THE LOAD FREQUENCY CONTROL SIMULATION OF A THERMAL GENERATOR INTERCONECTED ON AN INFINITE BUS BARS

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Abstract: In this paper is presented the simulation of the behavior in load frequency control for a power thermal generator interconnected with an infinite bus bars, generated by the frequency variations, caused by imbalances of production consumption balance. By using the MATLAB_SIMULINK in order to follow the time evolution of the angular speed / frequency and how to mobilize the primary control reserve a thermal generator of 330 MW by simulating the frequency variation in the infinite bus bars.

Key words: load frequency, infinite bus bars, power thermal generator.

1. INTRODUCTION:

It follows the static stability in combined turbine and generator to small frequency oscillations operating conditions generated by the electrical power disturbances. Generally, these oscillations arise from the transmission and distribution tie lines to generating units.

These oscillations are classified into the following types [6]:

- Inter-area oscillations with the typical oscillation between 0.1 - 0.7 Hz, the most interest in terms of primary control LFC .
- Local plant oscillations with the typical oscillation between 0.8- 2Hz.
- Intra-plant oscillations with the typical oscillation between 1.5 - 3 Hz. of interest in terms of their local stabilization.

The article aims to show how to approach the mathematical modeling and simulation the primary control LFC for thermal generators.

2. The mathematical modeling of the synchronous generators connected to the network.

Starting from the oscillation equation of synchronous machine [6] linearized to small perturbations connected to a infinite bus bars we consider the mechanical power Pm = ct.:

$$P_m - P_e = P_a = 0 \quad \text{(acceleration power)} \qquad (1)$$

$$2H\frac{d\omega}{dt} + D\cdot\Delta\omega + T_{12}\cdot\Delta\delta = 0 \quad \text{p.u.} \qquad (2)$$

$$\Delta\delta = \int \Delta\omega \cdot dt = \int \Delta f \cdot dt \quad \text{p.u.} \qquad (3)$$

Where:

P_m = the mechanical power
P_e = the electric power
P_a = the acceleration power
D = the damping constant [5]
T_{12} = the synchronization constant
H = the synchronization constant time r.u.

The first term represents the inertia of the angular speed (frequency in r.u), the second term represents the damping power and the last term represents and synchronization power.

The frequency of free oscillation to small disturbances in r.u. is:

$$f_0 = \sqrt{\frac{T_{12}}{M}} \quad \text{[p.u.]}. \qquad (4)$$

The moment of inertia is:

$$M = \frac{2\cdot E_C}{2\pi\cdot f_S} = \frac{2\cdot H}{\omega_S} \quad \left[\frac{\text{p.u..}}{\text{Hz}}\cdot s\right] \qquad (5)$$

In the literature [5] the inertia constant H is obtained by kinetic energy divided to the nominal apparent power Sn:

$$H = \frac{E_C}{S_n} \quad \text{[p.u. s]} \qquad (6)$$

For $\cos\phi \cong 1$ in the transport network, we can write without significant errors, the S [MVA] = P [MW] and we obtain the time constant of inertia:

$$M = 2H \qquad (7)$$

M = 2H is the turbine / generator axis constant of inertia [sec]

From (2) to determine that M_{min} and H_{min}, we use the following relationship [7]:

$$\frac{2H}{f_0}\cdot\frac{df}{dt}+D\cdot\Delta f=\Delta P \qquad (8)$$

and neglecting the damping factor of the load D [ur / Hz] we obtain:

$$\frac{df}{dt}=\Delta P\cdot\frac{f_0}{2H}\ [\mathrm{Hz/s}]<\left(\frac{df}{dt}\right)_{REL} \qquad (9)$$

$$H_{min}=\frac{\Delta P\cdot f_0}{2\left(\frac{df}{dt}\right)_{REL}} \qquad (10)$$

Were :

f_0 = nominal frequency in the system (pre-disturbance)

$$\Delta P=\frac{\Delta P_L}{P_T-\Delta P_L} \qquad (11)$$

the amplitude of perturbation in the system u.r.

ΔP_L = the local perturbation [MW]

P_T = the total power produced (pre-disturbance).

$$\left(\frac{df}{dt}\right)_{REL}=0{,}1[\mathrm{Hz/s}]$$

the value that is set the accelerometer relay.

The accelerometers relay is set to 0.1 [Hz / sec]. Many relays are set to 0.2 [Hz / sec]

The accelerometers relays used in SEN are numerical MICOM P941 and P943 type from AREVA. Relay measures the changes in frequency in a time of = 100 [msec] and calculate $\frac{df}{dt}$ every 25 [ms]. If the calculated value exceeds a prescribed value more than 50 samples relay acts [7].

Typical values of inertia constant H [7] are presented in the table below (Table 1).

Table 1. Typical values of inertia constant H for generators

No. crt.	The generators type	H [sec]
1	Hydro generators	
	Low speed (< 200rot/min)	2 – 3
	High speed (> 200rot/min)	2 – 4
2	Termal generators	
	With condensing (1500rot/min)	6 – 9
	With condensing (3000rot/min)	4 – 7
	Without condensing (3000rot/min)	3 - 4
3	synchronous motors for heavy shareholders	2

The T12 constant synchronization (the sync torque) is the "rigid" connection with the infinite bus bars:

$$T_{12}=\frac{U\cdot E_q}{X_T}\cdot\cos\delta^{(0)}=\left(\frac{\partial P}{\partial\delta}\right)_{\delta=\delta(0)} \qquad (12)$$

Were :

δ = the power angle.

$\delta^{(0)}$ = the power angle were the linearization is made

E_q = the electromotive voltage behind synchronous reactance.

U = the infinite bus bars voltage .

X_T = X_d + $X_{tr.\ bloc}$ + X_{retea} representing the total reactance across the generator terminals.

The generator active power pre-disturbance.

$$P^{(0)}=\frac{U\cdot E_q}{X_T}\cdot\sin\delta^{(0)}=P_{max}\cdot\sin\delta^{(0)} \qquad (13)$$

To study the frequency stability and the behavior of generators in the primary control is used the following simplifying assumptions:

- The loads are represented by admittance..
- Synchronous machines are represented as ideal voltage sources and equal to $E_q^{'}$ behind their internal synchronous reactance reactance Xd and the internal reactance of the machine is equal with transient reactance $X_d^{'}$ [5].
- The generator terminals voltage is constant.

Depending on the total reactance of the machine terminals will operate in the unperturbed system at different load angles, thus obtaining different values for synchronizing constant T12. As seen from (4) timing and constant values of the moment of inertia will influence the dynamic behavior of the angular speed / frequency. For Heat-synchronous PN = 330 MW nominal power operating at 80% of rated power at power angle δ = 25^0 (P_{max} = 638MW). The synchronization constant values u.r. for different loads are represented in table (Tab.2.)

Table 2. The synchronization constants depending on power angle δ

Angle $\delta^{(0)}$	5^0	10^0	15^0	20^0	25^0
T_{12} u.r.	1.93	1,9	1,86	1,8	1,75
P_e u.r.	0,16	0,33	0,5	0,66	0,8

If total the reactance on generator terminals decreases (shorter evacuation tie line) the evacuation power Pmax will increases and the evacuation of power will be made at a lower power angle by a greater synchronizing factor T12. For example, for a total reactance lower with 20% (Pmax = 789MW) the synchronizing constants are (see Table 3.)

Table 3. The synchronization constants depending on power angle δ .

Angle $\delta^{(0)}$	5^0	10^0	15^0	20^0	25^0
T_{12} u.r.	2,38	2,35	2,3	2,24	2,16
P_e u.r.	0,2	0,4	0,6	0,8	1

In the simulations we can see the influence on the dynamic behavior of the generator, the evacuation tie line influence and the power angle influence, around which linearization is made.

Next to view the behavior of thermo unit in parallel to a infinite bus bars we use the general mathematical model of two interconnected systems [5], [2] customized for a thermal generator P_N = 330 MW of the power plant CTE Turceni. Considering that the infinite bus bars is the gravity angular center GCU [5] will be considered the oscillation frequency source.

For a thermal generator with the nominal power P1 and the moment of inertia M1 interconnected with an infinite bus bars P2 (P2 >> P1) and moment of inertia M2 (M2 >> M1) we have:

$$M_1 + M_2 \cong M_2 = M_T \quad (14)$$

$$\frac{M_1}{M_T} \cong 0 \ ; \quad \frac{M_2}{M_T} \cong 1 \quad (15)$$

From (15) and (16), we can see that:

$$\delta_{CGU} \cong \delta_2$$

and

$$\Delta\omega_{CGU} \cong \Delta\omega_2 = \Delta f_{CGU} \cong \Delta f_2 \ \ \text{r.u.} \quad (16)$$

The mathematical model used [2], [7], is represented in the figure below (Fig.1.)

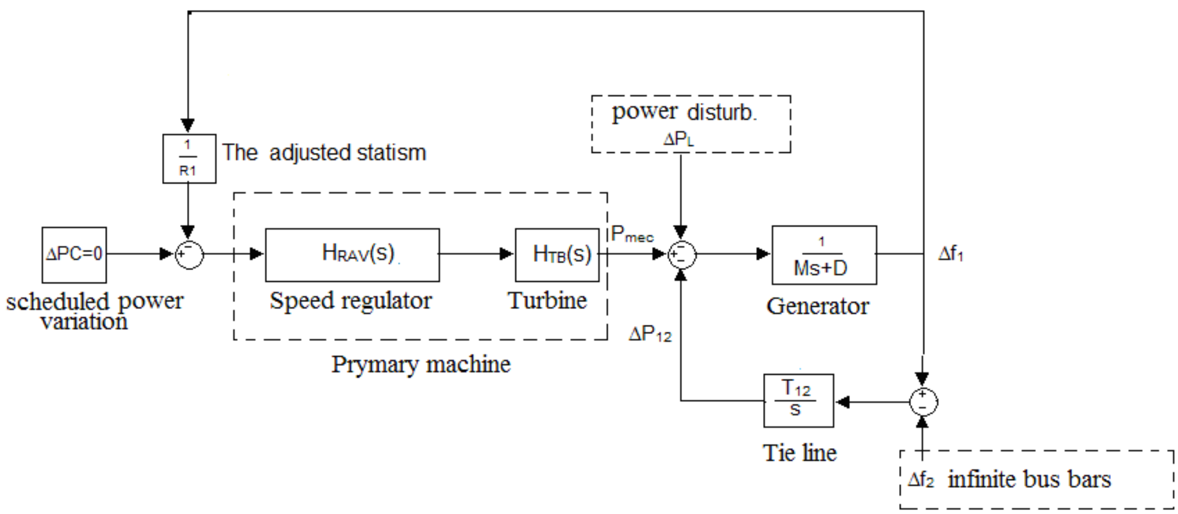


Fig. 1 – The mathematical model of an interconnected generator with a infinite bus bars

The equations for the general mathematical model, in Laplace, for the studied thermal generator interconnected with a infinite bus bar will be

$$P_{m1}(s) = \Delta P_{C1} - \Delta f_1(s) \cdot \frac{1}{R} \cdot H_{RAV1}(s) \cdot H_{TB1}(s) \quad (17)$$

$$\Delta P_{12}(s) = \frac{T_{12}}{s} \cdot [\Delta f_1(s) - \Delta f_2(s)] \quad (18)$$

$$\Delta f_1(s) = [P_{m1}(s) - \Delta P_{12}(s) - \Delta P_{L1}(s)] \cdot H_{G1}(s) \quad (19)$$

Were :

$$H_{G1}(s) = \frac{1}{M_1 s + D_1} \quad (20)$$

$\Delta P_{C1} \cong 0$; the variation of the scheduled power in primary control.

$\Delta P_{L1}(s)$ and Δf_2 (s) = disturbance.

2. THE MODELING OF THE PRIMARY MACHINE

The statism set R is determined according to the primary control reserve must be fully mobilized [8] for a stationary frequency deviation of 0.2 Hz = 0.004 pu. In SEN (the national power system) the primary control reserve is scheduled:

P_{REG}= +/- (1% P_N - 1.4% P_N) for the reference frequency deviation

$$\Delta f = + / - 0.4\% \, f_N. \quad (21)$$

The value of 1/R u.r. become :

$$\frac{1}{R} = \frac{P_{Re} \text{u.r.}}{\Delta f \text{u.r.}} = \frac{1\% - 1{,}4\%}{0{,}4\%} = [2{,}5 - 3{,}5] \text{u.r.} \quad (22)$$

For example for a group with nominal power P_N = 330 MW and 1/ R = 3 p.u., in absolute units we will have:

$$\frac{1}{R} = \frac{1}{R}[\text{u..r.}] \cdot \frac{P_N}{f_N} = 3 \cdot \frac{330\text{MW}}{50\text{Hz}} = 19{,}8\text{MW/Hz} \quad (23)$$

The active power mobilized in primary control for the reference incident $\Delta f = + / - 0.2$ Hz

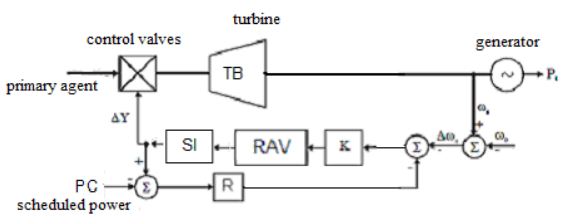
$$P_{Reg} = \pm\frac{1}{R}\cdot\Delta f = \pm 0{,}2Hz\cdot 19{,}8MW/Hz = \pm 3{,}96MW \quad (24)$$

The primary control band will be :

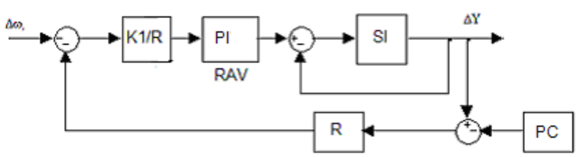
$$B_{Reg} = 2P_{Reg} = 7{,}92\ MW \approx 2{,}5\%P_N \quad (25)$$

3. THE STATIC SPEED REGULATOR PI TYPE

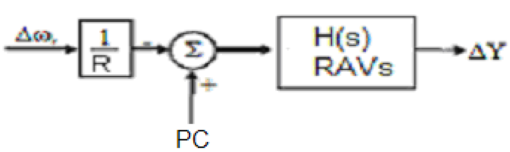
The practicality model of the static speed regulator is represented in diagrams below (Fig.2.)



a



b



c

Fig. 2 – The static loop regulation model a) schematic diagram; b) block diagram; c) the equivalent block diagram

Were:
SI = intermediate actuator
PC = the schedule active power oscillations .
RAV = automatic speed regulator typed (I,PI,PID)
R = the permanent statism.
$K = K_1 \cdot R$ the proportionality factor regulator [MW/Hz]
The proportionality constant K [MW / Hz], given the general structure of the RAV should be proportional to 1/R :

$$K = \frac{K_1}{R}\ [MW/Hz] \quad (26)$$

The mathematical model used is: (Fig. 3).

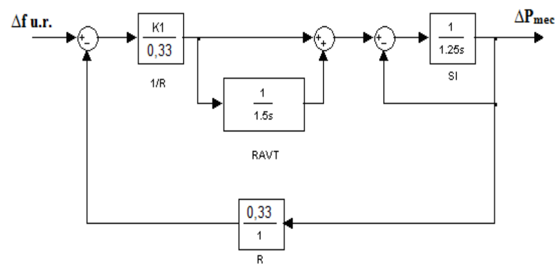


Fig. 3 – The mathematical model of the PI static regulator RAV

We will use the technical data for static PI RAV model (The CTE Turceni power plant model) PI type with it's proper constants :

$K_P = 1$; $T_I = 1{,}5$ sec, $T_{SI} = 1{,}25$ sec [$\Rightarrow K_1 = 5$, $R = 0{,}33$ u.r.

The RAV regulator transfer function will be:

$$H_{(RAV+EE)T} = -\frac{1}{R}\cdot\frac{50s + 33{,}33}{s^2 + 60s + 33{,}33} \quad (27)$$

The mathematical model used in stability studies for steam turbines is a simplified model with transfer function [1] ,[2]:

$$H_{TB}(s) = \frac{1 + F_{HP}T_{RH}s}{(1 + T_{RH}s)(1 + T_{CH}s)} \quad (28)$$

The typical constants for steam turbine with overheating cycle is : [2]:

$F_{HP} = 0{,}3$; $T_{RH} = (5\ -7)$ s ; $T_{CH} = 0{,}3$ s.

For the constant time $T_{RH} = 5$ sec specific for the steam turbines with overheating cycle the transfer function (30) will becomes:

$$H_{TB}(s) = \frac{1{,}5s + 1}{1{,}5s^2 + 5{,}3s + 1} \quad (29)$$

The disturbances in the infinite power system are done by simulating different frequency deviations of amplitude and time evolution (step signal or ramp signals at different rates of change of frequency in time). The qualification tests in primary control [8] are simulated used a frequency step deviation in upward or downward. The frequency deviation level in this case is maximum because in reality the frequency deviation after imbalance between production and consumption has a finite speed variation that depending on the inertia moment of the system generators and the consumption damping factor D [MW/Hz].

The cconstants necessary for the simulation of mathematical model are summarized in the table below (Table 4.)

Table 4. The general data used in simulation of LFC for an active power of 330 MW thermal generator in parallel with a infinite bus bars

p.u.** = P_n = 330 [MW] f_n = 50Hz = 1 p.u.	**Thermogenerator** **P_N = 330MW**	
******************	**a.u.**	**p.u.**
P_n	330 MW	1
1/R	19.8MW/Hz	3
M = 2H	10 sec	-
D1%	3,3 MW/Hz	0,5
T_{12}^1 $\delta = 25^0$ $P_a = 0,8$ p.u.	578 MW	1,75
T_{12}^2 $\delta = 20^0$ $P_a = 0,8$ p.u.	741 MW	2,24
P_{max1}	638 MW	1,93
P_{max2}	789 MW	2,39
Δf	0,2Hz	0,004
Df/dt	0,05Hz/sec	0,001/sec

Starting from (2) we can write:

$$\frac{2H}{f_0} \cdot \frac{df}{dt} + D \cdot \Delta f = \Delta P \tag{30}$$

and neglecting the damping factor of Task D we get:

$$\frac{df}{dt} = \Delta P \cdot \frac{f_0}{2H} \text{ [Hz/sec]} < \left(\frac{df}{dt}\right)_{REL} \tag{31}$$

Were:
f_0 = the nominal frequency in the system (pre-disturbance)

$\Delta P = \dfrac{\Delta P_L}{P_T - \Delta P_L}$ the amplitude of perturbance r.u.

ΔP_L = the perturbance [MW]

P_T = power produced in the system (pre-disturbance).

$$\frac{\partial^2 \delta}{\partial t^2} = \left(\frac{df}{dt}\right)_{REL} = 0{,}1 \text{[Hz/s]}$$

The acceleration values were is set tthe accelerometer relay.

The accelerometers relay is set to 0.1 [Hz / sec]. Many relays are set to drive set to 0.2 [Hz / sec]. The accelerometers relays that are used in SEN is numerical type MICOM P941 and P943 produced by AREVA. Relay measures the changes in frequency in a time of = 100 [msec] and calculate every 25 [ms]. If the calculated value exceeds a prescribed value more than 50 samples relay acts [7]. [7].

Using the data from (Tab. 3.), The mathematical model developed in MATLAB – SIMULINK become (Fig.4).

The model offer the possibilities to simulate different frequency steps Δf_2 in the infinite bus bars as step or linear ramp signals with different slopes df/dt. maintaining the disturbance $\Delta P_L = 0$ (see model above, without throwing the burden of group) or simulated load by throwing signals with different amplitudes maintaining $\Delta f_2 = 0$ in the infinite power system according to GCU (16) si (17).

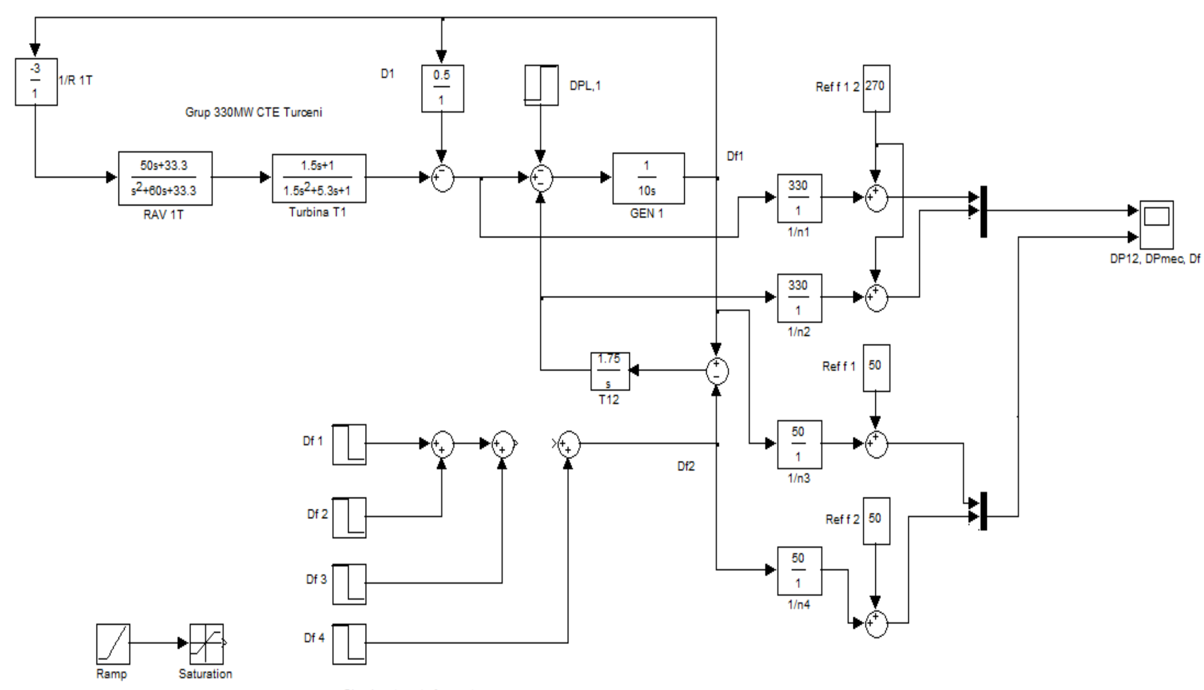
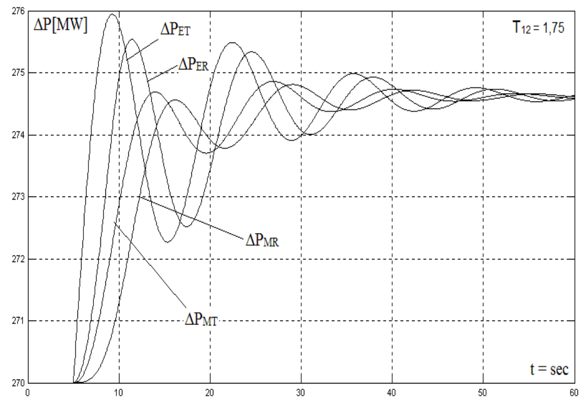
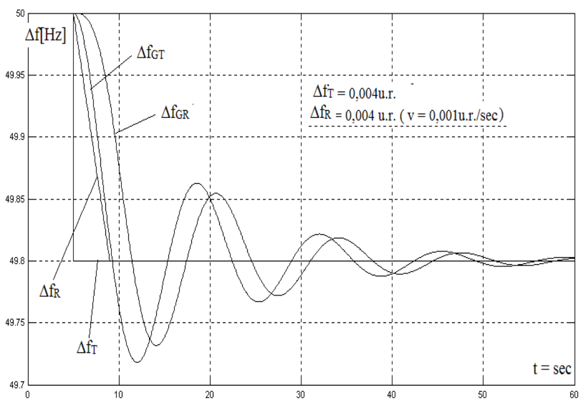


Fig. 4 – The mathematical model simulating primary control for a thermal generator P_N = 330 MW in parallel with a infinite bus bars.

Below are represented the diagrams obtained for different disturbances using the model from Figure 4. for time period t = 60 sec.

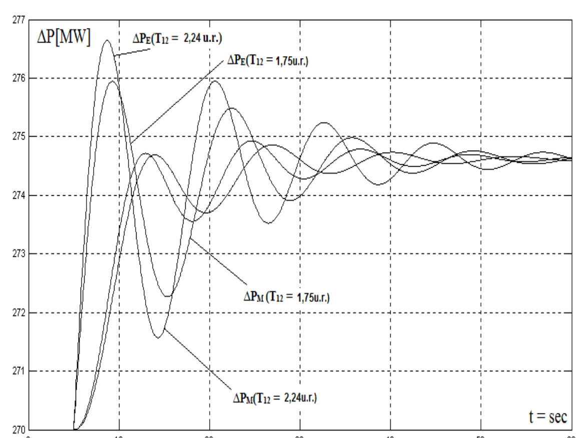


a) The variation of the electrical and mechanical power

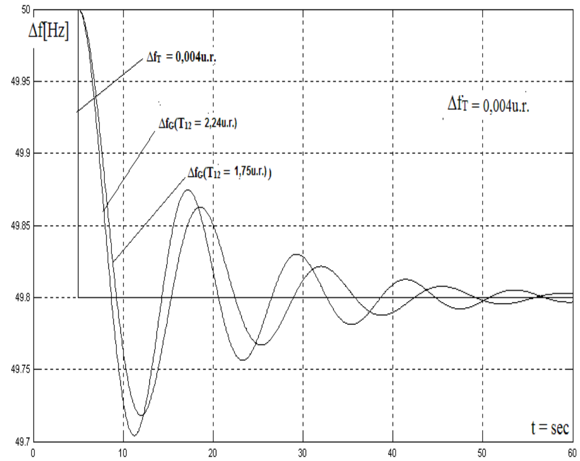


b) The step frequency variation 0,004 u.r. ; ramp 0,004 p.u. with v = 0,001u.r./sec

Fig. 5 – The thermal generator response to a frequency variation step Δf_T or ramp. Δf_R
Δf_T = 0,2Hz (0,004p.u..) step ; Δf_R = 0,2Hz V=0,05Hz/sec (V= 0,001p.u./sec) ramp;
For the generator: Δf_{GT} =The frequency variation to the step signal .
Δf_{GR} = The frequency variation to the ramp signal.
ΔP_{ET}, ΔP_{MT} = the variation of the electrical and mechanical power for the step signal frequency .
ΔP_{ER}, ΔP_{MR} = the variation of the electrical and mechanical power for the ramp signal frequency

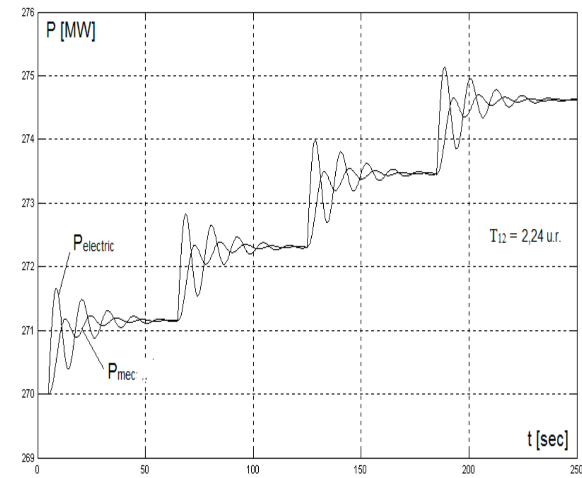


a) the electric and mechanical power variation T_{12}^1 =1,75 u.r. T_{12}^2 = 2,24 u.r.

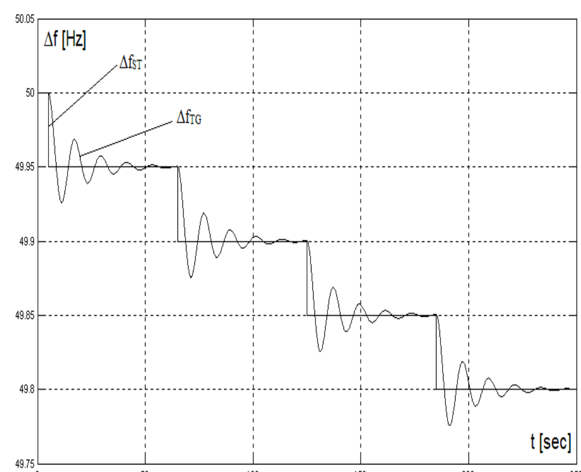


b) The step frequency variation 0,004 u.r.

Fig. 6 – The thermal generator response to the frequency step variation.
Δf_T = 0,2Hz (0,004u.r.) pentru $T_{12}^1 > T_{12}^2$



a) the variation of the electrical and mechanical power for Δf = 4 x 0,05 Hz



b) The generator frequency variation step disturbance Δf = 4 x 0,05Hz = 0,001u.r.

Fig. 7 – The primary control reserve mobilization to a frequency variation in four 50MHz level steps.
a) the electric variation and the mechanical power variation b) frequency variation

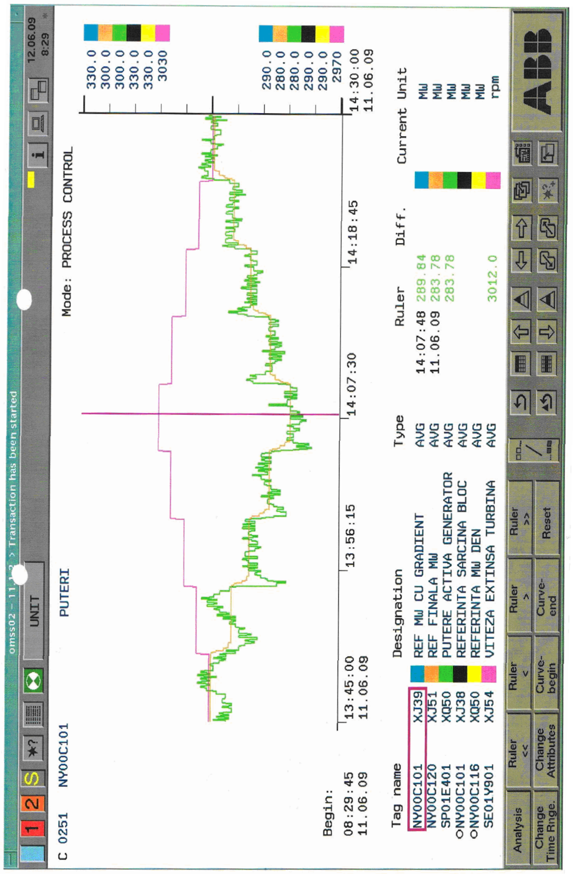


Fig. 8 – The qualification test in primary control group of 330 MW thermal CTE Turceni (Δf = 4 x 0,05Hz., in power regulation, the turbina lead)

The mathematical model for determining the equivalent transfer function is the generally insular one completed with the interconnection tie line, resulting the general model for an interconnected systems in radial network, as shown below (Fig. 9. a); b) ;Fig. 10. a); b); c).

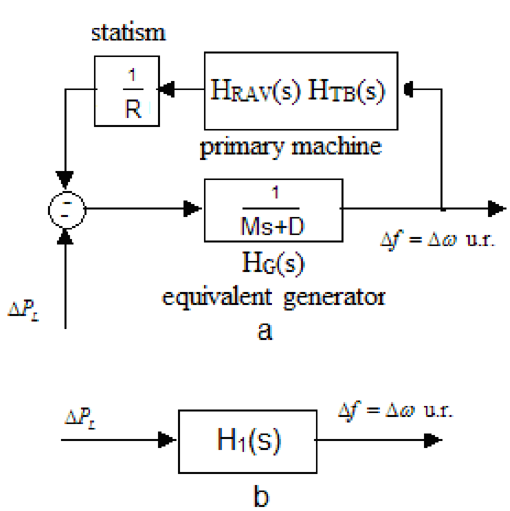


Fig .9 – The general insular mathematical model in primary control $\Delta P_L \cdot H_1(s) = \Delta f$

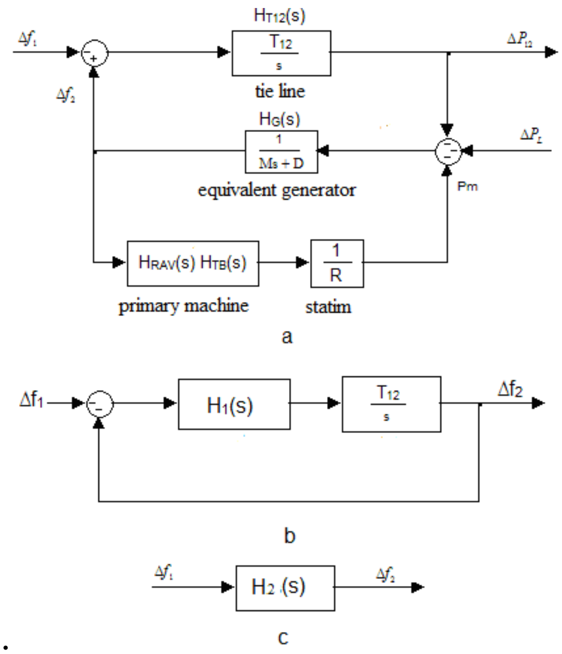


Fig. 10 – The mathematical model of the primary control in interconnected systems in radial network $\Delta f_1 \cdot H_2(s) = \Delta f_2(s)$

The equivalent transfer functions of the models (Fig. 8.si Fig. 9.) are :

$$H_1(s) = \frac{\Delta f(s)}{\Delta P_L(s)} = -\frac{H_G(s)}{1 + \frac{1}{R} \cdot H_G(s) \cdot H_{RAV}(s) \cdot H_{TB}(s)} \qquad (32)$$

and :

$$H_2(s) = \frac{\Delta f_2(s)}{\Delta f_1(s)} = -\frac{H_{T12}(s) \cdot H_1(s)}{1 + H_{T12}(s) \cdot H_1(s)} \qquad (33)$$

From the relations (27), (29), and the general data from tab. No. 4 introduced in the relations (32) and (33) will obtain the equivalent transfer function H2(s) for the termal generator interconnected with the European Power Sistem (EPS).

(the EPS is considered an infinite bus bars.) .

For $s = (j\omega)$ and $T_{12} = 1{,}75$ p.u..

We obtain the transfer functions $H_2(j\omega)$ and the corresponding Bode diagrams .(Fig. 11) :

$$H_{2T}(j\omega) = -\frac{3(j\omega)^4 + 190{,}6(j\omega)^3 + 738(j\omega)^2 + 473{,}2(j\omega) + 66{,}66}{15(j\omega)^6 + 953{,}8(j\omega)^5 + 3741(j\omega)^4 + 2972(j\omega)^3 + 1497(j\omega)^2 + 592{,}2(j\omega) + 66{,}66}$$

Note that : $H_{2T}(j\omega \to 0) = 1;\ f_1(j\omega \to 0) = f_2(j\omega \to 0)$

The Bode diagrams and the transfer function are performed in MATLAB according to the figure no. 11 :

```
>> a=[0 0 0 0 0 2];b=[0 1.5 95.3 369 236.6 33.33]
b =0    1.5000   95.3000  369.0000  236.6000   33.3300
>> num=conv(a,b)
num = 0         0         0         0         0         0    3.0000
190.6000  738.0000  473.2000   66.6600
>> c=[0 0 0 0 1 0];d=[15 953.8 3738 2781 758.6 119]
d =1.0e+003 *
   0.0150    0.9538    3.7380    2.7810    0.7586    0.1190
>> e=conv(c,d)
e = 1.0e+003 *
       0         0         0         0    0.0150    0.9538    3.7380
2.7810    0.7586    0.1190         0
>> den=e+num
den =1.0e+003 *
       0         0         0         0    0.0150    0.9538    3.7410
2.9716    1.4966    0.5922    0.0667
>> sys=tf(num,den)
Transfer function:
         3 s^4 + 190.6 s^3 + 738 s^2 + 473.2 s + 66.66
-----------------------------------------------------------------
15 s^6 + 953.8 s^5 + 3741 s^4 + 2972 s^3 + 1497 s^2 +
592.2 s + 66.66
>> bode(sys)
```

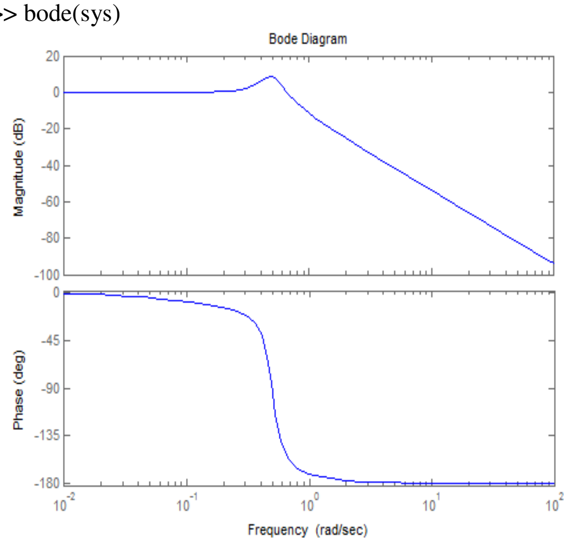


Fig. 11 – The Bode diagrams for the thermal generator P_n = 330MW infinit bus bars interconnected

$$\Delta f_2 \cdot H_{2T}(j\omega) = \Delta f_1$$

4. CONCLUSIONS

- The frequency diagrams show that the equipment have a characteristic of "low-pass filter" for frequency upper than 1Hz.

- The natural frequency of oscillation is[6] : $f_o = \sqrt{\frac{T_{12}}{M}} = \sqrt{\frac{T_{12}}{2H}} \in (0,1-0,7)\text{Hz} = (0,002-0,02)$ p.u.as can be seen in the simulations. The report between the constants T12 and M will influence both the amplitude and frequency oscillations of the angular speed / frequency and the power angle δ.

- The thermal generator behavior were satisfactory both in terms of duration required transient period (30 sec) and the dynamic frequency deviation, but the mechanical power oscillations due to the response of the speed regulator at frequency oscillations are inevitable in the absence of appropriate filtering.

- The sync. constant T12 influence the dynamic behavior of the thermal generator. If disturbance occurs in the infinite bus bars considered GCU (considered angular center) the oscillations amplitude and their frequency will be higher as the constant value increases. From here it can be concluded that the static stability of the machine decreases as it is downloaded.

The dynamic evolution of electric power represents at a different scale the dynamic evolution of power angle.

- The dynamic evolution of the frequency is at a different scale the dynamic evolution the angular speed.

- The thermal groups have behavior of a "low-pass filter" for frequency upper than 0.7 Hz exceeding their Inter-area oscillations (0.1 to 0.7Hz). [5]

- In order to damp the mechanical power fluctuations in the specific range 0.1 -0.7 Hz is required " an additional damping" of the mechanical with additional function PSS (power system stabilizer) for the automatic voltage regulator RAT [6].

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