbine – generator–system electro-power radial

Coordonator:

Student:

Content

1. Process presentation

Project Objective

The simplified design of the main control circuits for the following system: boiler-turbine-generator (an electric-energetic radial system) and the analysis of some important step responses.

Given Data:

Group Power	P = 122 [MW]
Pressure of the living steam	p = 90 [bar]
Thermal Efficiency (exact usage)	$1/\eta_\theta$ = 2392 [Mcal/MWh]
Enthalpy of the living steam	i_2 = 780 [Mcal/to]

We will design in a simplified form the main automated control circuits and we will analyze the significant responses to perturbations for a **Boiler group** (c) – **Turbine** (t) – synchronous **Generator** (g) system and a radial energetic system (s).
The details of the control circuit in a simplified form are :

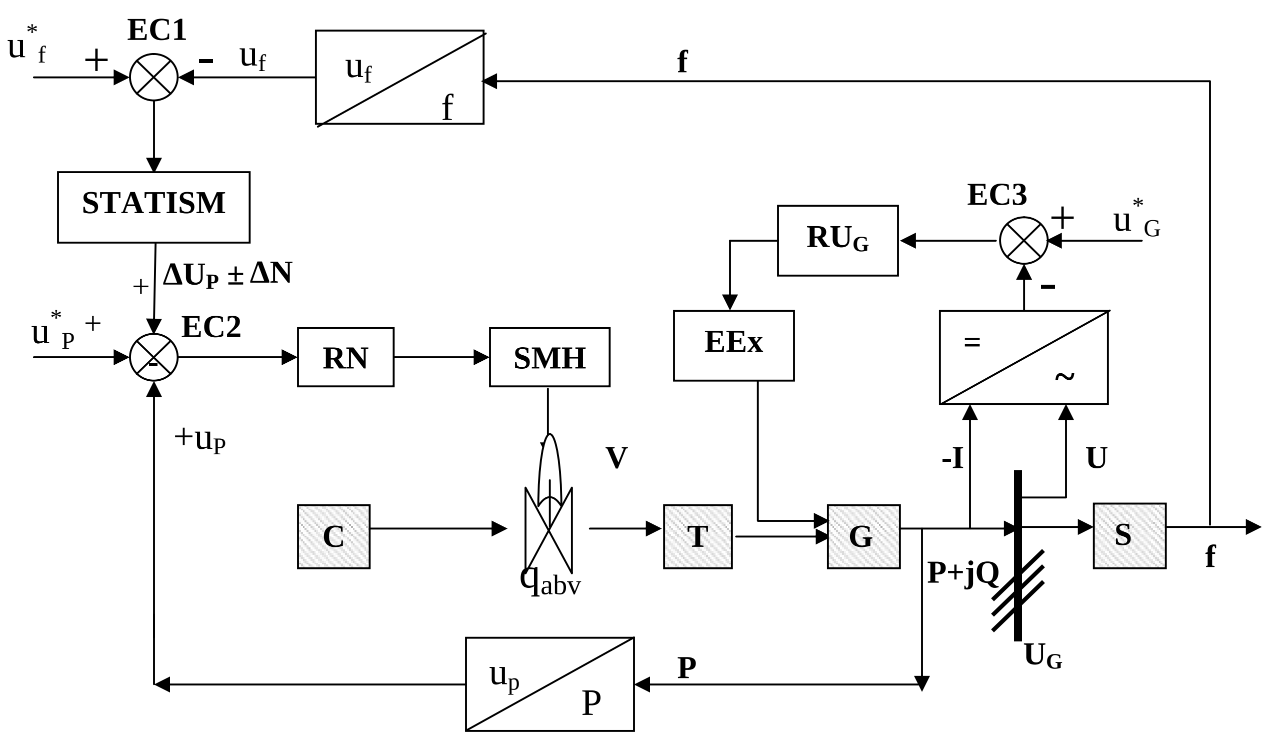


Figure 1: Radial energetic – electronic system(control circuit)

Notations: RN: active power regulator
SMH: hydraulic actuator drive of the partial intake valve V of the steam flow
q_{ab} at the entry point of the turbine
C: boiler
T: turbine
G: synchronous generator
S: radial power system
P/U_P : transducers and power-voltage adaptors; unified;
U/f : frequency adaptors - unified voltage;
Statism : corrective block formed out of an active quadripol which ensures a linear dependency with a certain predetermined slope for slope f(P) ;
=/~ : voltage rectifier block
RU_g : voltage regulator at the generators terminals
EEx : excitation element of the generator

Other notations :

- i_{apv}^* = pressure ref of processed steam;
- i_{O2}^* = ref of O_2 in burned gases ;
- $i_{\Delta PF}^*$ = source depressurization ref;
- $i_{\theta av}^*$ = temperature ref for processed steam;
- i_h^* = water level ref from the tambour(cylinder) ;
- i_S = salinity ref.

The system is formed out of 4 subsystems: boiler of the group **C**; turbine **T**; sync generator **G** ; radial power system **S** .

In the composition of the system there are control loops compared to active power (P) and relative to the frequency (f). Also there are regulators for the steam flow inside the turbine ensured by the hydraulic actuator drive (SMH) and valve (V) which ensures partial air admission into the turbine. We also have a control voltage system U at the generators terminals in association with current correction offsetting effect. There are transducers and power-voltage adaptors (P/U_P), frequency-voltage adaptors (f/U), statism block, a voltage rectification block from the voltage regulator at the generators terminals.

(~/=), power amplifier levels (EEx), representing the excitation circuit of the generator and others. The block scheme of the system is the following:

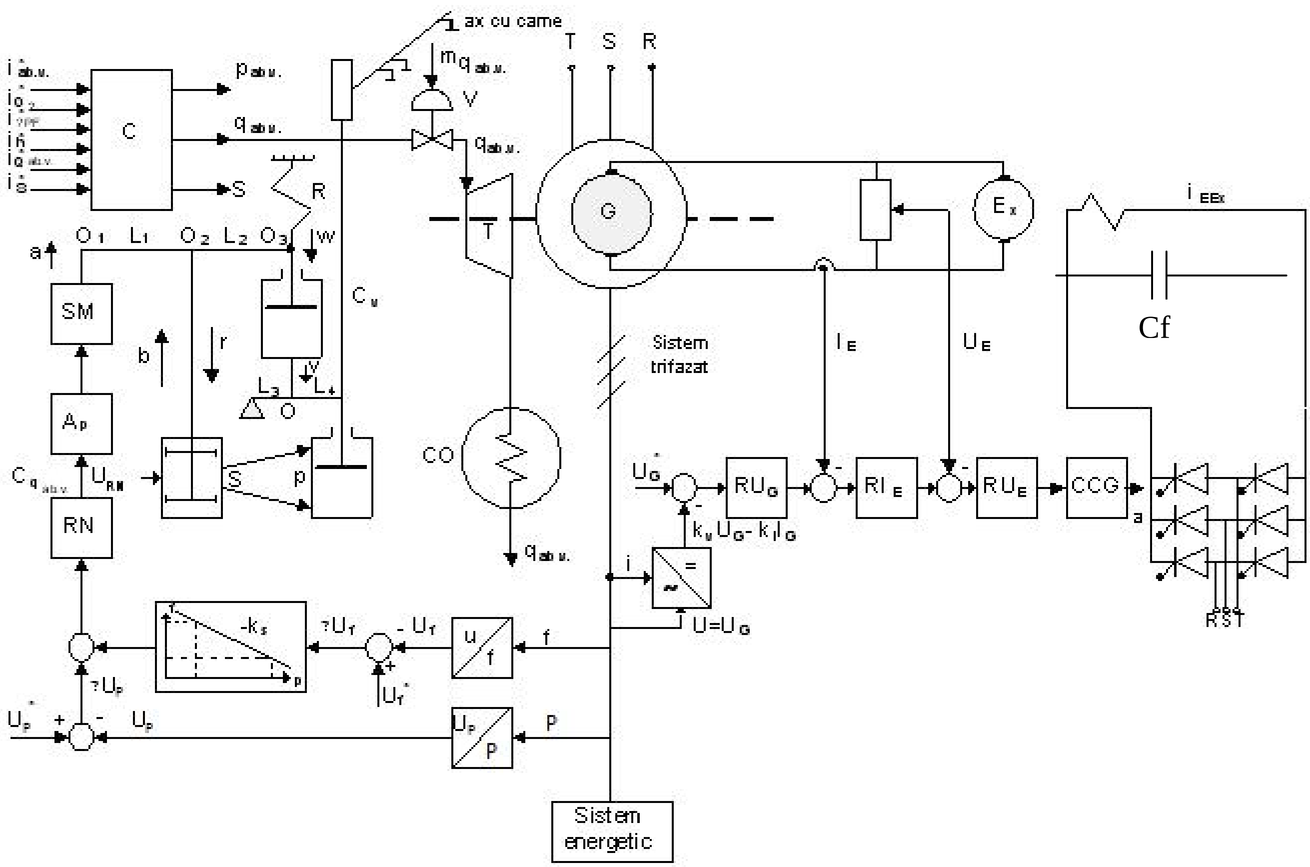


Figure 2: Block scheme of the system

The components of the previous scheme are:

1. The boiler (C) for which the minimum number of input signals is 6. Under the simplified form we consider only one output signal, q_{abv}, which is adjusted by strangulation with the valve (V), equivalent with the steam turbine inlet.
2. The turbine (T) drives the generator G. The live steam from the turbine enters the condenser CO and due to the cooling process we get the same flow of condensed water q_{abv}.
3. The execution element SMH is composed of a rack driven by a hydraulic slide-piston mechanism made of the slide S and the piston P. There also is a mechanical negative feedback of positioning type using the lever L1, L2. By using this negative feedback we get 2 advantages:

a) decreasing the equivalent mechanical inertia;

b) improving the linear behavior by decreasing the non-linear disturbances caused by dry friction, mechanical wear and mechanical disturbances.

Because the oil is incompressible it cumulates numerous benefits: very small mechanical inertia, undamped transient forces, high precision.

There are also functional blocks: RN – active power regulator; Ap – power amplifier; SM - **actuator**

4. The generator (G) triggered coaxially by the T turbine delivers in the energetic system in three phased regime RST, both active power, proportional with the mechanical power taken from the turbine and reactive power needed for the magnetization of the force circuits (transformers and electrical machines).
5. The generator rotor is powered in continuous excitation voltage, delivered by the Ex exciter, having active power at most 1% of generator power. The exciter excitation is powered in DC voltage at a current I_{exc} resulted from the output terminals of the controlled rectifier bridge formed by 6 thyristors.

The control of the medium rectified current is assured in the classical form that is through command pulses on the grid having variable phase (a). The modifying of a is done theoretically between 0˚ and 180˚, practically between 5˚ and 175˚.

The control of the active power is made through a parallel regulation schema in relation to the active power P and in relation to the f frequency. The decreasing linear characteristic f(P) assures through $-k_s$ the active power regulation statism. There are also two adaptors: power–unified voltage and frequency-unified voltage.

The voltage regulation and of the reactive power is assured through a triple cascade having R_{UG} (the voltage regulator at the generator terminals), R_{IE} (the excitation current regulator), R_{UE} (the excitation voltage regulator), that commands CCG block (the command complex on the grid). At the CCG output we obtain the variable phase shift in wide limits for grid command of the 6 thyristors. This equivalent loop in triple cascade has a positive current reaction with a much lower weight, of a couple of percents (compound reaction).

The 6 control loops (in a very general form) for a steam boiler are presented in the below figure:

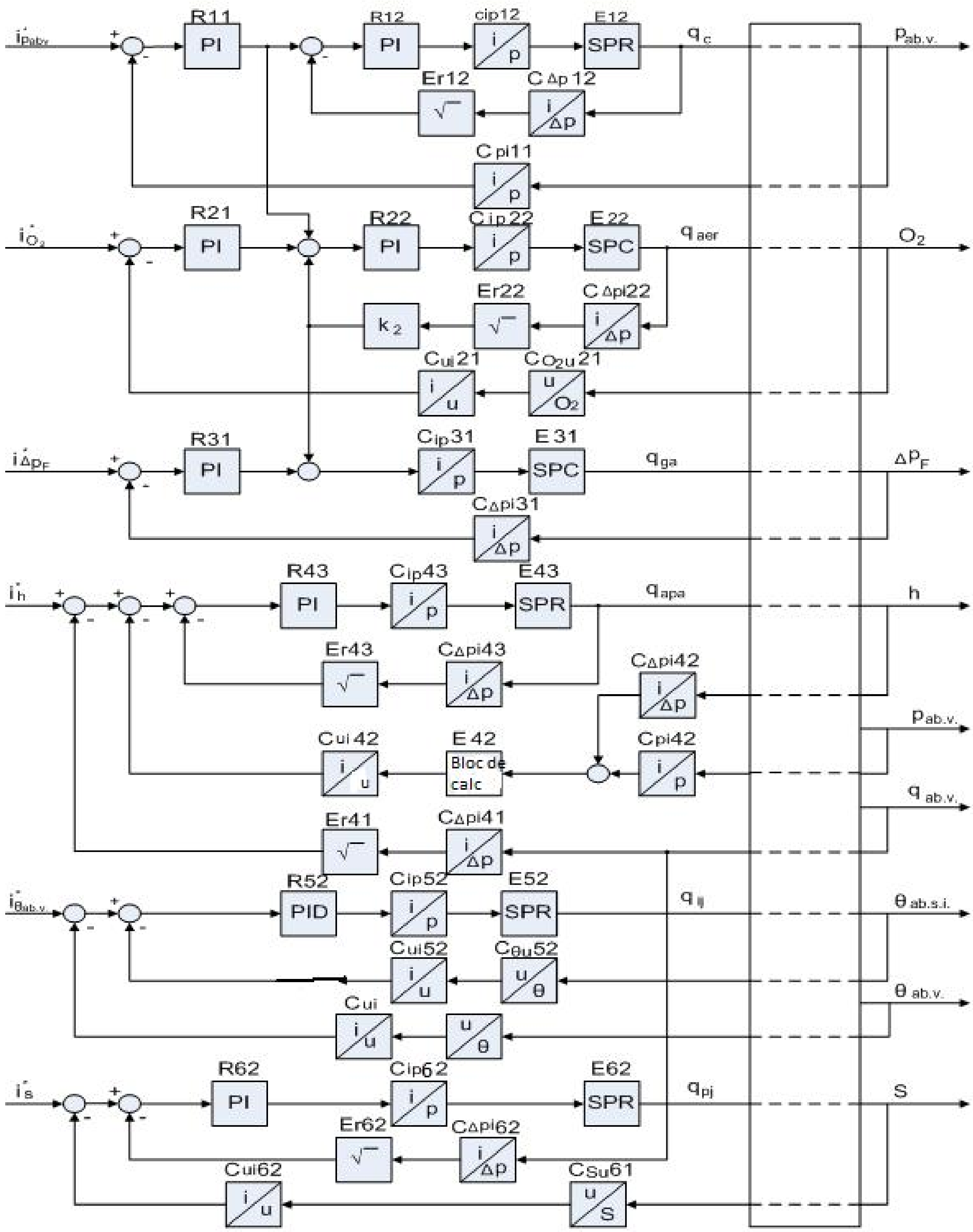


Figure 3:Control loops (general form) for a steam boiler

Functional details

q_{abv} - the steam flow controlled by a control active power classical circuit by comparing a reference power Up* proportional to the actual active power given by the system.

RN – the active power controller which commands the partial inlet steam valve V, through the hydraulic actuator SMH

The generator G is provided with adjustment reactions of the reactive power, terminal voltage UG through RUG regulator and Eex excitation element. UG* is the reference voltage generator.
Is deducted a comparison reaction against current i0. There is also ensured a statism reaction against frequency f by comparing a reference frequency (usually 50 Hz) to the voltage Uf proportional with the real frequency. The Uf*-Uf deviation is processed through a proportional effect in the statism element providing an additional component ΔUP of the active power.

The live steam pressure control is ensured through a scheme in cascade with two PI controllers. On the main circuit we have a pressure-unified current converter and on the internal circuit, a differential pressure –unified current converted, followed by a root extractor. In general, on the flow's feedback loop, a transducer with calibrated diaphragm, the differential pressure Δp being proportional to the square of the flow. It is required the use of a root extractor, this way, the unified current being proportional to the flow. The external feedback loop ensures the reaction against live steam pressure, and the inner loop ensures reaction against fuel flow qc.

The second control loop ensures proper combustion by maintaining the oxygen concentration resulted from the flue gas in acceptable limits. Has also a control loop in cascade, in relation to the oxygen for external loop, respectively combustion air, q_{aer}, for the internal loop.

The third control loop is for depressure in ΔpF outbreak. It is necessary to maintain a depressure of -2mmH2O (millimeters of water) inside the furnace. On the feedback loops there are differential pressure – unified current transducers.

The water supply flow control is provided through a convergent setting with the following reactions:
- In relation to the supply flow: q_{apa}
- In relation to the water level in the reel: h
- In relation to the live steam pressure: p_{abv}
- In relation to the live steam flow: q_{abv}

The transducers and converters type in unified signal is the same as in the previous schemes.

Process steam temperature control is a convergent regulation with respect to 2 reactions: the temperature of the process steam $\Theta_{abv,}$ and the temperature of the process steam inside an intermediary steam over-heater $\Theta_{absi.}$ On the feedback circuit a temperature to unified current/voltage converter appears.

The salinity (S) of condensed water control from the cold funnel of the boiler. The main loop is assured by the salinity, but there is also an additional correction loop which is linearly dependent on the process steam flow. The main loop includes salinity/voltage and a voltage/current transducers. The are also additional loops which provide a corrective effect.

Notations:

$\mathbf{i^*}$	– unified reference current
$\mathbf{u^*}$	– unified reference voltage
$\mathbf{t}$	– time
$\mathbf{\Theta}$	– temperature
$\mathbf{q_{ij}}$	– injection flow between 2 super-heater steps in order to regulate the process steam temperature
$\mathbf{i_p{}^*{}_{abv}}$	– reference in unified current for the process steam pressure
$\mathbf{Q_{pj}}$	– purge flow
$\mathbf{q_{abv}}$	– process steam flow that enters the turbine
$\mathbf{i_{O2}^*}$	– reference in unified current of oxygen for the fumes analyzer
$\mathbf{\Theta_{absi}}$	– steam temperature in the intermediary super-heater
$\mathbf{i_{\Delta pF}^*}$	– vacuum reference within the furnace
$\mathbf{\Theta_{abv}}$	– process steam temperature at turbine input
$\mathbf{i_h^*}$	– water level reference in the drum
$\mathbf{h}$	– water level in the drum
$\mathbf{i_{\Theta abv}^*}$	– process steam reference
$\mathbf{\Delta p_F}$	– furnace vacuum
$\mathbf{i_S^*}$	– salinity reference
$\mathbf{C_{ip}, C_{pi}}$	– current/pressure converter and vice versa
Q, q	– refers to flow
P	– refers to pressure
E	– execution element
$\mathbf{\Delta p}$	– differential pressure (output from the metering orifice)
$\mathbf{p_{abt}}$	– steam pressure in the drum
$\mathbf{E_r}$	– square root extractor
SPR	– pneumatic servomotor with tap
SPC	– pneumatic servomotor with clack
S	- salinity

Q_c,q_c -fuel flow
q_{aer}, q_{apa}, q_{ga}-combustion air flow, supply water flow and exhaust gas flow
EC -correction element
O_2[%] -molecular oxygen percentage concentration
SHR -hydraulic servo valve
SHP -hydraulic damper actuator
R -controller

Explanation:

STATISM: correcting block composed out of an active quadripol, that ensures a linear dependency, for the slope f(P), with a predetermined slope.

On the generator G terminals, the two power components (P, Q) are applied, obtaining S – apparent power: $S = \sqrt{P^2 + Q^2};[MVA]$

The frequency f of the radial electro-energetic system (unpaired with another system) is introduced in the transducer (uf/f) and the unified voltage signal ($-u_f$), which is linearly dependent on the frequency, is introduced in the comparison element EC1, where u_f^* is the frequency reference value in unified voltage. The EC1 block output error is corrected in the Statism element, representing a negative feedback signal which is introduced in EC2. The second unified reference signal is u_p^* - the active power reference which is compared with the negative feedback signal $-u_p$, that is linearly dependent on the active power P, generated by the generator G (the second feedback circuit).

The output error of EC2 is processed by the active power controller RN and the command signal operates the SMH execution element. The SMH output signal represents the axial displacement (high forces – hundreds of kg) that acts on the vent V, which is destined to control the steam flow (q_{abv}).

Control of the reactive power at the generator's terminals is achieved through a double reaction system that has a negative feedback for U and a positive feedback for I (with a much smaller weight). The two signals (U and I) are rectified and the unified voltage signal is applied as an equivalent feedback in EC3.

The output error of EC3 is processed in RU_G, and the command signal is applied on a complex element called excitation circuit. The output of this element is the excitation current of the generator G rotor, allowing it to produce the excitation flux.

Remarks:

- the **current** references are denoted by **i*** and refer to slow pocesses: *2-10 or 4-20 mAcc*; The natural zero (0 mA) is avoided in order to reduce the noise influence from the process, because the slow processes have at least one time constant bigger than 10 sec.
- the **voltage** references are denoted by **u*** and refer to fast processes *1-10V or ï 10Vcc*; the time constant is smaller than 10 sec.

All the liquid flows are denoted by q (Q), the temperatures by θ, the pressures with p, the differential pressure by Δp and the salinity by S. Thus, we have:

$$Q^2 = k * \Delta p; \qquad Q = k^{\frac{1}{2}} * \sqrt{\Delta p}; \qquad \Delta p = p_1 - p_2$$

There are two different control circuits :

1) with respect to the active power for frequency control;
2) with respect to the voltage at the G terminals for voltage control and reactive power control.

In the boiler control scheme we have the following control circuits:

1) the boiler charge, the charge controller, the pressure function acting both on the gas and the combustion air;
2) the combustion control, following the quality of the combustion, and the tracking control in stoichiometric proportion of the combustion air in relation to the gas;
3) the differential pressure in the burner;
4) the water supply, depending on the quality of the combustion relative to the gas;
5) the output steam temperature, having a correction relative to the steam temperature before the injection;
6) the continuous purge depending on the steam flow and the water salinity in the boiler.

The references for the six control circuits are: i_{apv}^*, i_{O2}^*, $i_{\Delta PF}^*$, i_h^*, i_{qav}^* i_S^*.

2. Data design

A. Thermal part

1) The main parameter: the nominal power of the generator:

$$\mathrm{P}_{\mathrm{Gnom}} = \mathrm{P} = 122[\mathrm{MW}];$$

2) The nominal pressure of the living steam in the boiler:

$$P_{abvnom} = p = 90[bar];$$

3) The thermic specific consumption:

$$\frac{1}{¦_{-}} = 2392 \left[\frac{Mcal}{MWh}\right];$$

4) The processed steam enthalpy:

i_2=780 [Mcal/tona];

5) The gas (methane gas) caloric power:

$$PC_{CH4} = 8{,}5\left[\frac{MCal}{Nm^3}\right]$$

6) The nominal gas flow:

$$q_{Cnom} = q_{CH_4 nom} = \frac{\frac{1}{¦_{-}}\left[\frac{MCal}{MWh}\right]\cdot P_{Gnom}[MW]}{PC_{CH4}\left[\frac{MCal}{Nm^3}\right]} = \frac{2335 \cdot 360}{8.5} = 98894.1176\left[\frac{Nm^3}{h}\right]$$

7) Nominal value of processed steam:

$$-_{abnom} = 530^0 C$$

8) Values of the molecular oxygen contained in the burned gas:

$O_2(\%) = 5\%$

9) Nominal pressure of the steam in the drum:

$$P_{abvtnom} = 1{,}1 \cdot P_{abvnom} = 1.1 \cdot 90 = 99 \text{ [bar]}$$

10) Nominal temperature of the steam after the first superheater

$$\overline{\ }_{ab\sin om} = 480^{0} C$$

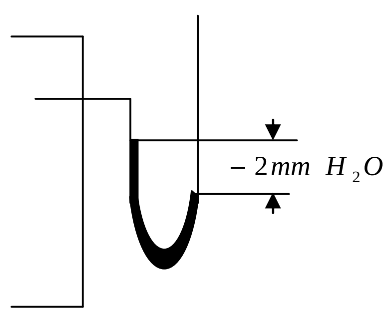
11) Nominal combustion air flow nominal:

$$q_{aernom} = q_{combnom}\left[\frac{Nm^3}{h}\right] \cdot \sim \cdot (a\frac{P_{CCH4}\left[\frac{Kcal}{Nm^3}\right]}{1000\left[\frac{Kcal}{Nm^3}\right]} + b) = 359338.34\left[\frac{Nm^3}{h}\right]$$

- ~ - excess combustion air; ~ =1.1;
- ~ a=1.09; si b=0.25; - coefficients that depend on the gas composition

12) Nominal thermal depressure:

$$\Delta p_{Fnom} = -2[mm\ H_2O]$$



13) Burned gas flow:

$q_{ganom} = q_{CH4nom} + q_{aernom} = 34332.235\ [Nm^3/h] + 359338.34\ [Nm^3/h] = 393670.576\ [Nm^3/h]$

14) Nominal processed steam flow:

$$q_{abvnom} = q_{abviu} = \frac{\frac{1}{\mid -}\left[\frac{MCal}{MWh}\right]\cdot P_{Gnom}\ [MW]}{(i_2 - i_1)\left[\frac{MCal}{tona}\right]} = 389.0986\ \left[\frac{tona}{h}\right]$$

i1: Enthalpy of the feedwater when exiting the condenser at 30^0C;

- Thermal energy contained in the pressurized water

$$i_1 = 30\left[\frac{MCal}{Tonă}\right]$$

i2: Enthalpy of the processed steam after the superheader (the parameter limits of the processed steam are taken into consideration and we determine the liniar interpolation).

P_{abvvar} = 100 [bar] => i2= 809 [Mcal/tonă]
P_{abvvar} = 210 [bar] => i2= 781 [Mcal/tonă]

15) Feedwater flow:

$q_{apanom} = q_{abvnom}$= 389.0986 [tona/h]

16) Nominal salinity:

S_{nom} = 0,01 [mg/tonă] = 10^{-8} [kg/tona]

17) Injection flow:

$q_{ijnom} = 10^{-2} * q_{abvnom}$ = 0.01 * 389.0986= 3.8910 [tona/h]

18) Purge flow:

$q_{pjnom} = 10^{-3}\ q_{abvnom}$ = 0.001 * 389.0986=0.3891 [tona/h]

B. **Electric Part**

The circuit parameters for the generator excitation:

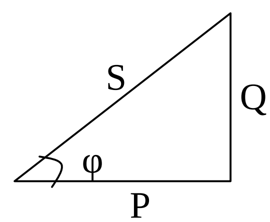
1. Power Factor:

$$\cos\varphi = \frac{P[W]}{S[VA]} = 0.825$$

The bigger the active power is, cosφ is higher by economical reason. A greater reserve of stability is assured. Commonly cosφ = 0,91-0,92 is not surpassed to ensure a reactive power big enough to force in short circuit regime the excitation of the generator.

$Q[VAr]$ - required reactive power to magnetize the magnetic circuits of the generator, transformers, electric engines. The compensation of reactive power is followed.

2. Apparent Power: P = UIcosφ; Q = UIsin φ



$$S_{Gnom} = \frac{P_{Gnom}\,[MW]}{\cos\varphi_{nom}} = 147.8788\ [MVA]$$

3. Nominal reactive power:

$Q_{Gnom}{}^2 = S_{Gnom}{}^2[MVA] - P_{Gnom}{}^2[MW] = 6984.1359\ [MVAr] \Rightarrow Q_{Gnom} = 83.5711\ [MVAr]$

4. Generator terminals tension: U_{Gnom} = 15 [kV]

5. Nominal excitation tension: U_{Enom} = 300 [V]

6. Exciter nominal Power: $P_{Enom} = 0{,}0025 * P_{Gnom}$ = 0.3[MW]

7. Controlled bridge nominal power: $P_{PCnom} = 0{,}01 * P_{Enom}$ = 0.003 [kW]

8. Excitation nominal current: $i_{Enom} = \frac{P_{Enom}\,[MW]}{U_{Enom}\,[V]}$ = 0.001 [kA]

9. Controlled bridge nominal tension: U_{PCnom} = 270 [V]

10. Exciter excitation time constant: T_{EE} = 0.1 [sec]

11. The time constant of the generator's excitation: T_E = 0.5 [sec]

12. The time constant of a three phased generator: T_G = 4 [sec]

13. The current of the bridge rectifier:

$$\mathbf{i_{Pcnom}} = \frac{P_{PCnom}\,[MW]}{U_{PCnom}\,[V]} = \mathbf{0.00001\ [A]}$$

The nominal values of U_{Gnom}, U_{Enom}, U_{Pcnom}, T_E, T_{EE}, T_G have been chosen according to the tables below:
(U_{PCnom} – the voltage drop of the bridge rectifier)

P_{Gnom} [MW] (aici =420)	100÷200	201÷300	301÷400	401÷>401
U_{Gnom} [kV]	15	20	25	30
U_{Enom} [V]	300	400	500	600
U_{Pcnom} [V]	270		360	

P_{Gnom} [MW]	100 – 300	301 – 500	>500
T_{EE} [sec]	0.1	0.15	0.2
T_E [sec]	0.5	0.75	1
T_G [sec]	4	5	6

U_{Gnom} – the voltage drop at the generator's terminals
U_{Enom} – the nominal voltage drop of the excitation
U_{PCnom} – the voltage drop of the bridge rectifier

T_{EE} – the time constant of the exciter's excitation

T_E – the time constant of the generator's excitation

T_G – the time constant of the three phased generator

3.Simplified identification of the steam boiler near a functional steady state value

It is considered that the boiler has 6 input signals and 9 output signals. Theoretically, there is a transfer function between each input and each output. Practically, most of these transfer functions have negligible weight, resulting only 19 important transfer function.

The graphical approach is used in order to establish the dependence between signals.

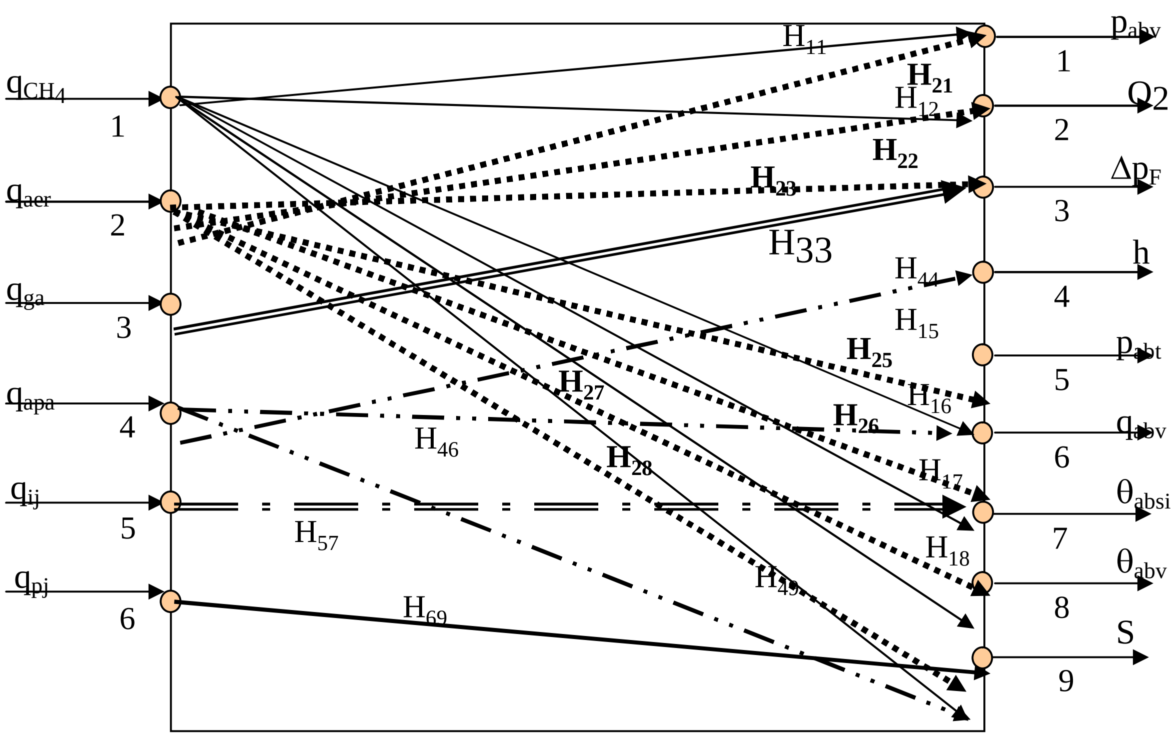


Figure 4. The connections between the main signals

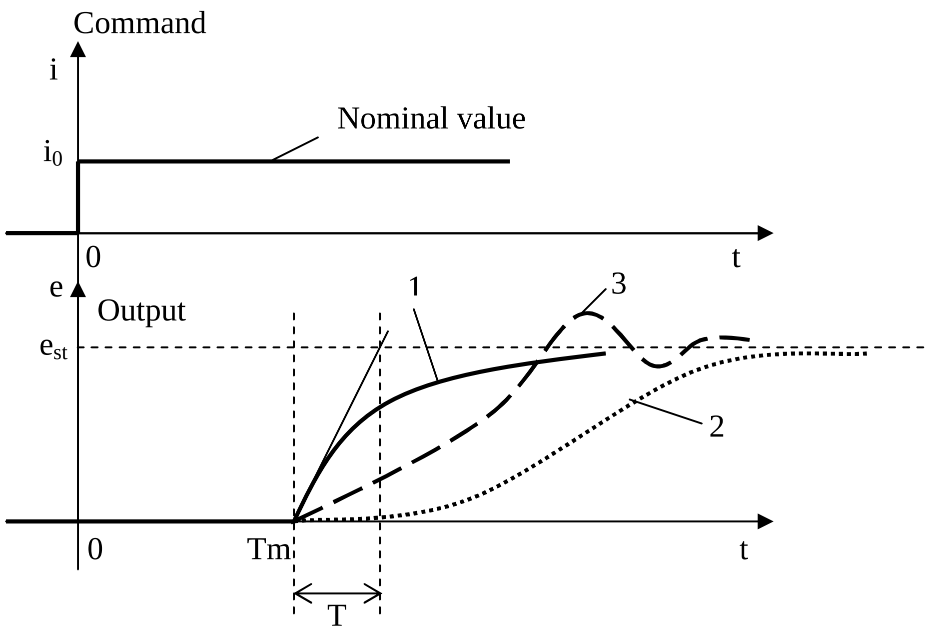
We will go through the significant step responses between these signals to approximate the transfer functions. Not all these transfer functions have a meaningful phenomenological interpretation or sufficient weight to be taken into account.

Only the ones having a sufficiently large magnitude will be taken into consideration.

4. Representative transfer functions for the boiler sub-processes

Taking into consideration the low-pass filter with phase delay characteristic of the majority of sub-processes included in the transfer functions, the approximations can be done through step response identification. Despite the fact that the approximation of transfer functions using proportional forms to first order functions can be somewhat rough, it is generally used in design, while the second order ones are rarely used.
We have two cases:

A.



In all the cases, we have a time delay Tm. (e=output, i=command)

For curve 1 we have:

$$H_1 = \frac{Le}{Li} = \frac{k}{1+Ts}\pounds^{-T_m s};$$

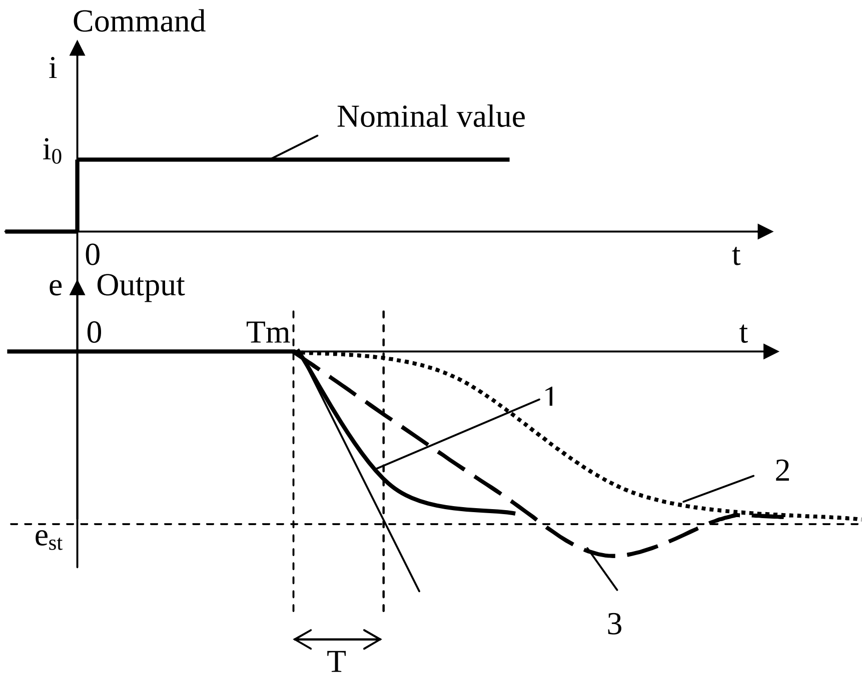
For curve 2 we have:

$$H_2 = \frac{Le}{Li} = \frac{k}{1+(T_1+T_2)s+T_1T_2s^2}\pounds^{-T_m s};$$

For curve 3 we have:

$$H_3 = \frac{Le}{Li} = \frac{k}{1+\frac{2\P}{\mu_n}s+\frac{1}{\mu_n^2}s^2}\pounds^{-T_m s};\mu_p = \mu_n\sqrt{1-\P^2};$$

B.



In this case, the transfer functions corresponding to each curve will be opposed to the ones at point A.
The following notations were used:
e_{st}- the stationary value of the output
i_0-the stationary value of the input
T- time constant of the sub-process
Tm-time delay constant

<u>Calculus of the main transfer functions*:</u>

1. The transfer function of the steam's pressure with regard to the fuel flow:

$$H_{11}(s) = \frac{L\{p_{abv}\}}{L\{q_c\}} = \frac{k_{11}}{1+T_{11}s}\pounds^{-T_{m11}s};$$

$$k_{11} = \frac{p_{abvnom}[bar]}{q_{cnom}[\frac{Nm^3}{h}]} = \frac{90}{34332.2352} = 2.6*10^{-3}[\frac{h*bar}{N*m^3}]$$

$$T_{m11} = 10[\min] = 600[\sec]; \qquad T_{11} = 100[\min] = 6000[\sec];$$

$$H_{11}(s) = \frac{2.6\cdot 10^{-3}\cdot \pounds^{-600s}}{1+6000s};$$

*k – steady state gain; T_m- delay time constant; T – time constant

2. Transfer function of O_2 content from exhaust in relation to the fuel flow:

$$H_{12}(s) = \frac{L\{O_2\}}{L\{q_c\}} = \frac{k_{21}}{1+T_{12}s}£^{-T_{m12}s}; \quad k_{12} = \frac{O_2[\%]}{q_{cnom}\left[\frac{Nm^3}{h}\right]} = 1.4563 \ * 10^{-4} \frac{[\% \cdot h]}{[Nm^3]}$$

$$T_{m12} = 10[\sec] \ ; \ T_{12} = 60[\sec];$$

$$H_{12}(s) = \frac{1.4563 \cdot 10^{-4} \cdot £^{-10s}}{1+60s};$$

3. Transfer function of the processed steam in the drum, in relation to the fuel flow:

$$H_{15}(s) = \frac{L\{p_{abt}\}}{L\{q_c\}} = \frac{k_{15}}{1+T_{15}s}£^{-T_{m15}s};$$

$$T_{m15} = 9[\min] = 540[\sec];$$

$$T_{15} = 90[\min] = 5400[\sec];$$

$$k_{15} = \frac{(1.1) \cdot p_{abvnom}[bar]}{q_{cnom}\left[\frac{Nm^3}{h}\right]} = \frac{99[bar]}{34332.2352\left[\frac{Nm^3}{h}\right]} = 2.8 \cdot 10^{-3}\left[\frac{h \cdot bar}{Nm^3}\right]$$

$$H_{15}(s) = \frac{2.9 \cdot 10^{-3} \cdot £^{-540s}}{1+5400s};$$

4. ***Transfer function of the processed steam flow in relation to the fuel flow:***

$$H_{16}(s) = \frac{L\{q_{abv}\}}{L\{q_c\}} = \frac{k_{16}}{1+T_{16}s}£^{-T_{m16}s};$$

$$T_{m16} = 12[\min] = 720[\sec];$$

$$T_{16} = 120[\min] = 7200[\sec];$$

$$k_{16} = \frac{q_{abvnom}\left[\frac{tonă}{h}\right]}{q_{cnom}\left[\frac{Nm^3}{h}\right]} = \frac{389.0987\left[\frac{tonă}{h}\right]}{34332.2352\left[\frac{Nm^3}{h}\right]} = 11.3 \cdot 10^{-3}\left[\frac{tona}{Nm^3}\right]$$

$$H_{16}(s) = \frac{11.3 \cdot 10^{-3} \cdot £^{-720s}}{1+7200s};$$

5. Transfer function of the steam temperature in the intermediary over-heater in relation to the fuel flow:

$$H_{17}(s)=\frac{L\{\overline{\ }_{abvsi}\}}{L\{q_c\}}=\frac{k_{17}}{1+T_{17}s}\pounds^{-T_{m17}s};$$

$$T_{m17}=10[\min]=600[\sec];$$

$$T_{17}=100[\min]=6000[\sec];$$

$$k_{17}=\frac{\overline{\ }_{ab\sin om}[^{\circ}C]}{q_{cnom}\left[\frac{Nm^3}{h}\right]}=\frac{480[^{\circ}C]}{34332.2352\left[\frac{Nm^3}{h}\right]}=14\cdot10^{-3}\left[\frac{h\cdot^{\circ}C}{Nm^3}\right]$$

$$H_{17}(s)=\frac{14\cdot10^{-3}\cdot\pounds^{-600s}}{1+6000s};$$

6. Transfer function of the processed steam temperature in relation to the fuel flow:

$$H_{18}(s)=\frac{L\{\overline{\ }_{abv}\}}{L\{q_c\}}=\frac{k_{18}}{1+T_{18}s}\pounds^{-T_{m18}s};$$

$$T_{m18}=12[\min]=720[\sec];$$

$$T_{18}=120[\min]=7200[\sec];$$

$$k_{18}=\frac{\overline{\ }_{abvnom}[^{\circ}C]}{q_{cnom}\left[\frac{Nm^3}{h}\right]}=\frac{530[^{\circ}C]}{34332.2352\left[\frac{Nm^3}{h}\right]}=15.4\cdot10^{-3}\left[\frac{h\cdot^{\circ}C}{Nm^3}\right]$$

$$H_{18}(s)=\frac{15.4\cdot10^{-3}\cdot\pounds^{-720s}}{1+7200s};$$

7. Transfer function of the processed steam pressure in the tank in relation to the combustion air flow :

$$H_{21}(s)=\frac{L\{p_{abv}\}}{L\{q_{aer}\}}=\frac{k_{21}}{1+T_{21}s}\pounds^{-T_{m21}s};$$

$$T_{m21}=10[\min]=600[\sec];$$

$$T_{21}=100[\min]=6000[\sec];$$

$$k_{21}=\frac{p_{abvnom}[bar]}{q_{aernom}\left[\frac{Nm^3}{h}\right]}=\frac{90[bar]}{359338.3407\left[\frac{Nm^3}{h}\right]}=2.5046\cdot10^{-4}\left[\frac{h\cdot bar}{Nm^3}\right]$$

$$H_{21}(s)=\frac{2.5046\cdot10^{-4}\cdot\pounds^{-600s}}{1+6000s};$$

8. The transfer function of the oxigen percentage contained in the exhaust gases with respect to the combustion air flow:

$$H_{22}(s) = \frac{L\{O_2\}}{L\{q_{aer}\}} = \frac{k_{22}}{1+T_{22}s}£^{-T_{m22}s};$$

$$T_{m22} = 10[\sec];$$

$$T_{22} = 60[\sec];$$

$$k_{22} = \frac{O_{2nom}[\%]}{q_{aernom}\left[\frac{Nm^3}{h}\right]} = \frac{5[\%]}{359338.3407\left[\frac{Nm^3}{h}\right]} = 1.3914\cdot 10^{-5}\left[\frac{\%\cdot h}{Nm^3}\right]$$

$$H_{22}(s) = \frac{1.3914\cdot 10^{-5}\cdot £^{-10s}}{1+60s};$$

9. The transfer function of the furnace vacuum with respect to the combustion air flow:

$$H_{23}(s) = \frac{L\{\Delta p_F\}}{L\{q_{aer}\}} = -\frac{k_{23}}{1+T_{23}s}£^{-T_{m23}s};$$

$$T_{m23} = 10[\sec];$$

$$T_{23} = 5[\sec];$$

$$k_{23} = \frac{\Delta p_{Fnom}[mmH_2O]}{q_{aernom}\left[\frac{Nm^3}{h}\right]} = \frac{-2[mmH_2O]}{359338.3407\left[\frac{Nm^3}{h}\right]} = \text{-}5.5658\cdot 10^{-6}\left[\frac{h\cdot mmH_2O}{Nm^3}\right]$$

$$H_{23}(s) = \frac{\text{-}5.5658\cdot 10^{-6}\cdot £^{-10s}}{1+5s};$$

When the air flow increases, the furnace vacuum decreases to negative values.

10. The transfer function of the steam pressure in the drum with respect to the combustion air flow:

$$H_{25}(s) = \frac{L\{p_{abt}\}}{L\{q_{aer}\}} = \frac{k_{25}}{1+T_{25}s}£^{-T_{m25}s};$$

$$T_{m25} = 9[\min] = 540[\sec];$$

$$T_{25} = 90[\min] = 5400[\sec];$$

$$k_{25} = \frac{(1.1)\cdot p_{abvnom}[bar]}{q_{aernom}\left[\frac{Nm^3}{h}\right]} = \frac{99[bar]}{359338.3407\left[\frac{Nm^3}{h}\right]} = 2.7551\cdot 10^{-4}\left[\frac{h\cdot bar}{Nm^3}\right]$$

$$H_{25}(s) = \frac{2.7551\cdot 10^{-4}\cdot £^{-540s}}{1+5400s};$$

11. The transfer function of the processed steam flow with respect to the combustion air flow:

$$H_{26}(s) = \frac{L\{q_{abv}\}}{L\{q_{aer}\}} = \frac{k_{26}}{1+T_{26}s}\pounds^{-T_{m26}s};$$

$$T_{m26} = 12[\min] = 720[\sec];$$

$$T_{26} = 120[\min] = 7200[\sec];$$

$$k_{26} = \frac{q_{abvnom}\left[\frac{tona}{h}\right]}{q_{aernom}\left[\frac{Nm^3}{h}\right]} = \frac{3.5934\left[\frac{tona}{h}\right]}{359338.3407\left[\frac{Nm^3}{h}\right]} = 1.1\cdot 10^{-3}\left[\frac{tona}{Nm^3}\right];$$

$$H_{26}(s) = \frac{1.1{\cdot}10^{-3}{\cdot}\pounds^{-720s}}{1{+}7200s};$$

12. The transfer function of the steam temperature in the intermediary superheate with respect to the combustion air flow:

$$H_{27}(s) = \frac{L\{\overline{\ }_{absi}\}}{L\{q_{aer}\}} = \frac{k_{27}}{1+T_{27}s}\pounds^{-T_{m27}s};$$

$$T_{m27} = 10[\min] = 600[\sec];$$

$$T_{27} = 100[\min] = 6000[\sec];$$

$$k_{27} = \frac{\overline{\ }_{ab\sin om}[{}^\circ C]}{q_{aernom}\left[\frac{Nm^3}{h}\right]} = \frac{480[{}^\circ C]}{359338.3407\left[\frac{Nm^3}{h}\right]} = 1.3\cdot 10^{-3}\left[\frac{h{\cdot}{}^\circ C}{Nm^3}\right];$$

$$H_{27}(s) = \frac{1.3{\cdot}10^{-3}{\cdot}\pounds^{-600s}}{1{+}6000s};$$

13. The transfer function of the process steam temperature with respect to the combustion air flow:

$$H_{28}(s) = \frac{L\{\overline{\ }_{abv}\}}{L\{q_{aer}\}} = \frac{k_{28}}{1+T_{28}s}\pounds^{-T_{m28}s};$$

$$T_{m28} = 12[\min] = 720[\sec];$$

$$T_{28} = 120[\min] = 7200[\sec];$$

$$k_{28} = \frac{\overline{\ }_{abvnom}\left[{}^\circ C\right]}{q_{aernom}\left[\frac{Nm^3}{h}\right]} = \frac{530\left[{}^\circ C\right]}{359338.3407\left[\frac{Nm^3}{h}\right]} = 1.5\cdot 10^{-3}\left[\frac{h{\cdot}{}^\circ C}{Nm^3}\right]$$

$$H_{28}(s) = \frac{1.5{\cdot}10^{-3}{\cdot}\pounds^{-720s}}{1{+}7200s};$$

14. Fdt of the depressure in the burner, in relation with the flow of burned gases :

$$H_{33}(s) = \frac{L\{\Delta p_F\}}{L\{q_{ga}\}} = \frac{k_{33}}{1+T_{33}s}\pounds^{-T_{m33}s};$$

$$T_{m33} = 5[\text{sec}];$$

$$T_{33} = 10[\text{sec}];$$

$$k_{33} = \frac{\Delta p_{Fnom}[mmH_2O]}{q_{ganom}\left[\frac{Nm^3}{h}\right]} = \frac{-2[mmH_2O]}{393670.576\left[\frac{Nm^3}{h}\right]} = \text{-}5.0804\cdot 10^{-6}\left[\frac{h\cdot mmH_2O}{Nm^3}\right]$$

$$H_{33}(s) = -\frac{5.0804\cdot 10^{-6}\cdot\pounds^{-5s}}{1+10s};$$

In the event of $q_{air} = 0$ and $q_{water} = 0$ it is considered that the pressure in the burner is equal with the outside pressure. If the exhausters are turned on at q_{ganom} maintaining $q_{aer} = 0$ in the burner, results a depressure which in stationary regime is –2 [mmH_2O].

15. Transfer function of the water level in the tambour in relation with the flow of the supply water:

$$H_{44}(s) = \frac{L\{h\}}{L\{q_{apa}\}} = \frac{k_{44}}{1+T_{44}s}\pounds^{-T_{m44}s};$$

$$T_{m44} = 20[\text{sec}];$$

$T_{44} = 20[\text{sec}]$; h_{nom}=100[mm]=0.1 [m];

$$k_{44} = \frac{h_{nom}[m]}{q_{apanom}\left[\frac{tona}{h}\right]} = \frac{0.1[m]}{389.0987\left[\frac{tona}{h}\right]} = 2.57*10^{-4}\left[\frac{h\cdot m}{tona}\right]$$

$$H_{44}(s) = \frac{2.57*10^{-4}\cdot\pounds^{-20s}}{1+20s};$$

16. Transfer function of the processed steam flow in relation with the flow of the supply water:

$$H_{46}(s) = \frac{L\{q_{abv}\}}{L\{q_{apa}\}} = \frac{k_{46}}{1+T_{46}s}\pounds^{-T_{m46}s};$$

$$T_{m46} = 12[\text{min}] = 720[\text{sec}]; \quad T_{46} = 120[\text{min}] = 7200[\text{sec}];$$

$$k_{46} = \frac{q_{abvnom}\left[\frac{tona}{h}\right]}{q_{apanom}\left[\frac{tona}{h}\right]} = \frac{389.0987\left[\frac{tona}{h}\right]}{389.0987\left[\frac{tona}{h}\right]} = 1;$$

$$H_{46}(s) = \frac{\pounds^{-720s}}{1+7200s};$$

17. Transfer function of the saltiness in relation with the flow of the supply water:

$$H_{49}(s) = \frac{L\{S\}}{L\{q_{apa}\}} = \frac{k_{49}}{1 + T_{49}s} £^{-T_{m49}s};$$

$$T_{m49} = 60[\min] = 3600[\sec];$$

$$T_{49} = 600[\min] = 36000[\sec];$$

$$k_{49} = \frac{S_{nom}[\%]}{q_{apanom}\left[\frac{tona}{h}\right]} = \frac{1[\%]}{389.0987\left[\frac{tona}{h}\right]} = 2.57 \cdot 10^{-5}\left[\frac{h \cdot \%}{tona}\right]$$

$$H_{49}(s) = \frac{2.57{\cdot}10^{-4} \cdot £^{-3600s}}{1{+}36000s};$$

18. Transfer function of the temperature of the processed steam in the intermediary overheater in relation with the injection flow (water or steam)

$$H_{57}(s) = \frac{L\{\bar{\ }_{absi}\}}{L\{q_{ij}\}} = \frac{k_{57}}{1 + T_{57}s} £^{-T_{m57}s};$$

$$T_{m57} = 10[\sec];$$

$$T_{57} = 10[\sec];$$

$$\Delta\bar{\ }_{ab\sin om} = 100°C;$$

$$k_{57} = -\frac{\Delta\bar{\ }_{ab\sin om}[°C]}{q_{ijnom}\left[\frac{tona}{h}\right]} = -\frac{100[^{\circ}C]}{3.890986\left[\frac{tona}{h}\right]} = -25.7004\left[\frac{h{\cdot}^{\circ}C}{tona}\right]$$

$$H_{57}(s) = -\frac{25.7004{\cdot}£^{-10s}}{1{+}10s};$$

19. Transfer function of the flow saltiness of purge :

$$H_{69}(s) = \frac{L\{S\}}{L\{q_{pj}\}} = \frac{k_{69}}{1 + T_{69}s} £^{-T_{m69}s};$$

$$T_{m69} = 60[\sec];$$

$$T_{69} = 60[\sec];$$

$$k_{69} = -\frac{\Delta S_{nom}[\%]}{q_{pjnom}\left[\frac{tona}{h}\right]} = -\frac{1[\%]}{0.3890986\left[\frac{tona}{h}\right]} = -0.0257\left[\frac{h \cdot \%}{tona}\right]$$

$$H_{69}(s) = -\frac{0.0257{\cdot}£^{-60s}}{1{+}60s};$$

The transfer matrix of the boiler having the dimension (9x6) with 19 transfer functions is now presented. The other 35 elements have the value of zero:

	q_c	q_{aer}	q_{ga}	q_{apa}	q_{ij}	q_{pj}
p_{abv}	H_{11}	H_{21}	0	0	0	0
O_2	H_{12}	H_{22}	0	0	0	0
Δp_F	0	H_{23}	H_{33}	0	0	0
h	0	0	0	H_{44}	0	0
p_{abt}	H_{15}	H_{25}	0	0	0	0
q_{abv}	H_{16}	H_{26}	0	H_{46}	0	0
θ_{absi}	H_{17}	H_{27}	0	0	H_{57}	0
θ_{abv}	H_{18}	H_{28}	0	0	0	0
S	0	0	0	H_{49}	0	H_{69}

This process is a typical example of a large process, having the following important characteristics: in theory, from one major input signal (q_c) to a major output signal (q_{abv}) there are complicated relations, but by interpreting some typical responses these can be approximated using transfer functions that only have a few dominant poles and a large number of residual poles which can be neglected; in this case with up to 2 dominant poles and at least 6 to 10 residual poles these approximations of the transfer functions are justified.

This observation is viable especially in the case of inertial processes, where the first two derivatives are significant, while the other derivatives are heavily damped, thus justifying that they can be neglected.

(q – flow rate; θ - temperature; h –level; ΔP_F – differential pressure; O_2 – concentration;
P – pressure
H_{26} – transfer function of the boiler having as input q_{aer} and as output q_{abv})

5. Controller tuning of the main control loops

A. Processed steam pressure adjustment

The control loop is a tracking system with respect to the referenced command, having a fast behaviour because of the low inertia of the pneumatic servomotor and the valve(SPR).

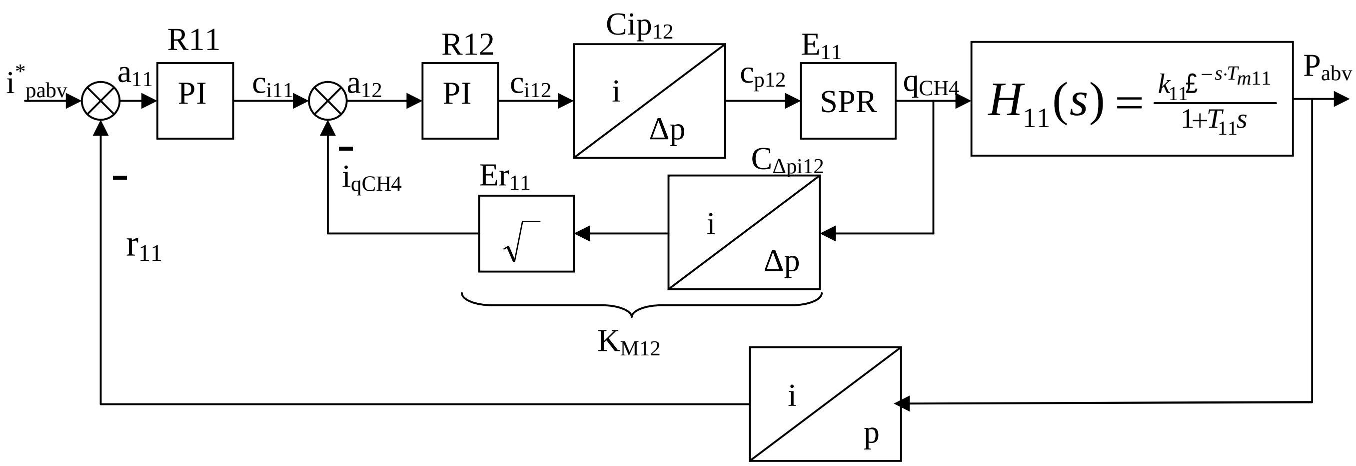


Figure 6

c_{ip12} — unified current converter for differential pressure

SPR —Pneumatic Servomotor with a Valve

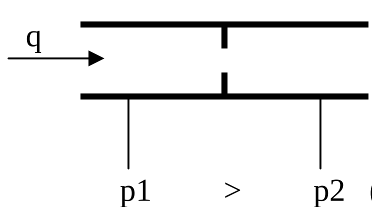
c_{pi12} — unified current-pressure convertor which ensures the external reaction (the main on in the steady state)

i^*_{pabv} — unified reference current for processed steam stabilization

E_{r12} — radical extractor

The internal control loop has a converter Δp_{i12} and because the differential pressure used as a output signal from the calibrated diaphragm is proportional to the square or the flow, we need a square-root extractor.

Calibrated diaphrahm:



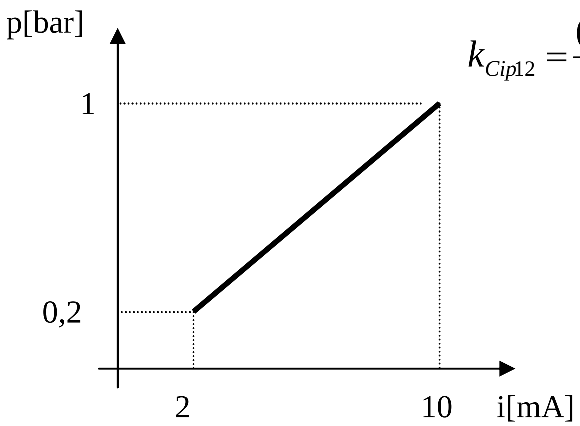
$(\Delta p = p_1 - p_2)$; $q^2 = k \cdot \Delta p$;

Note: - c_{i11} and c_{i12} are unified current control and c_{p12} is a control signal in unified pressure.

The composing transfer functions of the control loop above

a) Current-pressure converter C_{ip12}

- is considered non-inertial, with the proportionality factor resulting from the static characteristic of the generator

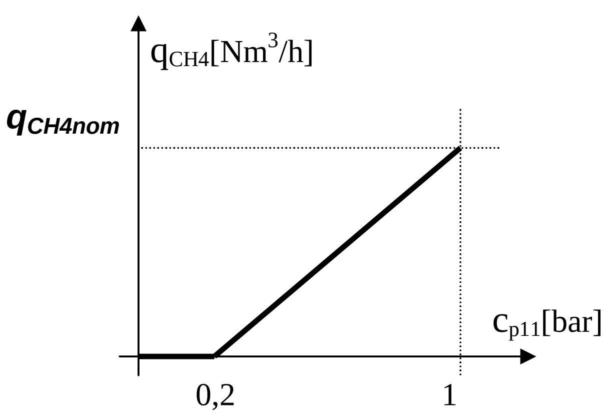


$$k_{Cip12} = \frac{(1-0.2)[bar]}{(10-2)[mA]} = 0.1\left[\frac{bar}{mA}\right] \Rightarrow H_{Cip12}(s) = k_{Cip12} = 0.1\left[\frac{bar}{mA}\right]$$

Figure 7

b) SPR pneumatic actuator

- is considered to have a liniar characteristic, but the inertia revealed by the1s time constant can't be neglected



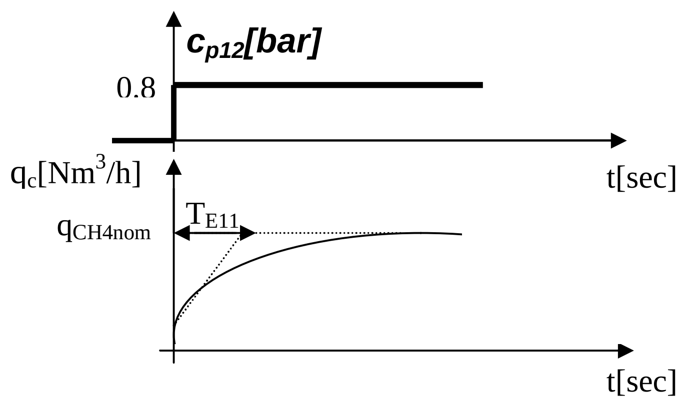


Figure 8 ***Figura 9: Step response of SPR***

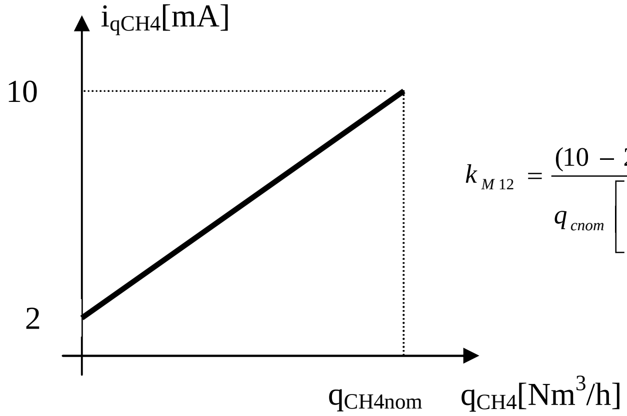
$$k_{E12} = \frac{q_{cnom}\left[\frac{Nm^3}{h}\right]}{(1-0.2)[bar]} = \frac{34332.2352\left[\frac{Nm^3}{h}\right]}{0.8[bar]} = 42915.294\left[\frac{Nm^3}{h \cdot bar}\right];$$

$$T_{E12} = 1[sec];$$

$$H_{E12}(s) = \frac{L\{q_c\}}{L\{C_{p12}\}} = \frac{k_{E12}}{1+T_{E12}s} = \frac{42915.294}{1+s}$$

c) **The internal feedback circuit**

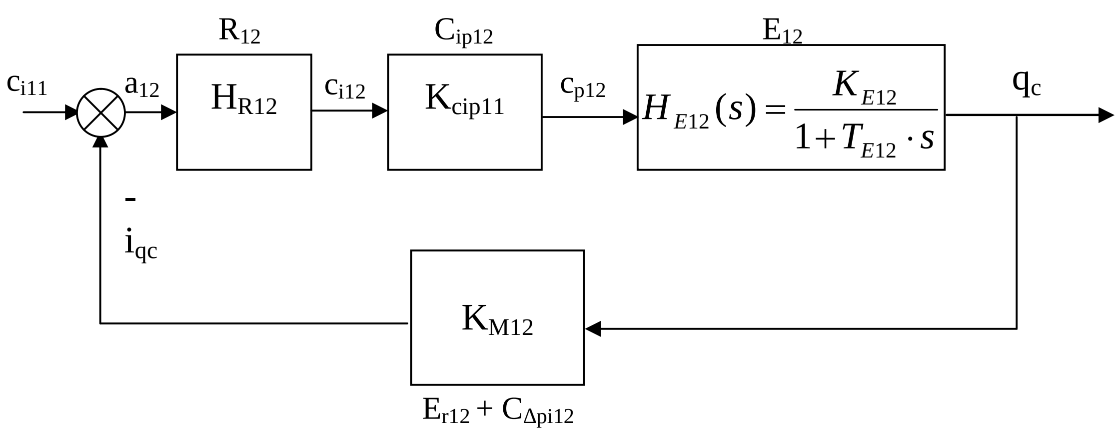
- includes differential pressure-flow transducer, differential pressure-current converter, the radical extractor which cancels the quadratic effect of the transducer. All these elements are considered to be overall non-inertial.
- the coefficient of proportionality in the figure bellow:



$$k_{M12} = \frac{(10-2)[mA]}{q_{cnom}\left[\frac{Nm^3}{h}\right]} = \frac{8[mA]}{34332.2352\left[\frac{Nm^3}{h}\right]} = 2.3301\cdot 10^{-4}\left[\frac{«A\cdot h}{Nm^3}\right]$$

Figure 10

The internal control loop has the following form:



This system being stabilizer and of small inertia, the controller R_{12} will be tuned using the modulus criterion, with the dead time constant neglected (no dead time Tm).

$$H_{R12}(s) = \frac{1}{2T_{\Sigma 12}s(1+T_{\Sigma 12}s)}\cdot\frac{1}{H_{EX12}(s)};$$

$$H_{EX12}(s) = \frac{K_{cip12}\cdot K_{E12}\cdot K_{M12}}{1+T_{E12}s}\,\frac{1}{1+T_{\Sigma 12}s} = \frac{K_{Ex12}}{(1+T_{E12}s)(1+T_{\Sigma 12}s)};$$

T_Σ – sum of time constants that can't be compensated, comparable in magnitude with T_{R12} in H_{R12} (here);

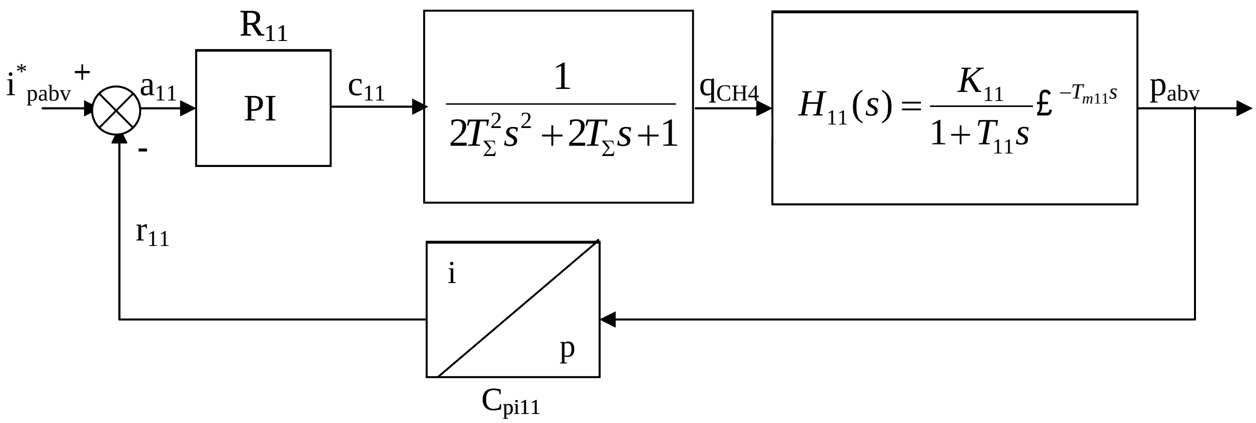
$T_{\Sigma 12} = 10^{-2}$ [sec] = 0.01 [sec] si T_{E12} = 1 [sec]; K_{EX12}=1;

$$H_{R12}(s) = \frac{1}{2T_{\Sigma 12}s(1+T_{\Sigma 12}s)} \cdot \frac{(1+T_{\Sigma 12}s)(1+T_{E12}s)}{1} = \frac{1+T_{E12}s}{2\cdot T_{\Sigma 12}s};$$

$$H_{R12}(s) = \frac{T_{E12}\cdot s}{2T_{\Sigma 12}s}\cdot\frac{1}{2T_{\Sigma 12}s} = \frac{1}{0.02} + \frac{1}{0.02s} = 50 + \frac{1}{0.02s} = V_{R12} + \frac{1}{T_{i12}\cdot s};$$

V_R=50; T_i=0.02 [sec]; → reg. P.I.

d) External feedback circuit

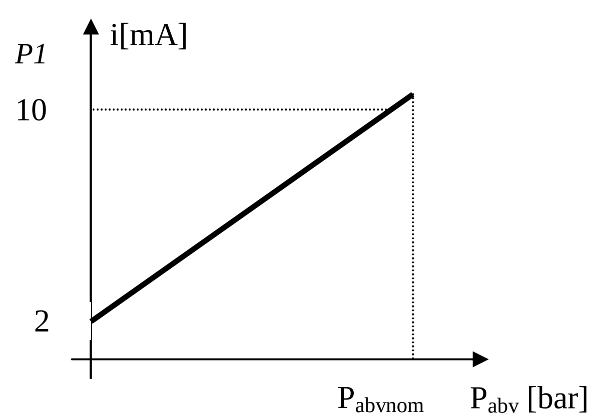


The external loop of the cascade control structure has a quite big time constant: T_{m11}=10 min. So, the controller tuning R_{11} will be made according to slow processes using Ziegler-Nichols method.

$$H_{EX11}(s) = \frac{1/K_{M12}}{1+2T_\Sigma s + 2T_\Sigma^2 s^2}\frac{K_{11}}{1+T_{11}s}£^{-T_{m11}s}K_{cpi11} \cong \frac{K_{11}K_{cpi11}}{1+T_{11}s}£^{-Tm_{11}s}$$

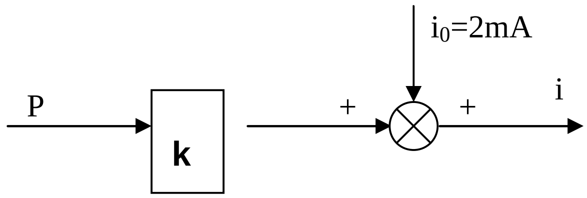
The proportionality constant K_{Cpi11} can be deduced from the following figure:

T_{11} = 100 min ($T_{\Sigma 12} << T_{11}$);
T_{m11} = 10 min ($T_{\Sigma 12} << T_{m11}$);



$$K_{cpi11} = \frac{(10-2)[mA]}{p_{abvnom}[bar]} = \frac{8[mA]}{90[bar]} = 0.08889\left[\frac{\text{mA}}{\text{bar}}\right]$$

Convertor design:



$$K = \frac{(10-2)[mA]}{p_{abvnom}[bar]} = \frac{8[mA]}{90[bar]} = 0.08889\left[\frac{\text{mA}}{\text{bar}}\right];$$

$$i = i_0 + K \cdot p = 2[mA] + 8[mA] = 10[mA];$$

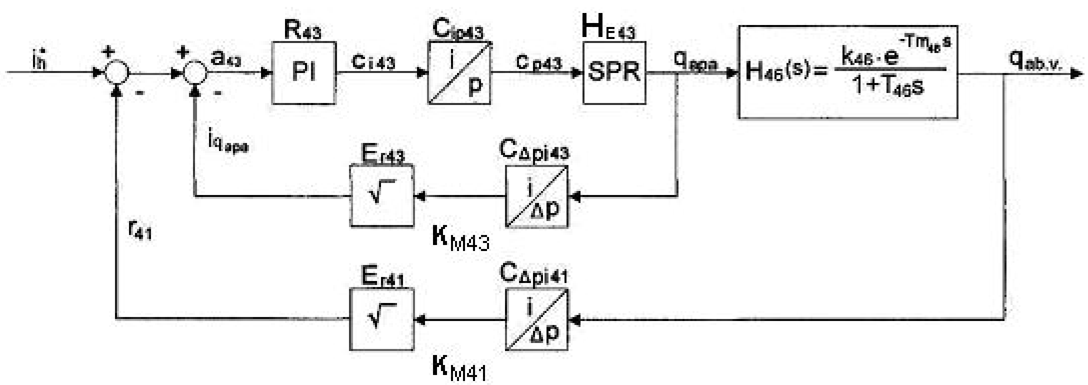
Using the Ziegler-Nichols criterion we obtain:

$$V_{R11} = 0.8\frac{T_{11}}{T_{m11}} = 0.8\frac{6000[\sec]}{600[\sec]} = 8;$$

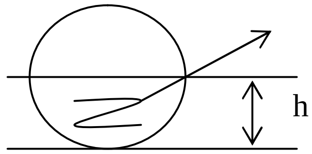
$T_{i11} = 3T_{m11} = 30$ [min] = 1800 [sec];

$$H_{R11}(s) = 8 + \frac{1}{1800s}; \Rightarrow reg.P.I.$$

B.Controller computation for the control loop of the processed steam



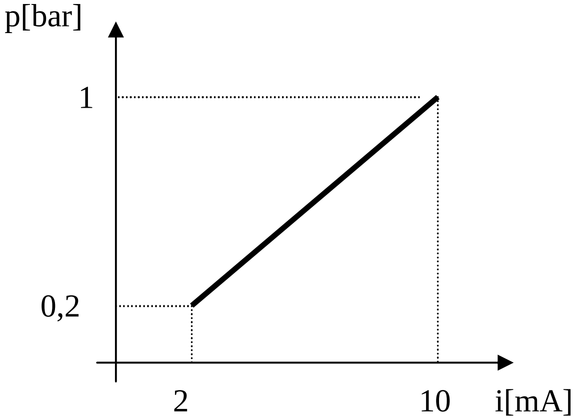
$i_h^* \rightarrow$ unified reference current of the water level in the drum(h)



The condensed water at boiling temperature in the drum

a) Current-pressure converter C$_{ip43}$

- it is considered non-inertial, with the proportionality factor resulting from the characteristic shown in the figure below:



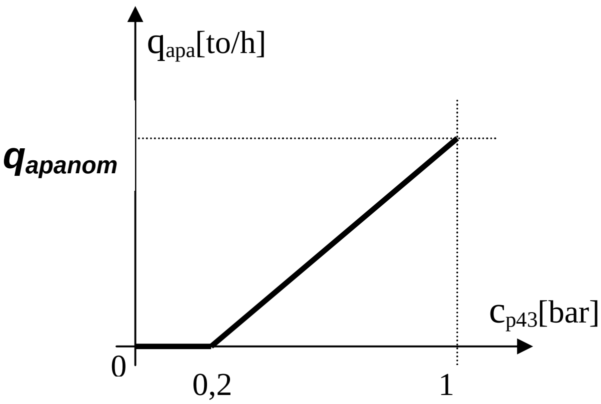
$$K_{Cpi43} = \frac{(1-0.2)[bar]}{(10-2)[mA]} = 0.1\left[\frac{bar}{mA}\right] \Rightarrow$$

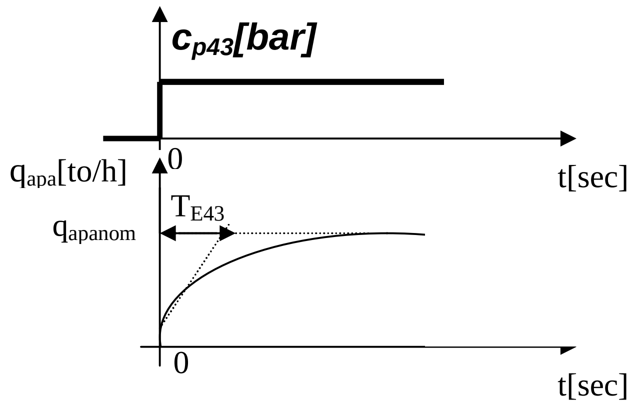
$$H_{Cpi43}(s) = K_{Cpi43} = 0.1\left[\frac{bar}{mA}\right];$$

Figure

b) Pneumatic servomotor with SPR control valve

- it is considered that it has a linear characteristic, with the proportionality coefficient resulting from the figure below:





$$K_{E43} = \frac{q_{apanom}\left[\frac{tona}{h}\right]}{(1-0.2)[bar]} = \frac{389.0987\left[\frac{tona}{h}\right]}{0.8[bar[} = 1945.493\left[\frac{tona}{h \cdot bar}\right];$$

$$T_{E43} = 1[\sec];$$

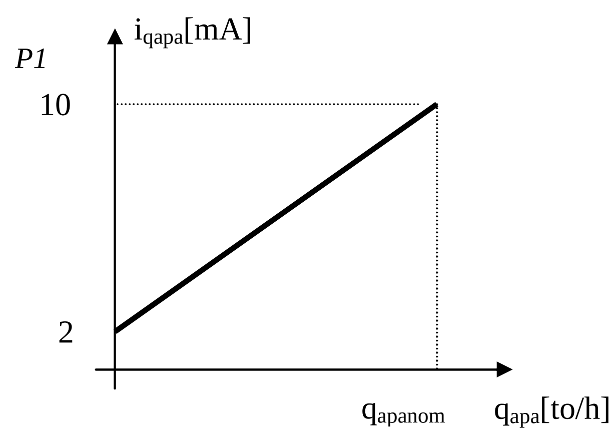
$$H_{E43}(s) = \frac{L\{q_{apa}\}}{L\{C_{p43}\}} = \frac{K_{E43}}{1+T_{E43}\cdot s} = \frac{1.945493}{1+s};$$

c) Internal reaction circuit

- it contains the flow-differential pressure transducer, the differential pressure-current converter and the square root extractor – whose effect compensates the squared effect of the transducer; all these elements are considered non-inertial, having the proportionality coefficient:

$$K_{M43} = \frac{(10-2)[mA]}{q_{apanom}\left[\frac{tona}{h}\right]} = \frac{8[mA]}{389.0987\left[\frac{tona}{h}\right]} = 205.603 \cdot 10^{-4}\left[\frac{mA \cdot h}{tona}\right];$$

The coefficient resulted from the figure below:



d) External reaction circuit

- it contains the same elements as the internal loop, having:

$$K_{M41} = \frac{(10-2)[mA]}{q_{abvnom}\left[\frac{tona}{h}\right]} = K_{M43} = 205.603 \cdot 10^{-4}\left[\frac{mAh}{tona}\right];$$

$$T_{m46} = 720[\sec];$$

$$T_{46} = 7200[\sec];\ K_{46} = 1;$$

$$fixed\ \ part\ \ is:\ H_{46}(s) = \frac{1}{1+T_{46}\cdot s}\cdot £^{-T_{m46}\cdot s} = \frac{1}{1+7200\,s}\cdot £^{-720\cdot s} = \frac{L\{q_{abv}\}}{L\{q_{apa}\}}$$

The process is slow, with a time constant T_{46}=7200 [sec] =2 [h] and it has a considerable time delay of T_{m46}=720 [sec] =12 [min]. Because of the high delay introduced in the process, the controller will act on the water flow through the internal reaction loop, at its tuning the effect of the external reaction loop being neglected.

Because the internal loop has no time delay, the controller can be tuned using the modulus criterion as follows:

$$H'_{Ext\,43}(s) = k_{Cip\,43} \cdot H_{E\,43} \cdot k_{M\,43} = k_{Cip\,43} \cdot \frac{k_{E\,43}}{1+T_{E\,43}s} \cdot k_{M\,43};$$

$$H'_{Ext\,43}(s) = 0.1 \cdot \frac{1.945493}{1+s} \cdot 0.0205603 = \frac{4}{1+s};$$

It is added to this a time constant $T_{\Sigma 43}$=0.01 [sec], considered to be the sum of the essentially uncompensated time constants.

$$H_{Ext43}(s) = H'_{Ext43}(s) \cdot \frac{1}{1+T_{\Sigma 43}s} = \frac{1}{1+s} \cdot \frac{1}{1+0.01s};$$

$$H_{R43}(s) \cdot H_{Ext43}(s) = \frac{1}{2T_{\Sigma}s(1+T_{\Sigma}s)} = \frac{1}{0.02s(1+0.01s)} \Rightarrow$$

$$\Rightarrow H_{R43}(s) = \frac{1}{0.02s(1+0.01s)} \cdot \frac{(1+s)(1+0.01s)}{1} = \frac{1+s}{0.02 \cdot s} = 50\frac{1+s}{s};$$

Thus, it is obtained a PI controller with V_R=50 and T_i=1[sec].

C. <u>**Control of the frequency and active power**</u>

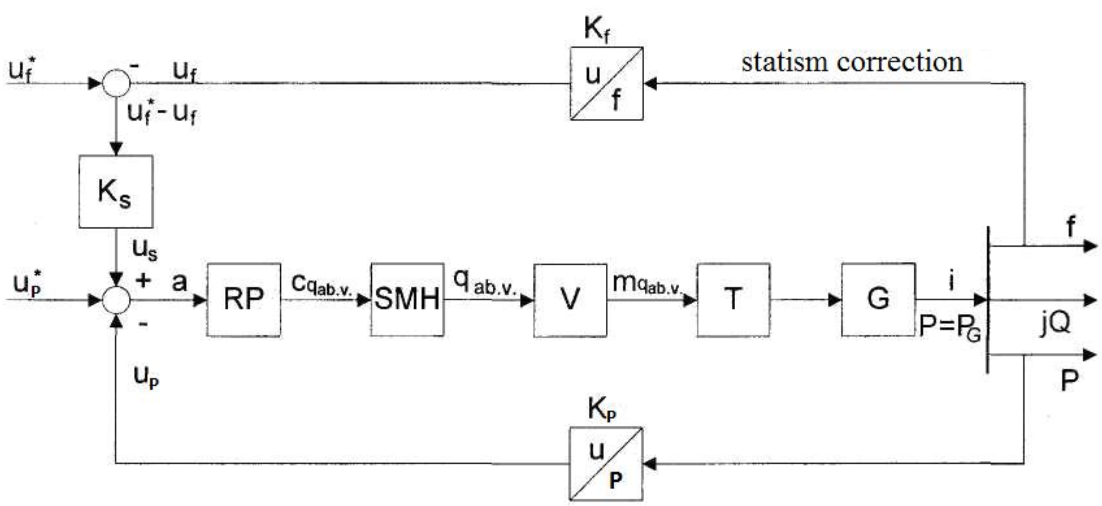


Figure : Control system

There are two main control loops:

- control relative to the active power
- control which provides correction statism

Remarks:

RP - *active power regulator*
SMH - *hydraulic actuator*
V - *partial inlet valve steam turbine*
T - *turbine*
G - *synchronous generator with a pair of poles under triphase regime*

U / f - *frequency-voltage converter*
Uf - *unified voltage (OV OM) proportional to frequency*
Uf * - *frequency reference voltage*
KS - *element of statism*

Since this control system enter in the category of fast processes, unified current signals are replaced by unified voltage signals. Unified current is used to slow processes for which distances are large and therefore suitable for induction noise.

Since the unified power generators have high output resistance which is associated to negative feedback of strong current, there is almost a complete desensitization to noise inductions and to changes of equivalent load resistance.

The presence of a false null desensitizes more noise influence.
Unified voltage is suitable for fast processes for which circuit's length is short.

It is suitable generating constant voltage supply with low output resistance because they are cheaper and more beneficial.

Uf *, Up * - *frequency reference voltage, active power*
Uf - *voltage proportional to the frequency response* ***uf***
Us - *output voltage of statism element Ks*
a - *deviation control between Up and Up* which is voltage proportional to the active power*
C_{qabv} - *live steam flow control*

m_{qabv} – *actuator signal of live steam flow: is the angular displacement that develops hydraulic camshaft and which opens gradually by turning the n partial steam inlet valves.*

The deviation between U_P and U_P^* is considered an input signal for the RP controller, resulting in the command signal C_{qabv} for the hydraulic actuator SMH, which through the valve operates the turbine T and the generator G.

The deviation between U_P and U_P^* represents the deviation from the regulation without the statism correction.

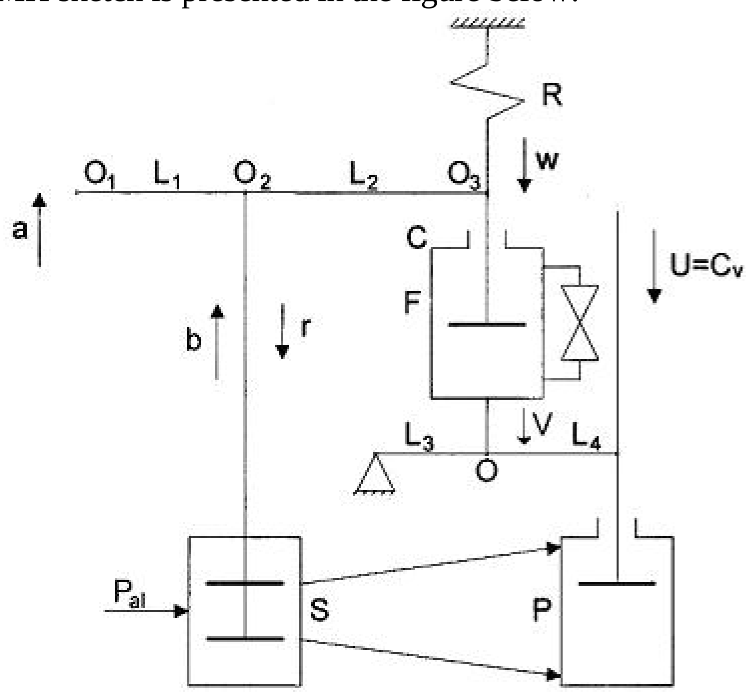
It is the main loop the one for which the weight of the statism correction is much smaller (about 10%) assuring the load of active power group, proportional with the rated power of the group, in the hypothesis of a deviation of the 50Hz frequency, in fault regime appears.

The statism correction is done through the deviation between U_F and U_F^* and of the statism element K_s.

We are interested in determining and interpreting the transfer functions of the elements' components.

a) Hydraulic Actuator SMH

The SMH sketch is presented in the figure below:



The valve (drawer) S fed at P_{al} pressure (between 6-100 atm) seals completely the two inlets, towards the P piston, only if the valve (small drawer) S is in a central position. As a consequence, the P piston is not moved and the output signal (axial displacement 'u') is zero.

The opposing spring R is calibrated according to the position of a tension screw. We have to assure an axial position of the hydraulic reaction element formed of the case C and interior piston F. There is no axial connection between the points O_3 and O, only by intermediary action, by varying the oil pressure above and beyond the piston P.

The input signal is the deviation (error) ‘a’, and the output signal is the command signal ‘u’ which acts directly on the valve. If the deviation ’a’ increases, the L1L2 lever starts to rotate around O_3, ensuring the displacement ’b↑’ and also the oil intake in the upper part of the piston P through the valve (small drawer) S, which will be driven downward(’u’ decreases). There will appear a reaction through L3L4, which starts to rotate round point O and finally resulting a downward displacement of L3L4 and ’v’. Thus descend the housing C too, resulting a small overpressure at the top of the piston F. This overpressure causes a downward movement of O_3 through 'w↓’. Thus descends O2, resulting ’r↓’.

Since ‘b↑’ and ’↓r’ are antagonistic, there appears a negative hydraulic reaction, which results some advantages:

- decreases the mechanical equivalent inertia
- improves linearity, by damping the attenuation of some mechanical disturbances
- increases the stability, by damping the attenuation of some possible oscillations.

Since the oil is incompressible, and taking into consideration the advantages of the negative hydraulic reaction, will result a low inertial valve-piston system, which ensures very high forces and torques. All these should present very complicated and inefficient solutions in the case of the electric motors.

There can be written the following equations:

(1) $$b = K_1 \cdot a \quad where \quad K_1 = \frac{L_2}{L_1 + L_2};$$

(2) $$c = b - r;$$

(3) $$\frac{du}{dt} = K \cdot c;$$

(4) $$v = K_2 \cdot u \quad where \quad K_2 = \frac{L_3}{L_3 + L_4};$$

(5) $$F \cdot \frac{d}{dt}(v - w) = R \cdot w;$$

(6) $$r = K_3 \cdot w \quad where \quad K_3 = \frac{L_1}{L_1 + L_2};$$

Equation (3) represents the speed of the piston P, which is proportional both to the intake surface of the valve (small drawer) and to the feeding pressure P_{al}.

Equation (5) represents the balance between force developed by the hydraulic damper F and the antagonistic force caused by spring R.

Finally after applying for the equations (l)÷(6) the Laplace transform will result:

(1) $L\{b\} = K_1 \cdot L\{a\}$

(2) $c = L\{b - r\};$

(3) $s \cdot L\{u\} = K \cdot L\{c\}$

(4) $v = K_2 \cdot u$

(5) $F \cdot s \cdot L\{v - w\} = R \cdot L\{w\}$

(6) $L\{r\} = K_3 \cdot L\{w\}$

Eliminating the intermediary variables L{b}, L{c}, L{u}, L{w}, L{r} we get the transfer function of the valve-piston system:

$$\frac{L\{u\}}{L\{a\}} = \frac{K_p + \dfrac{1}{T_i \cdot s}}{1 + T \cdot s} \quad unde$$

$$K_p = \frac{F \cdot K \cdot K_1}{R + K \cdot K_2 \cdot K_3 \cdot F}; \quad T_i = \frac{R + K \cdot K_2 \cdot K_3 \cdot F}{F \cdot K \cdot K_1}; \quad T = \frac{F}{R + K \cdot K_2 \cdot K_3 \cdot F};$$

F - the viscosity coefficient of the hydraulic damper

Because K is very big, the T constant usually has values that are a lot smaller than 1 second, so it can be neglected. We will get then $\frac{L\{u\}}{L\{a\}}$ with PI behavior, without self inertia.

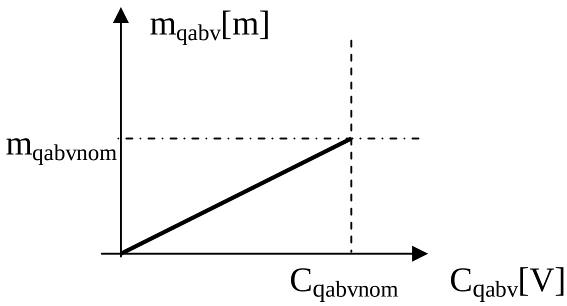
$$\Rightarrow H_{SMH}(s) \cong K_{SMH} + \frac{1}{T_{iSMH} \cdot s};$$

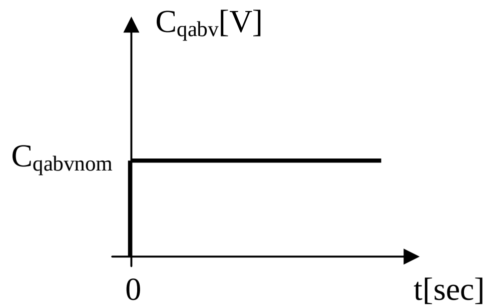
$$K_{SMH} = \frac{m_{qabvnom}}{c_{qabvnom}} = \frac{0.1[m]}{10[V]} = 0.01\left[\frac{m}{V}\right]$$

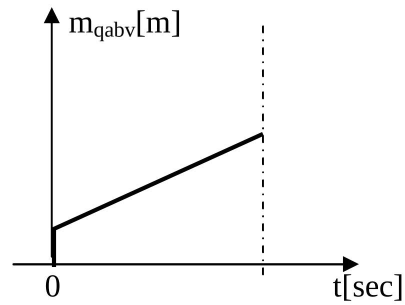
where $m_{q\ abv\ nom}$ – the displacement of the SMH rod at extremes.

$$T_{iSMH} = 20[\sec] \Rightarrow$$

$$\Rightarrow H_{SMH}(s) \cong 0.01 + \frac{1}{20 \cdot s};$$







b)<u>Valve V</u>

$$H_V(s) = \frac{L\{q_{abv}\}}{L\{m_{qabv}\}} = K_V = \frac{q_{abvnom}\left[\frac{tona}{h}\right]}{m_{qabvnom}[m]} = \frac{389.0987\left[\frac{tona}{h}\right]}{0.1[m]} = 3890.987\left[\frac{tona}{m \cdot h}\right]$$

<u>c) Turbine + generator T+G</u>

$$H_{T+G}(s) = \frac{L\{P_G\}}{L\{q_{abv}\}} = \frac{K_{T+G}}{1 + T_{T+G} \cdot s};$$

$$T_{T+G} \cong 10[\sec];$$

$$K_{T+G} = \frac{P_{Gnom}[MW]}{q_{abvnom}\left[\frac{tona}{h}\right]} = \frac{122[MW]}{389.0987\left[\frac{tona}{h}\right]} = 0.3135\left[\frac{MW \cdot h}{tona}\right] \Rightarrow$$

$$\Rightarrow H_{T+G}(s) = \frac{0.3135}{1 + 10 \cdot s}$$

<u>d) Active power feedback loop and statism correction</u>

1. For the active power-voltage transducer

$$K_p = \frac{L\{U_P\}}{L\{P\}} = \frac{10[V]}{122[MW]} = 0.0820\left[\frac{V}{MW}\right];$$

2. The transfer coefficient on the statism correction circuit

$$K_F = \frac{L\{U_f\}}{L\{f\}} = \frac{10[V]}{50[Hz]} = 0.2\left[\frac{V}{Hz}\right];$$

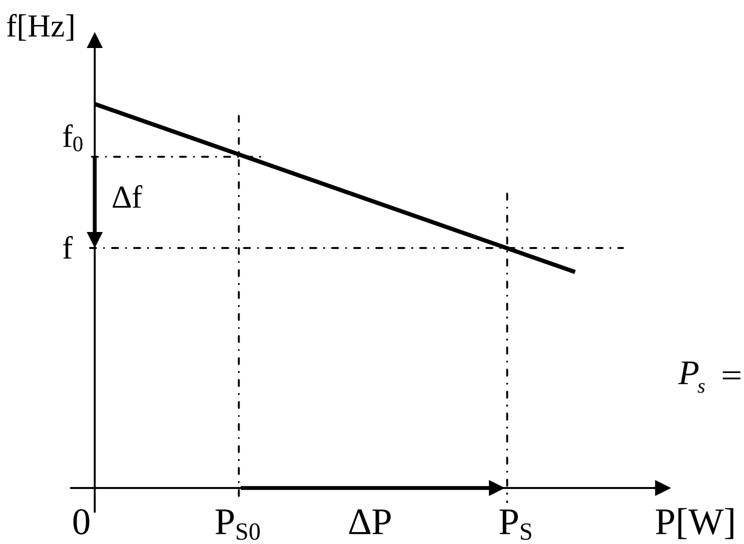
3. The coefficient of the statism reaction – K_S

The K_S coefficient results from the desired behavior in stationary regime.

Generally f(P) is considered to be linearized. If an accidentally decrease of the energy system's frequency with (-Δf) happens, the result is expected to be a certain rising contribution of the active power (+ΔP), proportional with the nominal power of the assembly, thus resulting an effect of partial bringing back of the frequency to the nominal value.

The statism S is defined as: $S = \frac{df}{dP}$;

Let P_S be the active power consumed in system. If for example the accidentally decrease (-Δf) appears, it results the automatic loading through the statism correction loop of the assembly from P_{SO} at P_S with effect of frequency's bringing back at the nominal frequency, as it can be seen in the following figure:



f= f_0 - Δf

$$P_s = ª \cdot U_f^{\,*} - «(f_0 - \Delta f) =$$
$$ªU_f^{\,*} - «f_0 + «\Delta f$$

P_{S0} ΔP

The next relations can be written:

$$U_S = K_S \cdot (U_f^* - U_f) = K_S \cdot (U_f^* - K_f \cdot f)$$

$$P_S = K_{SP} \cdot U_S = K_{SP} \cdot K_S \cdot (U_f^* - K_f \cdot f) \rightarrow P_s = \textit{statism correction power}$$

where KSP is the statism correction power related to the reaction

$$f = f_0 - \Delta f \Rightarrow P_S = ª \cdot U_f^* - «(f_0 - \Delta f) = ª \cdot U_f^* - « \cdot f_0 + « \cdot \Delta f = P_{S0} + \Delta P$$

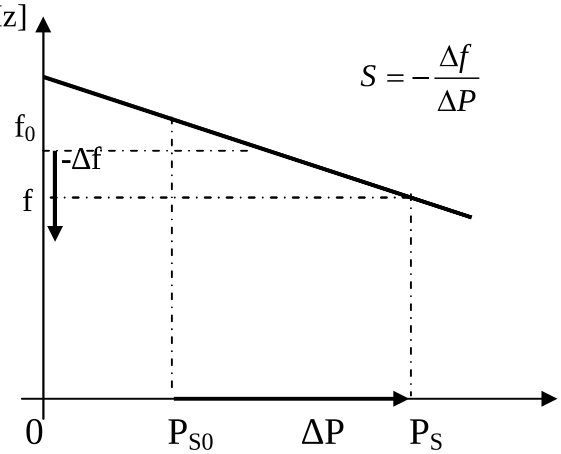
$$\textit{where} \quad « = K_{SP} \cdot K_S \cdot K_F \quad \textit{si} \quad ª = K_{SP} \cdot K_S$$

So for a decrease of (-Δf) corresponds from the power group a contribution ΔP = μΔf.

It requires this statism under the form:

$$S = -\frac{df}{dP} = -\frac{\Delta f}{\text{«} \cdot \Delta f} = -\frac{1}{\text{«}}$$

$$S = -\frac{0.4[Hz]}{P_{nom}[MW]} = -3.3 \cdot 10^{-3}\left[\frac{Hz}{MW}\right]$$

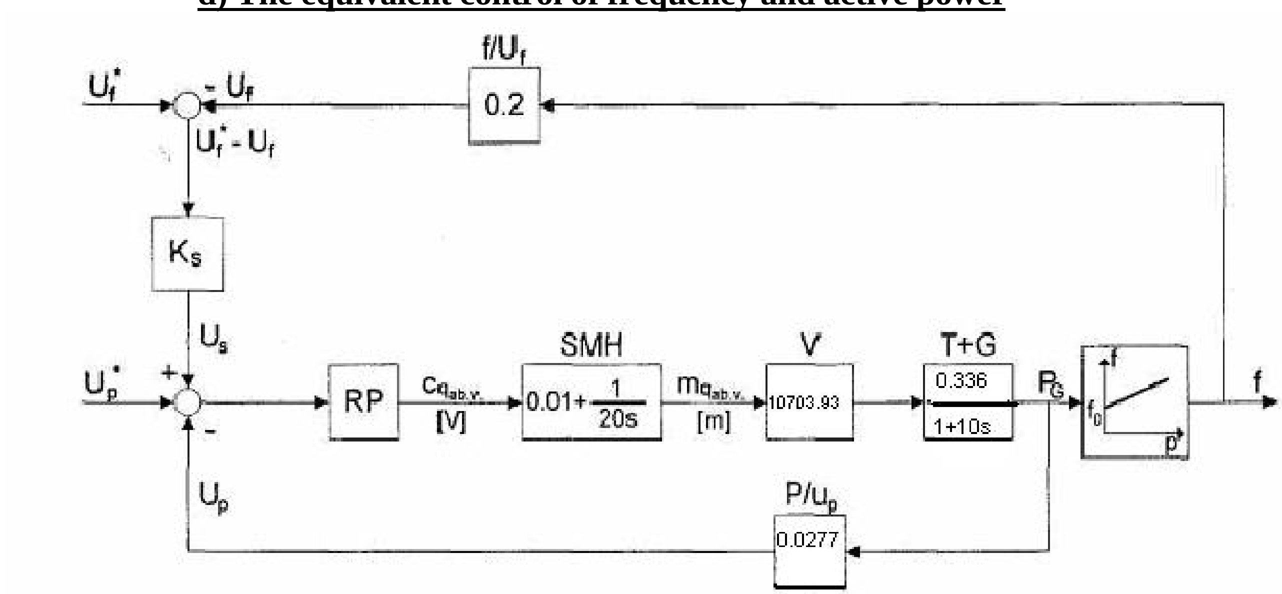


$$S = -\frac{\Delta f}{\Delta P}$$

where:

- 0.4 is the maximum frequency deviation around nominal frequency;
- S is the ratio between the power system frequency variation at the variation of the group power from "0" to P_{nom};

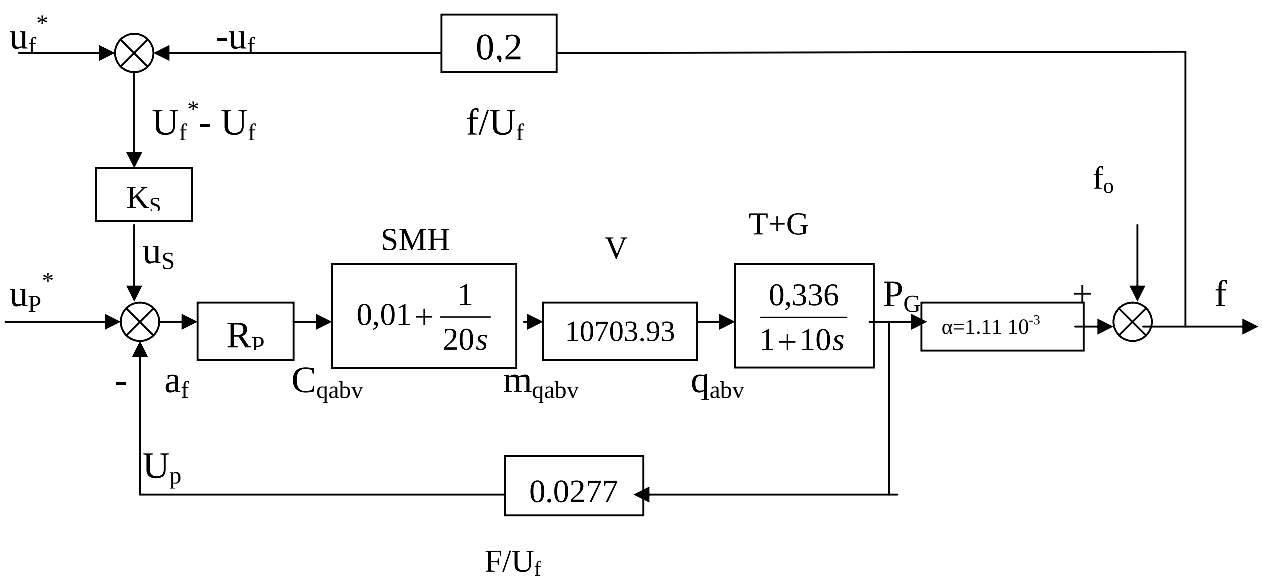
d) The equivalent control of frequency and active power



If the power supplied by the group is zero ($P_G = 0$), the power system frequency is f_0. Under the same consumption conditions, by progressively increasing P_G shows an approximately linear increase in frequency. If the group is charged to a power PG, but the load shows fluctuations due to statism, , the group will auto-charge / discharges as the frequency decreases or increases.

$$\mathbf{f = f_0 + \sim\cdot P_G \quad where \quad \sim = 3.3\ 10^{-3}[Hz/MW]}$$

As a result, a power delivered in the system PG = 122 [MW] will attract an increase in the system $3.3\ 10^{-3}$ [Hz]



Giving the controller active power RP is made after the module criterion, the equivalent system is the closest to a fast system, being imposed a frequency stabilization behaviour.

$$H_{Ex1}(s) = H_{SMH}(s) \cdot H_V \cdot H_{T+G}(s)$$

$$\text{Deci, } H_{Ex1}(s) = (0.01 + \frac{1}{20s}) \cdot 3890.987 \cdot \frac{0.3135}{1+10s} = 61 \cdot \frac{(0.2s+1)}{s(10s+1)}$$

The direct path circuit has the transfer function without regulator HE_X, the whole loop together with the active power-voltage converter will have transfer function:

$$H_d(s) = H_{Ex1}(s) \cdot K_P = 61 \cdot \frac{1+0.2s}{s(1+10s)} \cdot 0.0820 \cong 744 \frac{0.2s+1}{s\cdot(1+10s)}$$

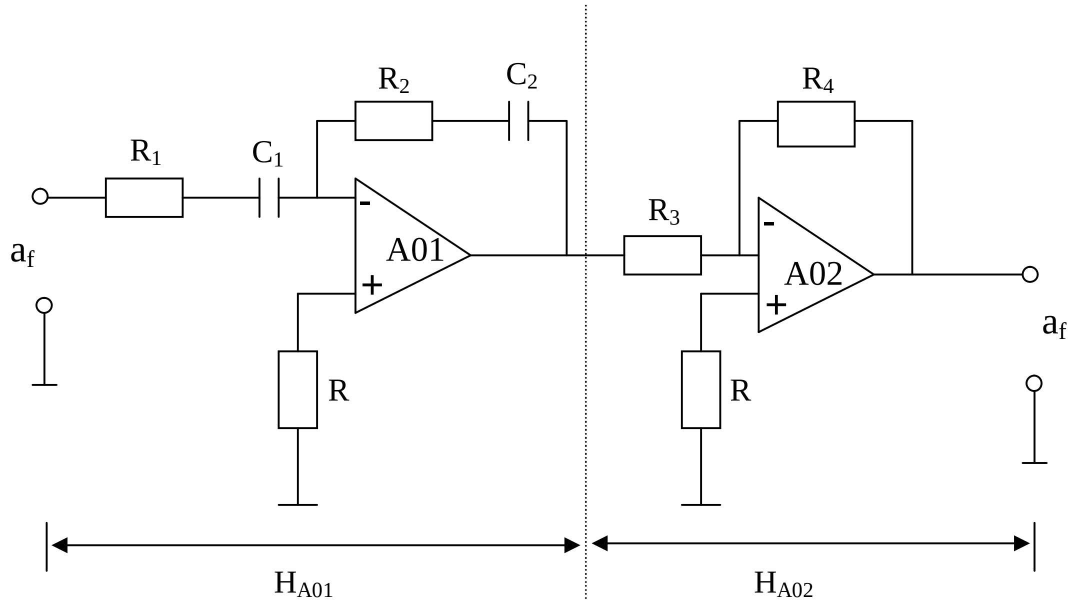
$$H_{Ex}(s) = H_d(s) \cdot \frac{1}{1+T_\Sigma \cdot s} = \frac{744(0.2s+1)}{s(10s+1)(0.01s+1)};$$

where T_Σ = 0.01 [sec] and represents the sum of the mainly irretrievable time constants.

$$H_{RP}(s) = \frac{1}{2 \cdot T_{\Sigma} \cdot s \cdot (1 + T_{\Sigma} \cdot s)} \cdot \frac{1}{H_{Ex}(s)} =$$
$$= \frac{1}{2 \cdot 0.01s(1 + 0.01s)} \cdot \frac{1}{744} \cdot \frac{s(1 + 10s)(1 + 0.02s)}{1 + 0.2s} = 0.0672 \frac{10s + 1}{0.2s + 1}$$

e) Analogical modeling of the controller

The transfer function of the regulator RP can be modeled analog with 2 operational amplifier connected in series, as it is shown in the figure below:



The properties of operational amplifiers:
- in open circuit the amplification factor is very high (at least 10^4)
- it has 2 input terminals: one is inverting (usually used) and another one is non inverting, that is associated with positive feedback
- the input impedance is very high (at least 1 MΩ)
- the output impedance is very low (1÷10Ω) – ideal generator at output
- the equivalent time constant is negligible (Max 10^{-4})

$$H_{AO}(s) = \frac{L\{V_o\}}{L\{V_i\}} \cong \frac{-Z_R}{Z_i}$$

R is calibrated in the way that the equivalent resistive bridge has to be balanced in steady state.
Consider that $C_1 = C_2 = C$

$$H_{AOech}(s) = -\frac{R_2 + \frac{1}{C_2 \cdot s}}{R_1 + \frac{1}{C_1 \cdot s}} \cdot (-1) \cdot \frac{R_4}{R_3} = \frac{1 + T_2 \cdot s}{1 + T_1 \cdot s} \cdot K$$

$$unde \quad K = \frac{R_4}{R_3}; \quad T_1 = R_1 C; \quad T_2 = R_2 C;$$

The first amplifier brings in a pole and a zero. The second one is an inverting amplifier. Using identification: ($H_{RP}(s) = H_{AOech}(s)$) is obtained.

For AO1:

$$H_{AO1}(s) = \frac{1+T_2 \cdot s}{1+T_1 \cdot s} = \frac{1+R_2 C \cdot s}{1+R_1 C \cdot s} = \frac{1+10 \cdot s}{1+0.2 \cdot s}$$

$$\Rightarrow \begin{cases} T_1 = R_1 C = 0.2[\sec] \\ T_2 = R_2 C = 10[\sec] \end{cases}$$

The value of capacitor C is chosen from the catalog:

$$C = 10[«F]$$

$$\Rightarrow \begin{cases} R_1 = T_1 / C = 20[k\Omega] \\ R_2 = T_2 / C = 1[M\Omega] \end{cases}$$

Resistance R1 can be obtained by connecting in series two resistances of 10 kΩ or by a 10 kΩ resistance and a potentiometer of 1 - 100 *k*Ω.

For AO2:

$$H_{AO2}(s) = K = \frac{R_4}{R_3} = 10$$

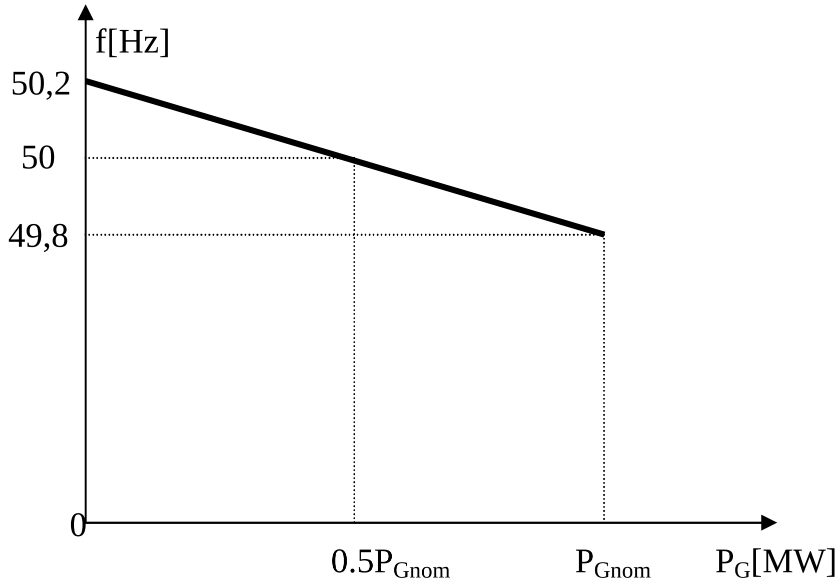
The values of resistances R_3 and R_4 are chosen from the catalog: $\Rightarrow \begin{cases} R_3 = 100[k\Omega] \\ R_4 = 1[M\Omega] \end{cases}$

f) Computetion of the statism correction loop:

Coefficient K_S is calculated from the condition that the frequency range ±0.2Hz, i.e. Δf=0.4Hz, around the nominal frequency of 50 Hz, can be ensured by the nominal power of the group.

$$S = -\frac{\Delta f[Hz]}{P_{Gnom}[MW]} = -\frac{0.4}{122} \cong -3.278 \cdot 10^{-3} \left[\frac{Hz}{MW}\right]$$

The increase of nominal power P_{Gnom} has the effect of decreasing the frequency f, as shown in the figure below:



Power transducer has the coefficient 0.2[V/Hz].
In steady state regime:

$$P_G = \frac{1}{10} \cdot P_{Gnom} \cdot (U_P^* + U_S) = \frac{1}{10} \cdot P_{Gnom} \cdot \left[U_P^* + K_S \cdot (U_f^* - 0.2 \cdot f)\right]$$

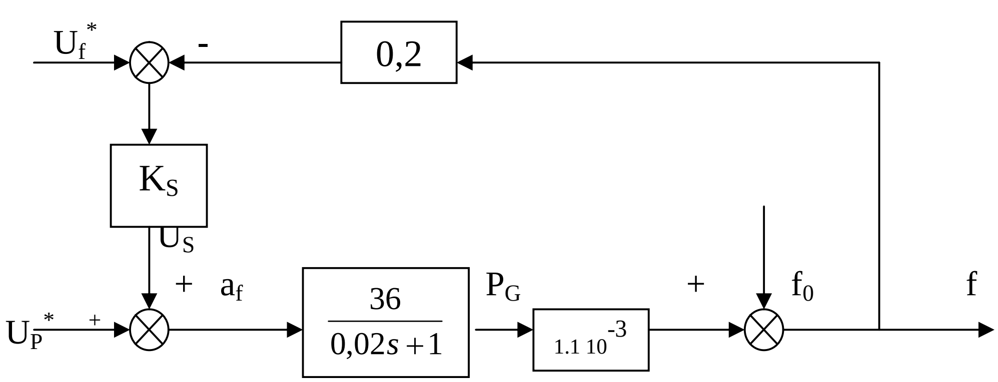
$$P_G = \frac{1}{10} \cdot P_{Gnom} \cdot (U_P^* + K_S \cdot U_f^*) - 0.02 \cdot P_{Gnom} \cdot K_S \cdot f$$

$$\Rightarrow f = \frac{1}{0.02 \cdot P_{Gnom} \cdot K_S} \left[\frac{1}{10} \cdot P_{Gnom} \cdot (U_P^* + K_S \cdot U_f^*) - P_G\right]$$

$$S = \frac{df}{dP_G} = -\frac{1}{0.02 \cdot P_{Gnom} \cdot K_S} \Rightarrow K_S = -\frac{1}{0.02 \cdot P_{Gnom} \cdot S} = \frac{1}{0.02 \cdot 122 \cdot 3.278 \cdot 10^{-3}} = 125.026 \cong 125$$

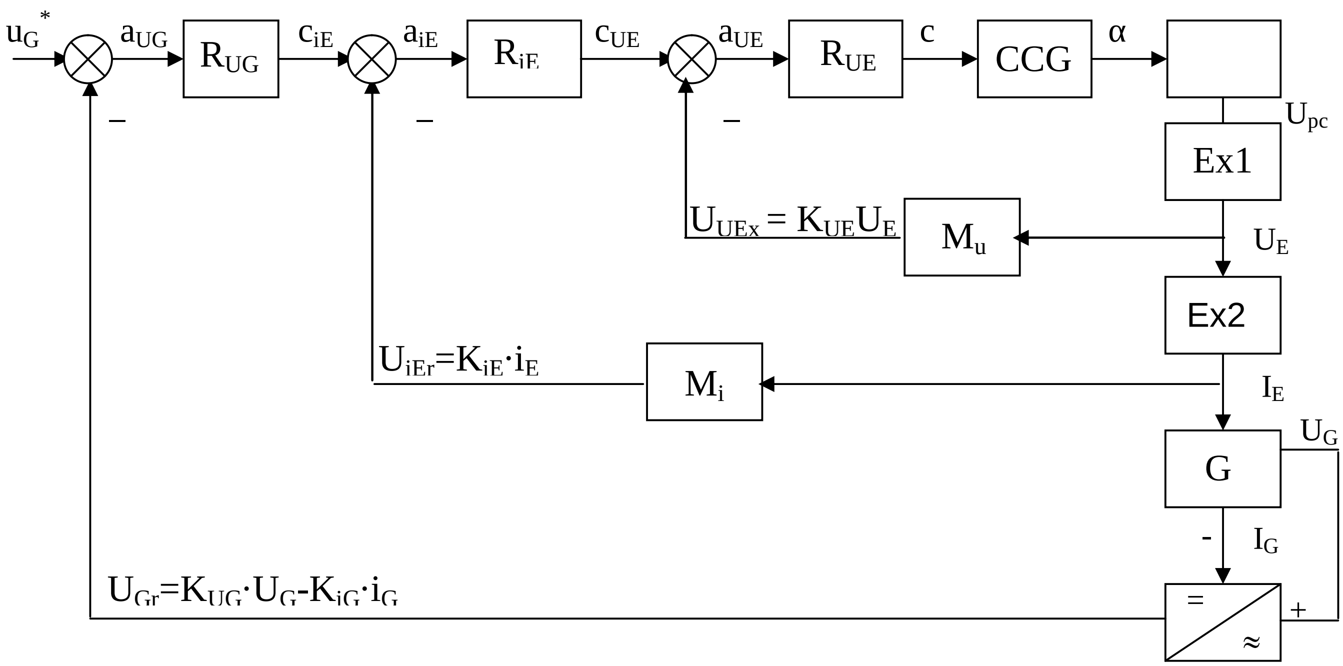
Remark: *(1/10)*P_{Gnom}* shows the reserved power adjustable with frequency, imposed by the dispatcher based on the group performance.

From the above modification, it results the following figure:



D. Reactive power and voltage control

It implements a triple-cascade control, with respect to the voltage across the generator's terminals, excitation current, excitation voltage.



On the above figure, the following notations are used:

RU_G – generator terminal voltage regulator
RI_E – excitation current regulator
RU_E – excitation voltage regulator
M_u, M_i – measurement transducers+ current, voltage adaptors
c_{iE} – excitation current's command
c_{uE} – excitation voltage's command

We have a cascade of three controllers, with respect to the signals: u_E, i_E si u_G. Generator's voltage deviation, a_{uG} is the difference between the reference voltage u_G^* and reaction voltage $u_{Gr}=K_{uG}\cdot u_G - K_{iG}\cdot i_G$, where K_{uG} and K_{iG} are the weighting coefficients of voltage and current reactions. The deviation a_{uG} is applied to the controller at generator's terminals resulting the command signal: c_{iE}. The deviation between this signal and the reaction voltage u_{iEr} , is proportional with the excitation current and it is applied to the current excitation controller RI_E. Deviation between c_{uE} and the voltage proportional with the excitation voltage u_{uEr} , is applied to the excitation voltage controller, RU_E. The complex control on the grid CCG, generates an impulse at the output, having the phase α which controls the bridge's power, PC resulting the voltage U_{PC}.

a) <u>Main component elements</u>

<u>1. Synchronous generator</u>

Apparent nominal power S_{Gnom}= 147.8788 [MWA]

Power factor **cos¨=0.825**

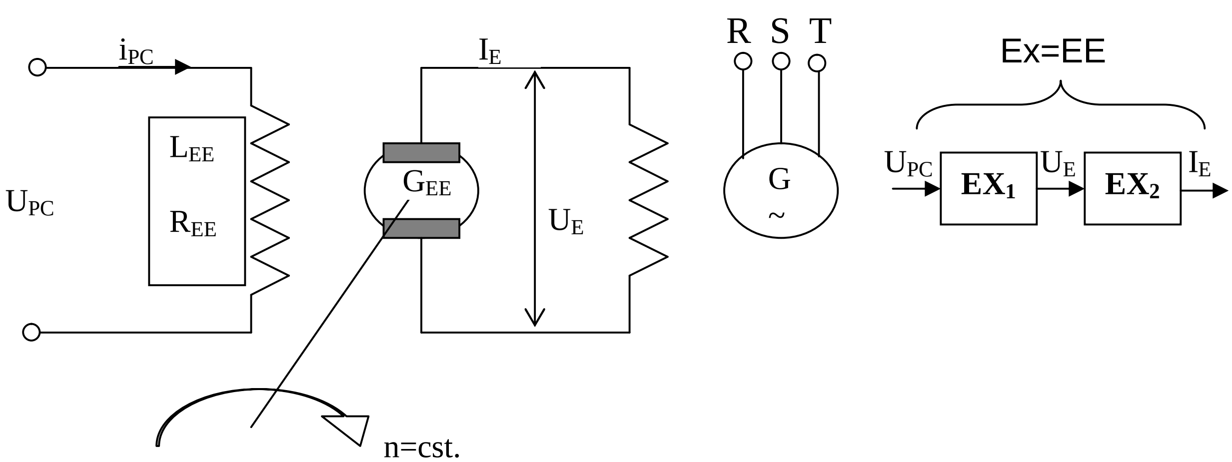
Voltage at generator terminals **U_{Gnom}=15 [KV]**

$$I_{Gnom} = \frac{S_{Gnom}}{\sqrt{3}\cdot U_{Gnom}} = \frac{147.8788\cdot 10^6}{\sqrt{3}\cdot 15\cdot 10^3} = 5.6919[kA] = 5691.9[A]$$

$$P_{Gnom} = S_G \cdot \cos¨ = 147.878\cdot 0.825 = 122[MW]$$

$$Q_{Gnom} = \sqrt{S_{Gnom}{}^2 - P_{Gnom}{}^2} = \sqrt{21868.26 - 14884} = 83.5711[MVAr]$$

<u>2. EE Exciter</u>



$$P_{Enom} \cong 0.25\% \cdot P_{Gnom} = 0.0025\cdot 122 = 0.3[MW]$$

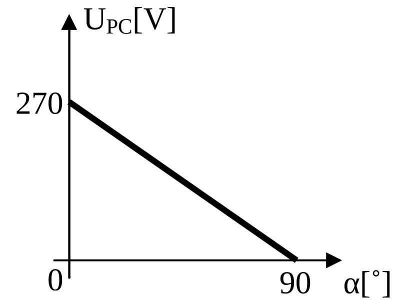
$$U_{Enom} = 300[V]$$

$$I_{Enom} = \frac{P_{Enom}[MW]}{U_{Enom}[V]} = \frac{0.3\cdot 10^6}{300} = 1000[A]$$

3. PC Controlled bridge

It supplies operating winding of the exciter with the voltage U_{PC} , current i_{PC} and power P_{PC} :

$$P_{PCnom} \cong 1\% \cdot P_{Enom} = 0.01 \cdot 0.3 \cdot 10^6 = 3[kW]$$



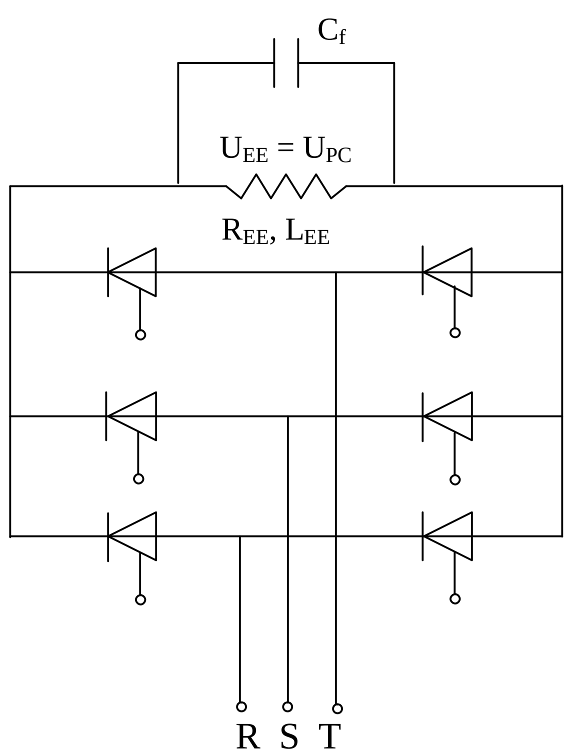
It is considered U_{PCnom} = 270 [V] for which

$$i_{PCnom} = \frac{P_{PCnom}[W]}{U_{PCnom}[V]} = \frac{3 \cdot 10^3}{270} = 11.11[A]$$

It is considered: $U_{PC} = 270 - \frac{270}{90} \cdot \sim.$

This way we obtained, through approximation, a linear dependence between U_{PC} and α. The α angle, through an adapter, belongs to 0˚ and 90˚.

4. Complex grid control



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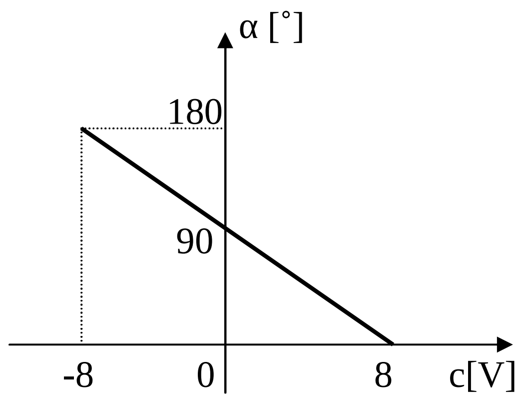
In circuit analysis, the dead time of this block will be neglected: $T_{mCCG} \approx 0$;

The voltage-pahse conversion factor is defined: $K_{CCG} = \frac{-\Delta\sim}{\Delta c} = \frac{90°}{8V} = -11.25\left[\frac{°}{V}\right]$

This ratio corresponds to a maximum variation of the phase shift control pulses of current to the grid which for a 8V variation of the voltage into CCG achieved by designing a maximum phase shift of 90^0.



The control voltage of the regulator denoted by „c” is between –8V and 8V.
The condition is ensured: c=0 => α =90˚

$$\sim = 90° - \frac{90°}{8V} \cdot c = 90° - 11.25 \cdot c$$

$$U_{PC} = 270 - 3 \cdot \sim = 270 - 3 \cdot (90° - 11.25 \cdot c) = 33.75 \cdot c$$

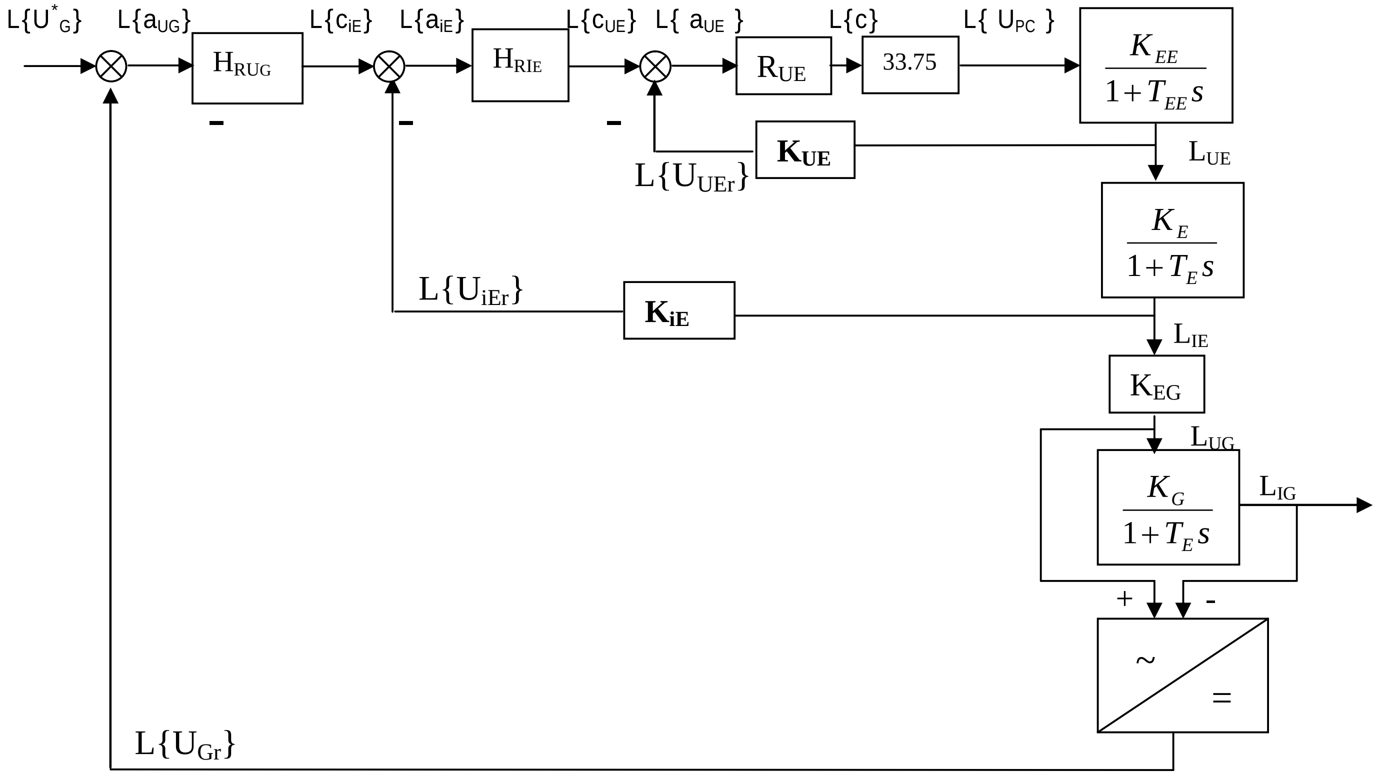
$$In \quad general:$$

$$U_{PC} = U_{PCnom} - \frac{U_{PCnom}}{90} \cdot \sim = U_{PCnom} - \frac{U_{PCnom}}{90} \cdot (90 - 11.25 \cdot c)$$

$$\Rightarrow U_{PC} = \frac{U_{PCnom}}{90} \cdot 11.25 \cdot c$$

$$For \quad U_{PCnom} = 270[V] \Rightarrow U_{PC} = 33.75 \cdot c$$

The control scheme looks like the figure below:



b) The calculation of the transfer functions of the component elements

1. **The transfer function of the excitation of the excitation circuit EE**

$$H_{EE}(s) = \frac{L\{U_E\}}{L\{U_{PC}\}} = \frac{K_{EE}}{1+T_{EE}s}$$

$$\begin{cases} U_{PC} = L_{EE} \cdot \dfrac{di_{PC}}{dt} + R_{EE} \cdot i_{PC} \\ U_E = K_{EE} \cdot i_{PC} \end{cases}$$

We apply the Laplace transform for zero initial conditions:

$$\begin{cases} U_{PC}(s) = (L_{EE} \cdot s + R_{EE}) \cdot L\{i_{PC}\} \\ U_E(s) = K_{EE}{}' \cdot L\{i_{PC}\} \end{cases}$$

$$T_{EE} = \frac{L_{EE}}{R_{EE}} = 0.1[\sec];$$

$$K_{EE} = \frac{U_{Enom}[V]}{U_{PCnom}[V]} = \frac{300[V]}{270[V]} = 1.11 \Rightarrow H_{EE}(s) = \frac{1.11}{1+0.1\cdot s}$$

2. The transfer function of generator excitation

$$H_E(s) = \frac{L\{i_E\}}{L\{u_E\}} = \frac{K_E}{1+T_E s}$$

$$K_E = \frac{i_{Enom}[A]}{U_{Enom}[V]} = \frac{1000[A]}{300[V]} = 3.33\left[\frac{A}{V}\right]$$

$$T_E(s) = 0.5[\sec] \Rightarrow H_E(s) = \frac{3.33}{1+0.5s}$$

3.The transfer function of generator

$$H_{EG}(s) = \frac{L\{i_G\}}{L\{u_G\}} = K_{EG}$$

$$K_{EG} = \frac{U_{Gnom}[V]}{i_{Enom}[A]} = \frac{15\cdot 10^3[V]}{1000[A]} = 15\left[\frac{V}{A}\right]$$

$$K_G = \frac{i_{Gnom}[A]}{U_{Gnom}[V]} = \frac{5.6919\cdot 10^3[A]}{15\cdot 10^3[V]} = 0.3795\left[\frac{A}{V}\right]$$

$$T_G(s) = 4[\sec]$$

$$\Rightarrow H_G(s) = \frac{0.3795}{1+4\cdot s}$$

4. Transfer function of compoundation reaction

- K_{UG} – is chosen in hypothesis i_G=0 for which:

$$\begin{cases} U_{Gr} = K_{UG}\cdot U_G \\ U_G^* = 10[V] \Rightarrow K_{UG} = \dfrac{10}{15\cdot 10^3} = 0.66\cdot 10^{-3} \\ U_{Gr} = U_G^* \end{cases}$$

- K_{iG} – is chosen in hypothesis: $K_{iG} = \dfrac{0.5[V]}{i_{Gnom}[A]} = \dfrac{0.5[V]}{5691.9[A]} = 8.78\cdot 10^{-5}\left[\dfrac{V}{A}\right]$

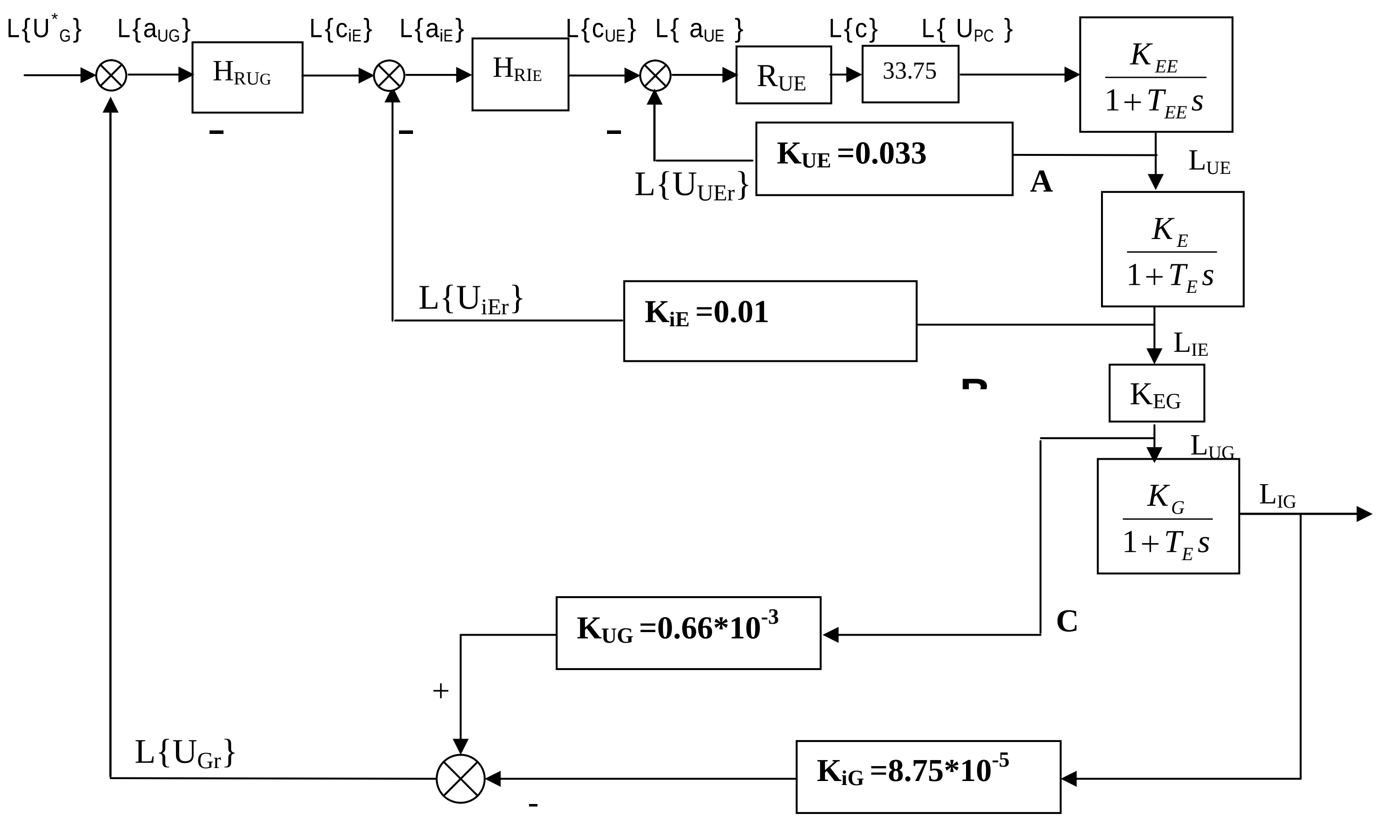
- K_{iE} – is chosen in hypothesis:

$$U_{iEr} = 10[V]; \quad si \quad K_{iE} = \frac{U_{iEr}[V]}{i_{Enom}[V]} = \frac{10[V]}{1000[V]} = 0.01\left[\frac{\mathrm{V}}{\mathrm{A}}\right]$$

- K_{UE} – is chosen in hypothesis:

$$U_{UEr} = 10[V]; \quad si \quad K_{UE} = \frac{U_{UEr}[V]}{U_{Enom}[V]} = \frac{10[V]}{300[V]} = 0.033\left[\frac{\text{V}}{\text{V}}\right]$$

The following block diagram is resulted:



Regulators adjustment will be made based on the module criterium, because of the perturbations which occur and are of the step type and the desired effect is the stabilization.

a) <u>Internal loop A</u>

$$H'_{Ex}(s) = K_{CCG+PC} \cdot \frac{K_{EE}}{1+T_{EE}\cdot s} \cdot K_{UE} = 33.75 \cdot \frac{1.11}{1+0.1\cdot s} \cdot 0.033 = \frac{1.2362}{0.1\cdot s+1}$$

$$H_{ExA}(s) = H'_{Ex}(s) \cdot \frac{1}{1+T_\Sigma \cdot s} \quad where \quad T_\Sigma = 10^{-2}[\text{sec}];$$

$$\Rightarrow H_{RUE}(s) = \frac{1}{2T_\Sigma s(1+T_\Sigma\cdot s)} \cdot \frac{1}{H_{ExA}(s)} = \frac{1}{0.02\cdot s\cdot(1+0.01\cdot s)} \cdot \frac{(1+0.1\cdot s)\cdot(1+0.1\cdot s)}{1.2362}$$

$$H_{RUE}(s) = \frac{(0.1\cdot \text{s}+1)}{0.02472 s} = 4.0453 + \frac{1}{0.02475\cdot s} \cong 4.045 + \frac{1}{0.025\cdot s}$$

A PI controller such that: $\begin{cases} V_{RUE} = 4.045 \cong 4 \\ T_{iRUE} \cong 0.025[\text{sec}] \end{cases}$

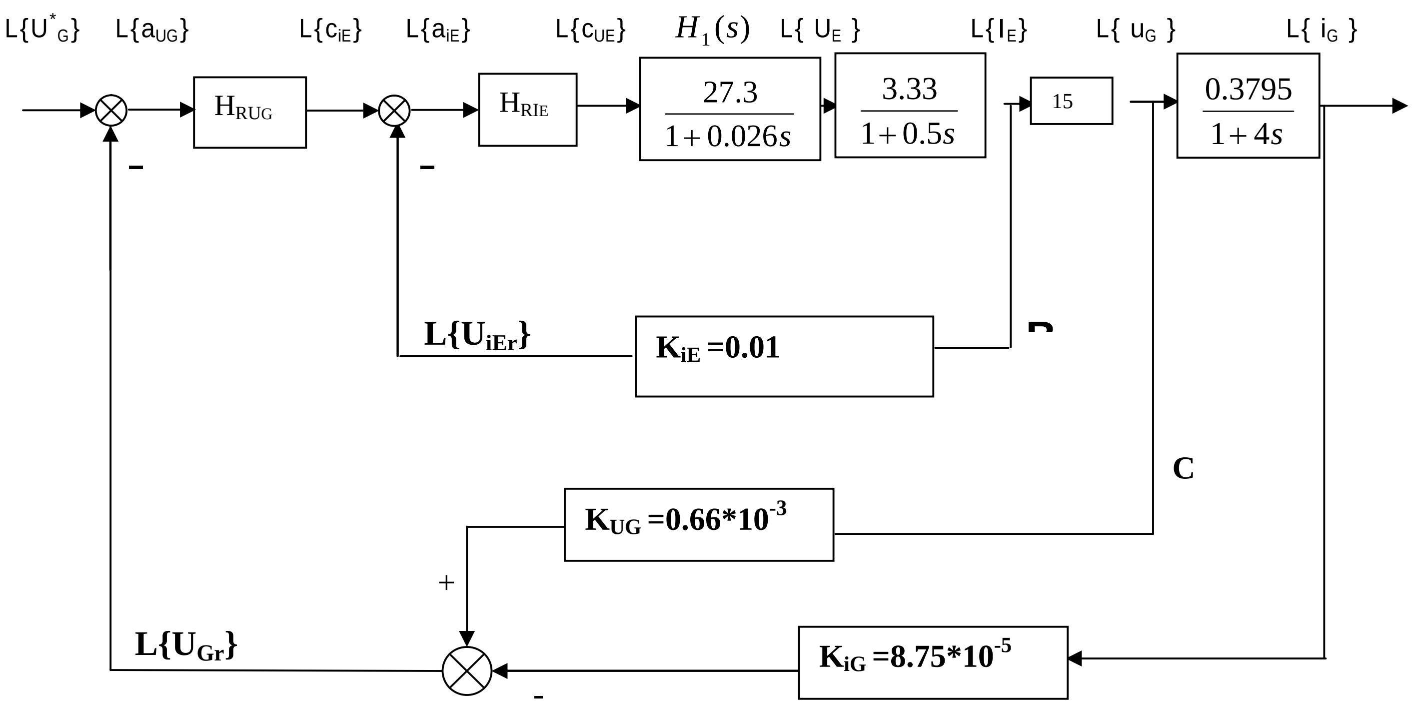
a) <u>Internal loop B</u>

The transfer function of the interior loop is:

$$H_1(s) = \frac{L\{U_E\}}{L\{c_{IE}\}} = \frac{H_{RUE}(s)\cdot K_{CCG+PC}\cdot H_{EE}(s)}{1 + H_{RUE}(s)\cdot K_{CCG+PC}\cdot H_{EE}(s)\cdot K_{UE}}$$

$$H_1(s) = \frac{\dfrac{1+0.1s}{0.03296s}\cdot 33.75\cdot\dfrac{1.11s}{1+0.1s}}{1+\dfrac{1+0.1s}{0.03296s}\cdot 33.75\cdot\dfrac{1.11s}{1+0.1s}\cdot 0.033} = \frac{\dfrac{37.46}{0.03296s}}{1+\dfrac{33.75\cdot 1.11\cdot 0.033}{0.03296s}}$$

$$H_1(s) = \frac{27.3014}{0.026s+1}$$



$$H''_{Ex}(s) = H_1(s)\cdot\frac{K_E}{1+T_E\cdot s}\cdot K_{IE} = \frac{27.3014}{1+0.026s}\cdot\frac{3.33}{1+0.5s}\cdot 0.01 \cong \frac{0.9091}{(1+0.026s)\cdot(1+0.5s)}$$

$$H_{ExB}(s) = H''_{Ex}(s)\cdot\frac{1}{1+T_\Sigma\cdot s} \quad \textit{unde} \quad T_\Sigma = 10^{-2}[\sec];$$

$$H_{ExB}(s) = \frac{0.9091}{(1+0.026s)\cdot(1+0.5s)\cdot(1+0.01s)}$$

$$\Rightarrow H_{RIE}(s) = \frac{L\{c_{UE}\}}{L\{a_{iE}\}} = \frac{1}{2T_\Sigma s(1+T_\Sigma\cdot s)}\cdot\frac{1}{H_{ExB}(s)}$$

$$H_{RIE}(s) = \frac{1}{0.02s(1+0.01s)}\cdot\frac{(1+0.02s)(1+0.01s)(1+0.5s)}{0.9091}$$

$$H_{RIE}(s) = \frac{(1+0.02s)(1+0.5s)}{0.01818s} = \frac{1}{0.01818s} + 28.6 + 0.55s$$

$$H_{RIE}(s) = 28.6\left(\frac{1}{0.519s} + 0.019s\right)$$

which represents a PID controller with the following parameters:

$$\begin{cases} V_{RIE} = 29 \\ T_{iRIE} = 0.519[\sec] \cong 0.52[\sec] \\ T_{dRIE} = 0.019[\sec] \cong 0.02[\sec] \end{cases}$$

c) <u>Internal loop C</u>

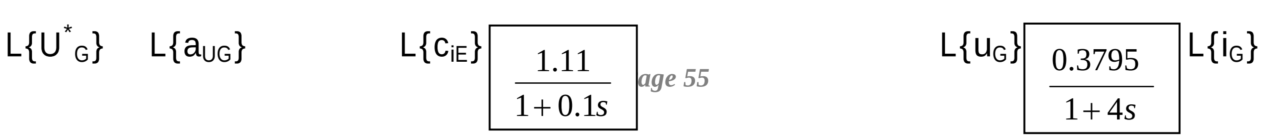
The transfer function of the internal loop $H_2(s)$ from the simplified block scheme from the figure is:

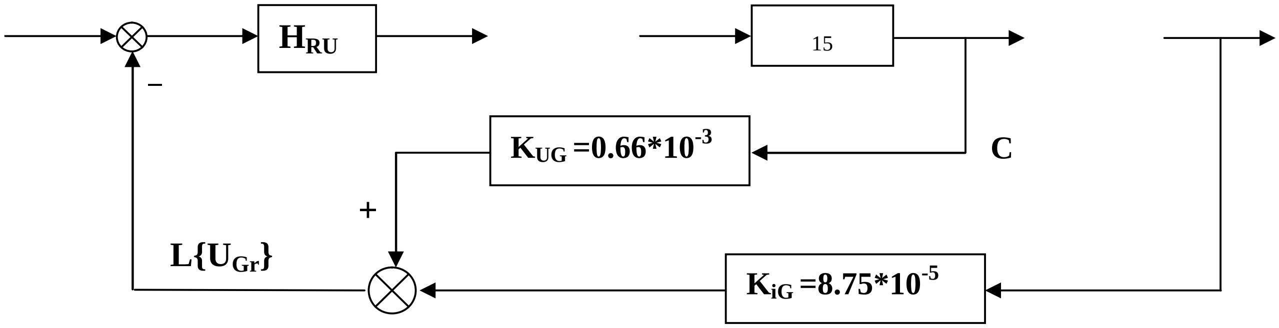
$$H_2(s) = \frac{L\{i_E\}}{L\{c_{IE}\}} = \frac{H_{RIE}(s)\cdot H_1(s)\cdot H_E(s)}{1+H_{RIE}(s)\cdot H_1\cdot H_E(s)\cdot K_{IE}}$$

$$H_2(s) = \frac{\frac{(1+0.02s)(1+0.5s)}{0.01818s}\cdot\frac{27.3014}{0.026s+1}\cdot\frac{3.33}{1+0.5s}}{1+\frac{(1+0.02s)(1+0.5s)}{0.01818s}\cdot\frac{27.3014}{0.026s+1}\cdot\frac{3.33}{1+0.5s}\cdot 0.01} =$$

$$H_2(s) = \frac{100}{1+0.0199\cdot s}`$$

The block scheme will have the following structure:

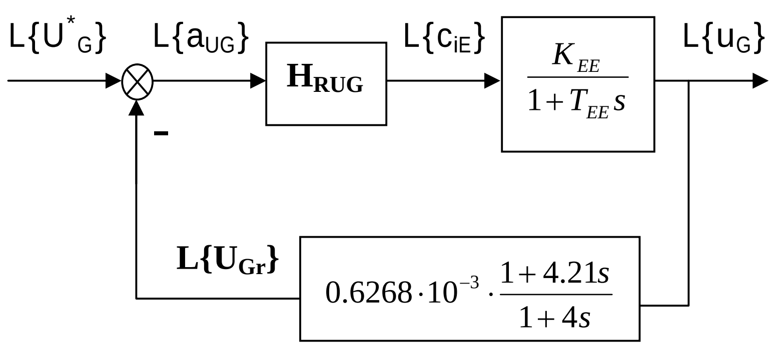




The scheme is transfigured:

$$H_{reactie}(s)=\frac{0.66\cdot10^{-3}-3.32\cdot10^{-5}+2.64\cdot10^{-3}\cdot s}{1+4s}=\frac{0.6268^{-3}(1+4.21s)}{1+4s}$$

$$H_{direct}(s)=\frac{100}{1+0.02\cdot s}\cdot15=\frac{1500}{1+0.02\cdot s}$$



$$H_{Ex}(s)=\frac{1500\cdot0.63\cdot10^{-3}\cdot(1+4.21\cdot s)}{(1+4s)\cdot(1+0{,}02\cdot s)}\cdot\frac{1}{(1+T_{\Sigma}\cdot s)}\quad\text{with } T_{\Sigma}=0{,}01[\text{sec}]$$

$$\Rightarrow H_{Ex}(s)=\frac{0.945\cdot(1+4.21\cdot s)}{(1+4s)\cdot(1+0{,}02\cdot s)\cdot(1+0{,}01\cdot s)}$$

$$H_{RU_G}(s)=\frac{L\{c_{i_E}\}}{L\{a_{U_G}\}}=\frac{1}{2\cdot T_{\Sigma}\cdot s\cdot(T_{\Sigma}\cdot s+1)}\cdot\frac{1}{H_{Ex}(s)}=\frac{(1+4s)(1+0.02s)(1+0.01s)}{0.945\cdot(1+4.21s)}\cdot\frac{1}{0.02s(1+0.01s)}=$$

$$=\frac{52.91\cdot(1+4s)\cdot(1+0{,}02s)}{s(1+4.21s)}\Rightarrow$$

1. If it is considered $1+4s \approx 1+4.21s \Rightarrow$ a PI controller :

$$H_{RU_G}(s) = 52.91 \cdot \frac{(1+0{,}02 \cdot s)}{s} \cong 1.05(1+\frac{1}{0{,}02 \cdot s})$$

$$\begin{cases} V_{R\,RU_G} = 1.05 \\ T_{i\,RU_G} = 0{,}02[\sec] \end{cases}$$

2. Thus, results a PID controller with a first order filter:

$$H_{RU_G}(s) = 52.91 \cdot \frac{1+4.02s+0.08s^2}{s(1+4.21s)} = 52.91 \cdot \frac{4.02+\frac{1}{s}+0{,}08 \cdot s}{1+4.21s} = 212.7 \cdot \frac{1+\frac{1}{4.02s}+0.02s}{1+4.21s}$$

$$\Rightarrow \begin{cases} V_{R\,RU_G} = 212.7 \\ T_{i\,RU_G} = 4.02[\sec] \\ T_{d\,RU_G} = 0{,}02[\sec] \\ T_N = 4.21[\sec] \end{cases}$$

The model of the RU_G controller:

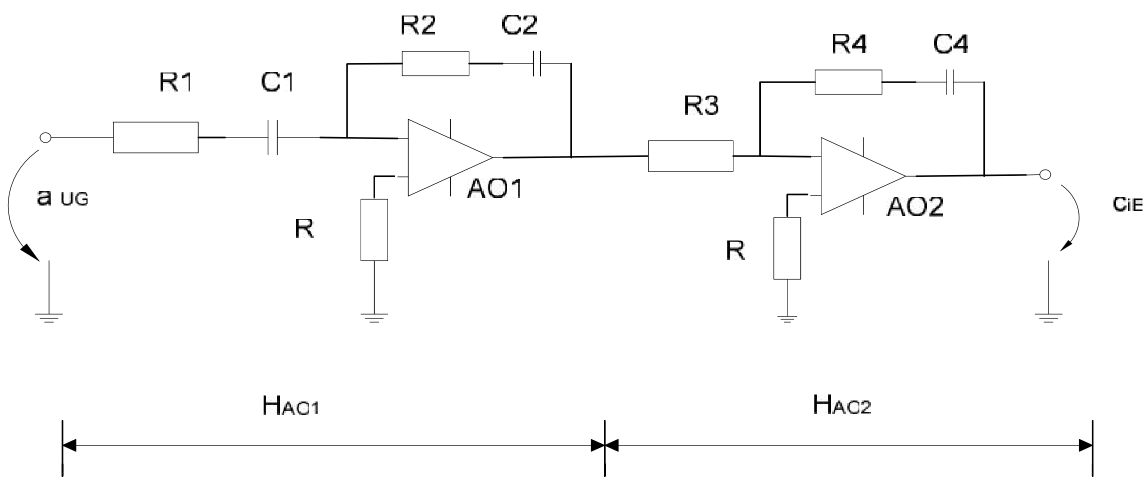


Fig. 45

$$H_{RU_G}(s) = H_{AO_1}(s) \cdot H_{AO_2}(s) \text{, where } H_{AO_1}(s) = -\frac{R_2+\frac{1}{C_2 \cdot s}}{R_1+\frac{1}{C_1 \cdot s}} \text{ şi } H_{AO_2}(s) = -\frac{R_4+\frac{1}{C_4 \cdot s}}{R_3}$$

$$\Rightarrow H_{RU_G}(s) = \left(\frac{R_2+\frac{1}{C_2 \cdot s}}{R_1+\frac{1}{C_1 \cdot s}}\right) \cdot \left(\frac{R_4+\frac{1}{C_4 \cdot s}}{R_3}\right) = \frac{C_1}{C_2 \cdot C_4 \cdot R_3} \cdot \frac{(R_2 \cdot C_2 \cdot s+1) \cdot (R_4 \cdot C_4 \cdot s+1)}{R_1 \cdot C_1 \cdot s+1}$$

By identification methods $\Rightarrow$

$T_1 = R_1 \cdot C_1 = 4.21[\sec]$; we choose $R_1 = 100K\Omega \Rightarrow C_1 = \frac{4.21}{10^5} = 42«F$

$T_2 = R_2 \cdot C_2 = 0{,}02[\sec]$; we choose $R_2 = 100k\Omega \Rightarrow C_2 = \frac{0{,}02}{10^5} = 0{,}2«F$

$T_4 = R_4 \cdot C_4 = 4.02[\sec]$; we choose $R_4 = 100K\Omega \Rightarrow C_4 = 40«F$

We choose the condensers from the catalog, E6 condensers, with 6 types, between 1 and 10 and which have standardized values, multiple of 1, 2.2, 3.3, 4.7, 6.8, 10.

In this way we choose C_1=4.7µF $\Rightarrow R_1 = \frac{0.4}{4.7 \cdot 10^{-6}} = 85.106K\Omega$, but we don't have a resistance with that value in the catalog so we connect in series $R_1^{’}$= 82KΩ with a variable resistance $R_1^{”}$= 4.7KΩ, we choose C_2=0.22µF$\Rightarrow R_2 = \frac{0.02}{0.22 \cdot 10^{-6}} = 90.909K\Omega$ and we obtain $R_2^{’}$=85kΩ connected in series with a variable resistance $R_2^{”}$=10kΩ, we choose C_4=4.7µF$\Rightarrow R_4 = \frac{0.52}{4.7 \cdot 10^{-6}} = 110.638K\Omega$ and we get $R_4^{’}$=110k Ω connected in series with a variable resistance $R_4^{”}$= 820Ω.

$V_R = \frac{C_1}{C_2 \cdot C_4 \cdot R_3} = \frac{4.7}{0{,}22 \cdot 4.7 \cdot 10^{-6} \cdot R_3} = 40.22 \Rightarrow R_3 = \frac{1}{0.22} \cdot 10^6 \Rightarrow R_3 = 4.54k\Omega$ which we obtain from $R_3^{’}$=4.3kΩ connected in series with the variable resistance $R_3^{”}$=390Ω.

Therefore, $R_1 = R_1^{'} + R_1^{''}$; $R_2 = 100k\Omega$; $R_3 = R_3^{'} + R_3^{''}$;

$R_4 = R_4^{'} + R_4^{''}$ $C_1 = 4.7«F$, $C_2 = 0{,}22«F$; $C_4 = 4.7«F$;