Grid Frequency Control. Secondary Frequency Control Tuning taking into account Distributed Primary Frequency Control.

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***Abstract*—** A new method developed and applied to tune Secondary Control Loop (SCL) for grid frequency control is presented.

The presented method is based on an equivalent representation of all active distributed Primary Control Loop (PCL) in the grid for frequency control.

The characteristic of each PCL is associated to prime mover and its governors: Hydraulic, gas or steam.

The equivalent model of distributed PCL takes into account all active representative composition of PCL in the grid for each typified power flow (seasons, working/not-working day, peak/valley, morning/afternoon/night, etc).

By this way, each equivalent model of distributed PCL allows to find the best tuning of SCL for each typified power flow.

This method was applied to tune the SCL of Yacyretá, a hydraulic power plant with 20 Kaplan turbines of 155 MW each one.

Yacyretá is one of the power plants that have SCL in the "Sistema Argentino de Interconexión" (SADI), the largest power grid of Argentina.

***Index Terms*—** Frequency control. Governors. Primary Frequency Control. Secondary Frequency Control. Spinning reserve. Turbines.

I. NOMENCLATURE

AGC	Automatic Generation Control of a power plant
AJC	Automatic Joint Control of Electrical Power of a power plant
F	Frequency
F SP	Frequency Set Point
FPC:	Frequency Primary Control.
FSC:	Frequency Secondary Control
PE	Electrical Power
PM	Mechanical Power
PCL:	Primary Control Loop
SCL:	Secondary Control Loop.

II. INTRODUCTION

Imbalance between demand and generation gives rise to variations in the kinetic energy accumulated in the spinning masses of the whole grid, resulting in variations of frequency.

To keep generation and demand balanced, the coarse action is based on estimating or predicting the demand for the next hour and put in service the necessary generation.

Not predicted demand variations and/or untimely shutdowns of generators or of other equipment involved in grid operation may also alter the load-generation balance.

The goal of the frequency control is to keep demand and generation balanced at all times, by automatically producing the generation changes needed to achieve this balance.

The FPC aims to adapt quickly the generated power to the demand. This causes small changes in many units over the system.

For the FPC operation, it is not only necessary that governors work appropriately but also it is necessary to have immediate available spinning reserve. The aim of FSC is to ensure the reserve for the proper operation of FPC. The FSC is performed alternatively by one of three or four big hydraulic power plants. Yacyretá with 20 Kaplan turbines of 155 MW each is one of them.

This paper describes the utilized method to adjust the FSC of Yacyretá power plant.

III. GRID FREQUENCY CONTROL

Fig. 1 displays a simplified block diagram of the grid frequency control. This block diagram is only valid to obtain the mean value of grid frequency in the long term. The grid frequency control has the following variables: Electrical Power (PE), Frequency (F), Frequency Set Point (F SP) and Mechanical Power (PM) of generators.

The grid frequency control has the following blocks: Grid Load, Grid Spinning Masses, Distributed Primary Control Loop, Secondary Control Loop and Tertiary Control Loop.

A. Grid Load

Block "Grid Load" of Fig. 1 represents the total Electrical Power (PE) of grid loads.

B. Grid Spinning Masses

Block "Grid Spinning Masses" of Fig. 1 represents the rotating masses equation of the whole system.

C. Distributed Primary Control Loop

For short times, from a few seconds to several minutes, the active turbine governors react modifying turbines mechanical power to correct frequency grid when a frequency deviation takes place.

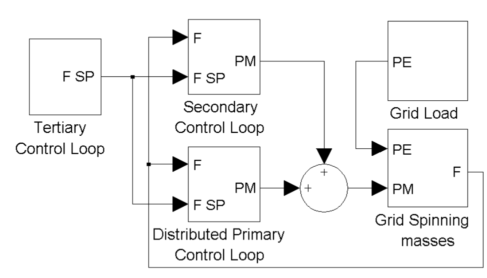

Fig. 1: Grid Frequency Control. Simplified Block Diagram.

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All governors are proportional control (P type) for its controlled speed/frequency inputs.

These P type controls are not able to cancel frequency error. Because of that, a small grid frequency error is still present after the action of governors.

This kind of frequency control action is referenced hereinafter as Frequency Primary Control (FPC).

D. Secondary Control Loop

For long times, several minutes time interval, another control system reacts until obtaining a null frequency error.

Only one system control of this kind must be active at the same time in the grid system, since this control must be integral type control (I or P+I type).

This kind of frequency control action is referenced hereinafter as Frequency Secondary Control (FSC).

Each turbine performing FPC recovers its initial spinning reserve when the FSC cancels the grid frequency error.

E. Tertiary Control Loop

The Grid Dispatch Center manually changes the grid frequency set point hourly. This set point is introduced in all active governors for FPC and in the FSC.

By this way, daily average grid frequency is equal to nominal grid frequency.

This kind of frequency control action is referenced hereinafter as Frequency Tertiary Control.

Generator Spinning Reserve

In a generator, the spinning reserve is the maximum amount of mechanical power variation allowed (by governor o by physical limits).

Grid Spinning Reserve

The grid spinning reserve is the sum of whole generators spinning reserve.

Having more grid spinning reserve available for the same demand means to generate the same amount of power with more generators.

The smaller the available grid spinning reserve is, the higher the probability that the grid spinning reserve will be exhausted by unpredicted variations.

In addition, it increases the probability that the consequent action of under-frequency relays will produce load shedding.

There are several methods to define grid spinning reserve level. In [1] the method applied in Argentina is presented. In [2] a similar mechanism is also presented.

In Argentinian grid, the spinning reserve level for FPC varies hourly and has an average value of 3 % of total dispatched power. The grid spinning reserve level for FSC is the same than for FPC.

Besides, the Grid Dispatch Center distributes the grid spinning reserve for FPC in all generators with FPC. Maximum spinning reserve devoted to any generator is 5 % for gas/steam turbines and 10 % for hydraulic turbines.

Also, the Grid Dispatch Center devotes the entire grid spinning reserve level for FSC to the power plant or to the set of power plants in charged of performing FSC.

IV. Equivalent Model for Distributed Primary Control Loop

In order to tune a FSC it is necessary to know either the dynamic characteristic or transfer function of the complete Primary Control Loop.

A. Simplified Grid Masses Equation

Each generator j has the following small signal spinning masses equation:

$$2 * H_j * \omega_j * \frac{d\,\omega_j}{dt} = P_{Mj} - P_{Ej} - D_j * (\omega_j - 1) \qquad (1)$$

Where: P_{Mj} is the mechanical power [pu], P_{Ej} is the electrical power [pu], H_j is the generator inertia [s], ω_j is the rotor angular velocity or the rotor speed (equivalent to the frequency when generator is connected to the grid) [pu], and D_j is the damping coefficient [pu/pu].

The speed ω_j of each unit could be separated into a slow variation component (periods of some seconds or more) and a fast variation component (periods up to some seconds).

The fast variation component take into account the kinetic energy interchange between units and constitute the electromechanical oscillations.

The slow variation component ($\overline{\omega}$) are associated with changes in the kinetic energy accumulated in all the rotating masses. These variations are the same for all units.

For the analysis of the adjustment of primary and secondary control loops, only the slow components are considered so it is valid to consider:

$$\omega_j = \overline{\omega} \quad \text{and} \quad \frac{d\omega_j}{dt} = \frac{d\overline{\omega}}{dt} \qquad (2)$$

Multiplying by the generator MVA base (MVA_j), adding all the grid generators and dividing by the sum of all generator MVA bases:

$$\frac{\sum_{j=1}^{N} 2 * H_j * MVA_j * \omega_j * \frac{d\Delta\omega_j}{dt}}{\sum_j MVA_j} = \frac{\sum_{j=1}^{N} MVA_j * P_{Mj} - \sum_{j=1}^{N} MVA_j * P_{Ej} - \sum_{j=1}^{N} MVA_j * D_j * \left(\omega_j - 1\right)}{\sum_{j=1}^{N} MVA_j} \qquad (3)$$

Replacing (2) in (3) and defining the following variables expressed in per unit of total generators MVA:

Average Inertia: $$H = \frac{\sum_{j=1}^{N} MVA_j * H_j}{\sum_{j=1}^{N} MVA_j} \qquad (4)$$

Average Damping: $$D = \frac{\sum_{j=1}^{N} MVA_j * D_j}{\sum_{j=1}^{N} MVA_j} \qquad (5)$$

Total Mechanical Power: $$P_M = \frac{\sum_{j=1}^{N} MVA_j * P_{Mj}}{\sum_{j=1}^{N} MVA_j} \qquad (6)$$

Total Electrical Power:

$$P_E = \frac{\sum_{j=1}^{N} MVA_j * P_{Ej}}{\sum_{j=1}^{N} MVA_j} \qquad (7)$$

The equation (3) may be rewritten as:

$$2 * \overline{\omega} * \frac{d\overline{\omega}}{dt} * H \cong P_M - P_E - D * (\overline{\omega} - 1) \qquad (8)$$

B. Distributed Primary Frequency Control Model. Proposed Approximation Method

The proposed approximation method to find distributed Primary Control Loop transfer function is based on equivalent models of thermal and hydraulic units.

Fig 2 shows the equivalent models of thermal and hydraulic units respectively.

The models are composed by a permanent droop and some transfer functions.

The approximation method begins with the simulations of a small frequency grid transient with the whole representation of the grid.

This simulation is performed with a program used for power system dynamic studies (PSS/E of Siemens), using Dynamic Data Base of the grid. In Argentina, this Data Base has been verified by conducting normalized tests [3-7] in almost all power plants.

The mechanical power outputs from simulations are typified as: Thermal (P_{MT}) with active PCL, Hydraulic (P_{MH}) with active PCL, and Fixed (P_{MF}) with PCL out of operation.

The mechanical powers of each kind are added to obtain the output vectors P_{MT}, P_{MH}, P_{MF}.

The average Grid Frequency ($\overline{\omega}$) is obtained by adding the individual speed of each operating generator and dividing by the number of operating generators (N). The Grid Electric Power (P_E), the Total Generators rating (MVA), the Average Grid Inertia (H) and Damping (D) are also calculated.

The variables obtained in this way are referenced as "actual" hereinafter.

The performed simulations take into account all representative composition of active PCL in the grid for each typified power flow (morning / afternoon / night, working / not working day, seasons, etc).

The standard models of both thermal and hydraulic units shown in Fig. 2 were adjusted to fit the output "actual" variables P_{MT} and P_{MH} of the complete model, using $\overline{\omega}$ as input.

As an example, Table I shows the equivalent model parameters, for peak and valley cases.

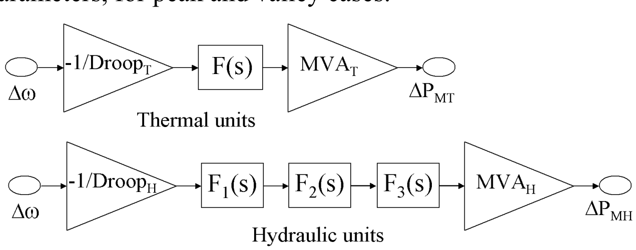

Fig. 2: Equivalent models of thermal and hydraulic units.

Table I: Equivalent models parameters.

	Parameter	Peak	Valley
Hydraulic	$1/Droop_H$	20.5	25.9
	$F_1(s)$	$\frac{-1s+1}{0.1s+1}$	$\frac{-2.5s+1}{0.1s+1}$
	$F_2(s)$	$\frac{1.5s+1}{12s+1}$	$\frac{0.5s+1}{4.5s+1}$
	$F_3(s)$	$\frac{35s+1}{75s+1}$	$\frac{10s+1}{61s+1}$
Thermal	$1/Droop_T$	18.2	23.3
	$F(s)$	$\frac{8s+1}{11.1s^2+12.7s+1}$	$\frac{5.6s+1}{12.6s^2+11.7s+1}$

With these equivalent models of distributed PCL a new set of output variables, called hereinafter "reduced", were obtained by simulations in the SIMULINK program.

Fig. 3 and Fig. 4 show a comparison between the "actual" P_{MT} and P_{MH} variables and the same "reduced" variables obtained as the output of the SIMULINK models. The simulations were performed in an open-loop condition.

Mechanical powers are expressed in per unit [pu] of total generators MVA in the grid.

The "reduced" PCL consists of three independent blocks (PCL hydraulic, PCL thermal and Fixed Mechanical Power) which combine their outputs to obtain the "reduced" Total Mechanical Power ($P_M = P_{MT} + P_{MH} + P_{MF}$).

Fig. 5 and Fig. 6 show a closed-loop simulation to obtain $\overline{\omega}$ and Total Mechanical Power (P_M) from the "actual" and "reduced" variables.

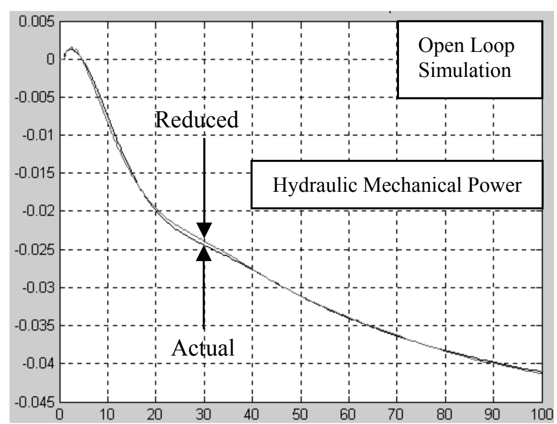

Fig. 3: PCL Model. "Actual" and "Reduced" P_{MH}.

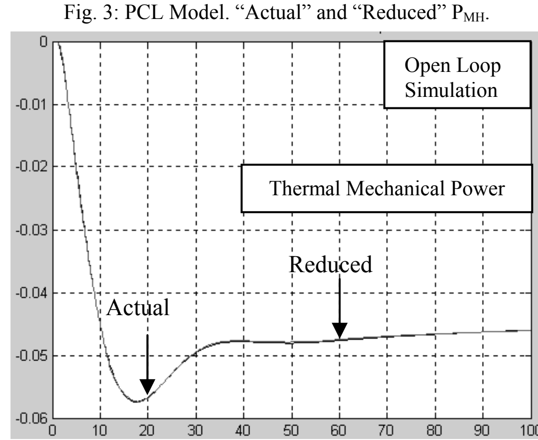

Fig. 4: PCL Model. "Actual" and "Reduced" P_{MT}.

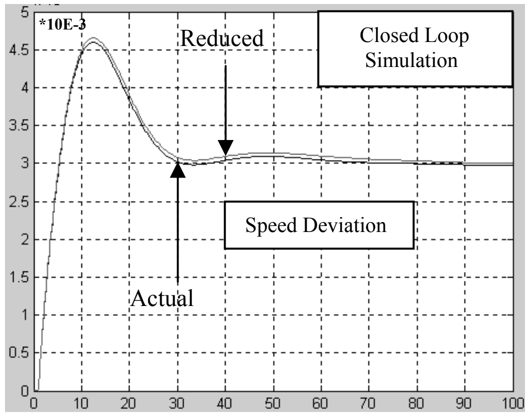

Fig. 5: PCL Model. "Actual" and "Reduced" $10^{-3} * \overline{\Delta\varpi}$.

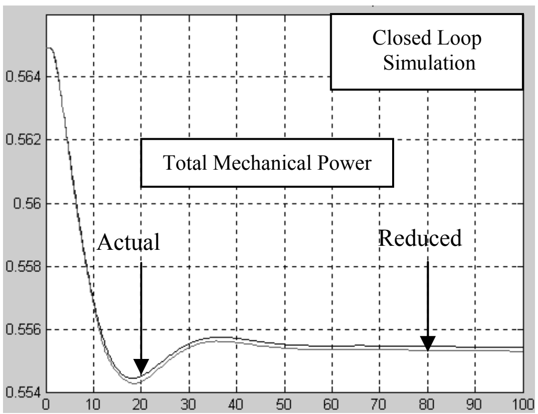

Fig. 6: PCL Model. "Actual" and "Reduced" $P_M = P_{MT} + P_{MH} + P_{MF}$.

Speed Deviation is in per unit of nominal speed and Total Mechanical Power (P_M) is in per unit of total MVA in the grid. The perturbation was the disconnection of an industrial load.

These simulations were made without the PCL corresponding to Yacyretá power plant. By these simulations it was possible to know the equivalent grid PCL for several representative states of both grid generation and load.

V. Secondary Control Loop. Modeling and Tuning

A. *Introduction*

Fig. 7 shows a simplified block diagram of SCL when Yacyretá power plant is performing SFC.

The blocks shown are: Grid, Automatic Generation Control (AGC) of Yacyretá Power Plant, Yacyretá Units with PCL and Yacyretá Units without PCL.

The Grid block contains grid spinning masses equation and PCL (hydraulic and thermal) and fixed mechanical power of the rest of generator in the grid (excluding Yacyretá generators).

This block receives: Mechanical Power from Yacyretá generators without (PM1) and with (PM2) PCL and frequency set point (F SP). The grid frequency (F) is the output of this block. The blocks Units with PCL and Units without PCL represent the corresponding generators in Yacyretá power plant.

These blocks receive: power set points (P1 SP and P2 SP respectively), frequency set point (F SP) and grid frequency (F). The corresponding mechanical powers (PM1 and PM2) are the outputs of these blocks.

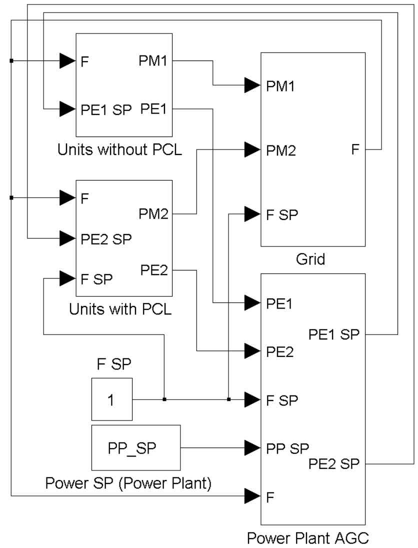

Fig. 7: Power Plant SCL. Simplified block diagram.

The block Power Plant AGC represents the Electrical or Active Power Joint Control (AJC) of Automatic Generation Control (AGC) of Yacyretá power plant. The AGC is a PROKON-SLX type from Siemens.

The AJC determines the corresponding power set point for each generator unit of Yacyretá. The AJC function is to match the electrical power delivered by power plant to the power set point (PP SP) of the power plant, plus the correction for FSC.

The AJC determines the individual power set points using also the electrical powers PE1 and PE2 respectively delivered by each group of generators.

The AJC modifies the individual power set points (PE1 SP and PE2 SP) with a SCL when it is active.

The SCL is basically a P+I type control. The SCL generates an error signal with the difference between the measured grid frequency (F) and the grid frequency set point (F SP). The measured grid frequency (F) is obtained as the output of a moving average digital filter of 60 seconds. The input of this filter is taken from the average of three different frequency transducers, which are sampled every 5 seconds.

The calculation time of P+I controller is 30 seconds and its output is retained with a Zero-order hold every 30 seconds.

The retained output of P+I controller is send to the Stepping Control. This block is an integrator with gradient limiter (output gradient limited to a maximum, positive or negative). The calculation time of this block is 30 seconds.

The output of this block is divided by the number of power plant generators with AJC in operation. The previously conformed signal is retained with a Zero-order hold with 60 seconds of cycle time. This hold output is sent to each generator with AJC in service, and it is used as the electrical power set point (PE SP) for the governor.

A simplified block diagram of the SCL is shown in Fig. 8.

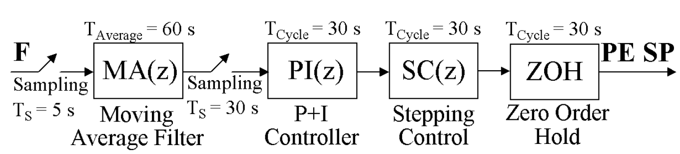

Fig. 8: Simplified block diagram of SCL.

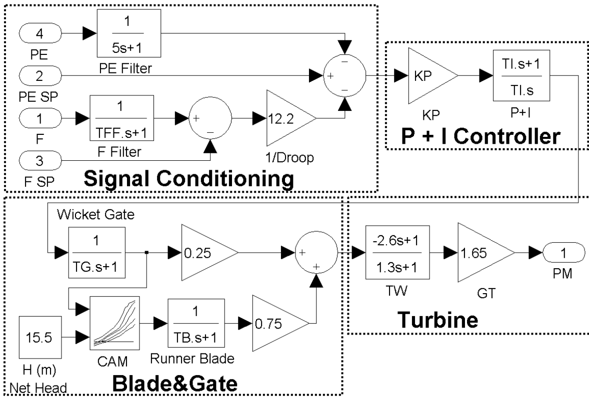

Fig. 9: Linearized model for PCL tuning.

B. Linearized Model of Yacyretá Primary Control Loop

Fig. 9 shows the linearized model of Yacyretá PCL. This model receives: electrical power (PE), electrical power set point (PE SP), grid frequency (F) and grid frequency set point (F SP). The model output is the mechanical power (PM). The input PE was connected to the output PM for the analyses carried out. The model is composed by four main parts: Signal Conditioning, P+I Controller, Blade&Gate and Turbine.

Fig. 9 shows the numerical values of model parameters that have not been readjusted meanwhile Table II presents the parameters that have been readjusted together with the original ones.

Table II: Readjusted parameters of Yacyretá PCL.

Parameter	Original	Readjustment 1	Readjustment 2
TFF	1	1	0.1
KP	0.237	0.079	0.128
TI	4	15	10
TG	10	4	0.4
TB	20	2	0.25

C. Secondary Control Loop. Tuning Procedure

Fig. 10 shows the model utilized to tune SCL. The transfer functions involved are:

The PCL Hydraulic block, the PCL Thermal block, the grid spinning masses equation (loop formed by integrator, system Inertia H and system Speed Damping D), and PCL and SCL Yacyretá blocks. PCL Yacyretá block represents the primary control action due to frequency variations.

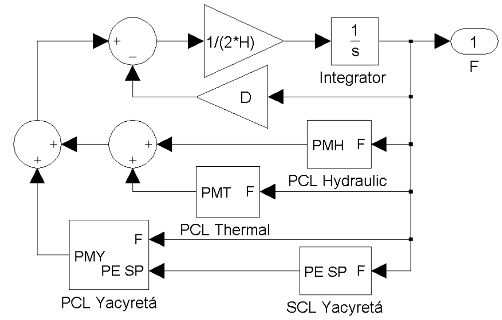

Fig. 10: Complete model for SCL tuning.

SCL Yacyretá block (see details in Fig. 8) represents the secondary control action that modifies the power set point (see Fig. 9) of Yacyretá units in AJC.

With model of Fig. 10 analyses were made in the frequency domain (Bode diagrams) for all typified grid load states previously mentioned.

Fig. 11 and Fig. 12 show Bode diagrams, module and phase, for the Open Loop transfer function of grid PCL (involving Rotating masses, PCL Hydraulic, PCL Thermal and PCL Yacyretá), obtained with Original and Readjustment 1 parameters of P+I Controller respectively (see Table II).

Fig. 11 and Fig. 12 were performed in grid valley condition and with 20 units of Yacyretá with PCL active.

The curve marked with the small black square of Fig. 11 and of Fig. 12 corresponds to a linearised model of Blade&Gate valid for small signal perturbation in the time domain.

The other curve of Fig. 11 and of Fig. 12 corresponds to a linearised model valid for large signal perturbation in the time domain.

The grid PCL in grid valley condition, with 20 units of Yacyretá with PCL active and with Original parameters is unstable. However, grid PCL in such a condition becomes stable with Readjustment 1 of Yacyretá.

The total transfer function is the product of the following transfer functions: closed loop of grid PCL, SCL, and the transfer function from PE SP to PM of Yacyretá PCL.

The Open Loop Bode diagram of the total transfer function for different operating conditions is shown in Fig.13 to Fig. 16.

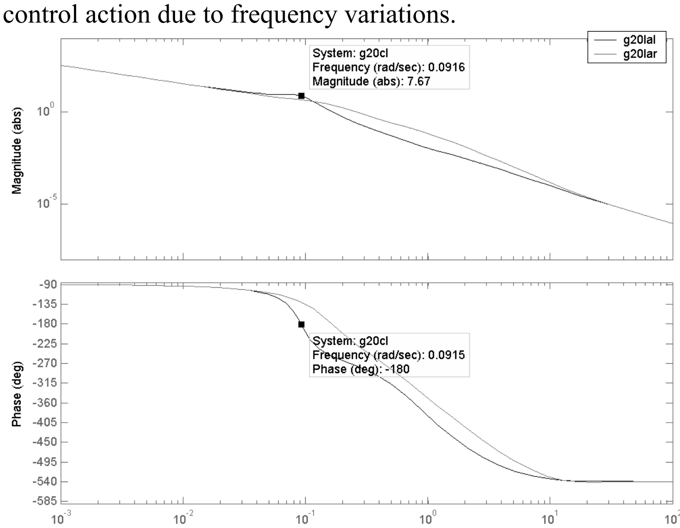

Fig. 11: Open loop Bode diagram. Original PCL (unstable).

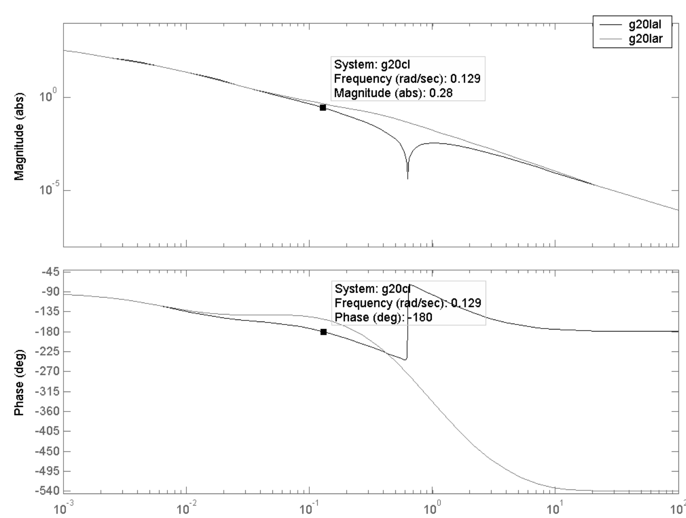

Fig. 12: Open loop Bode diagram. PCL Readjustment 1 (stable)

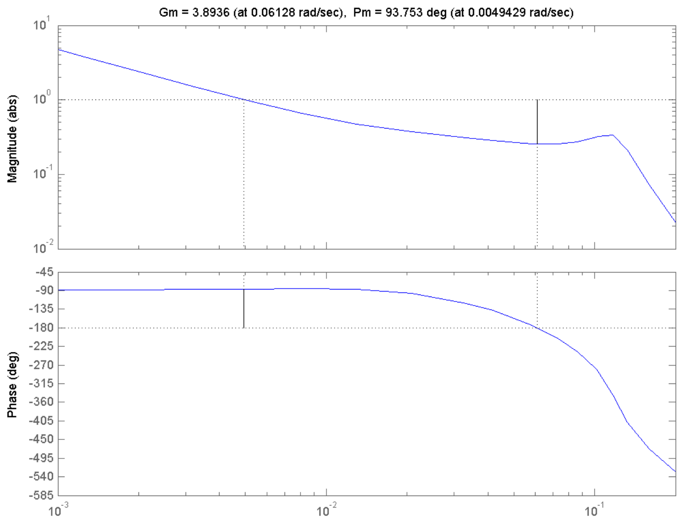

Fig. 13: Valley condition. 5 units with PCL active. PCL Original.

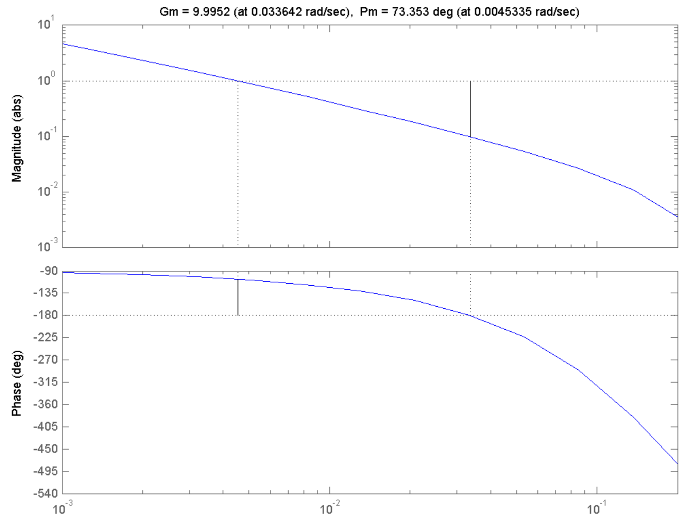

Fig. 14: Valley condition. 5 units with PCL active. PCL Readjustment 1.

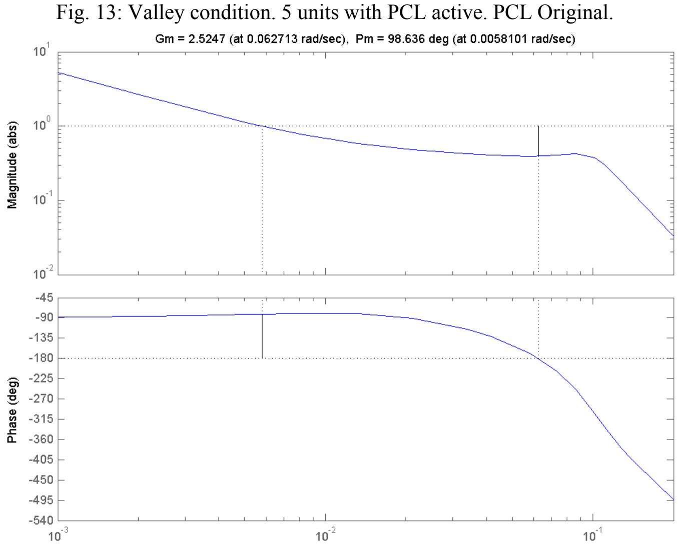

Fig. 15: Peak condition. 5 units with PCL active. PCL Original.

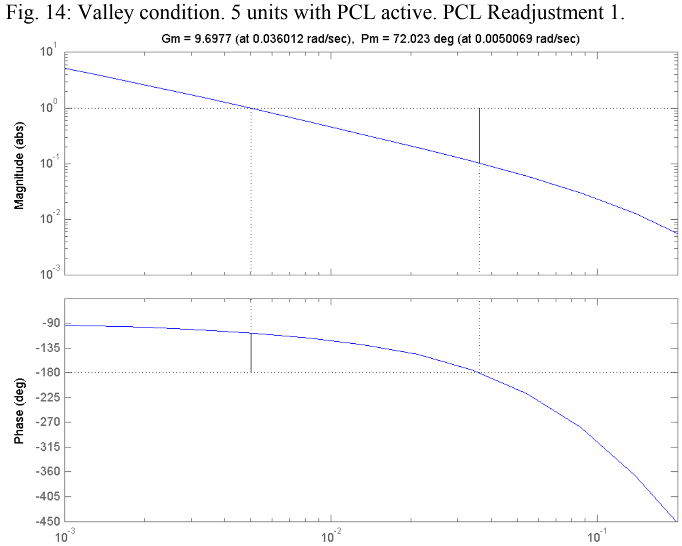

Fig. 16: Peak condition. 5 units with PCL active. PCL Readjustment 1.

Major conclusions extracted from the studies made about SCL adjustments are:

- It is necessary to have a correct tuning for all distributed Primary Control Loop before tuning SCL.
- The integral action time constant of P+I control for SCL does not depend of grid load states analyzed. This time constant was 60 seconds.
- The gain of proportional action for P+I control for SCL depends strongly on grid load states analyzed. This gain was 260 MW/Hz and 1050 MW/Hz (≅1/4 relation) for valley and peak conditions of grid load respectively.

The grid load used for the analysis was 17300 MW and 7700 MW for peak and valley conditions respectively.

D. Simulations in the time domain

Simulations in the time domain were made with a detailed model of Yacyretá power plant.

A load reduction of 1% of grid load was used as a perturbation in the simulations.

All the 20 generators in Yacyretá were in AJC, 10 with active PCL and 10 with not active PCL.

Fig. 17a and 17b show the simulation results for Readjustment 1 (see Table II) of PCL and 1035 MW/Hz of proportional gain in the SCL.

Fig. 18a and 18b show the simulation results for Readjustment 2 (see Table II) of PCL and 690 MW/Hz of proportional gain in the SCL.

Parts a) of Fig. 17 and Fig. 18 show the grid frequency and the Mechanical Power deviation for: all generators in the grid, all PCL in the grid (hydraulic, thermal and generators of Yacyretá with PCL) and all Yacyretá generators.

Parts b) of Fig. 17 and Fig. 18 show the following variables of Yacyretá: the Electrical Power set point of power plant, and the Mechanical Power deviation in Yacyretá of generators without and with active PCL, and of the sum of the Mechanical Power of all power plant generators.

The analyzed case is characterized by:

- 17310 MW for all generators in the grid.
- 8869 MW for all generators with PCL in the grid.
- 1794 MW for SCL in Yacyretá power plant
- 897 MW for generators with and without active PCL in Yacyretá power plant

Parts a) of Fig. 17 and Fig. 18 show the Mechanical Power deviation provided by generators with PCL immediately after the grid frequency perturbation.

For short times, the grid frequency deviation is reduced by the action of PCL.

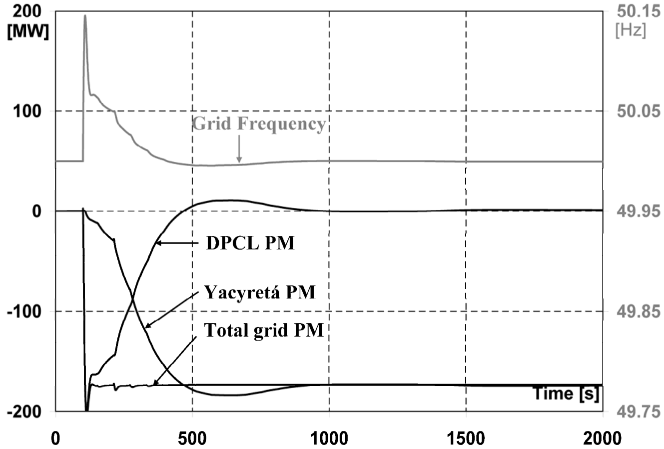

Fig. 17.a. SCL action with Yacyretá PCL Readjustment 1.
Mechanical Powers in left scale. Frequency in right scale.

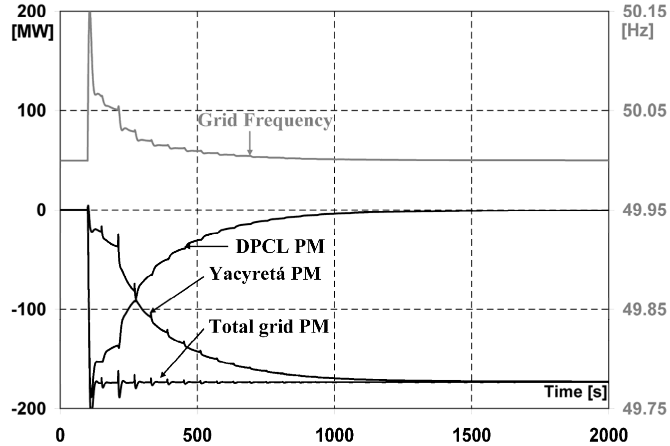

Fig. 18.a. SCL action with Yacyretá PCL Readjustment 2.
Mechanical Power in left scale. Frequency in right scale.

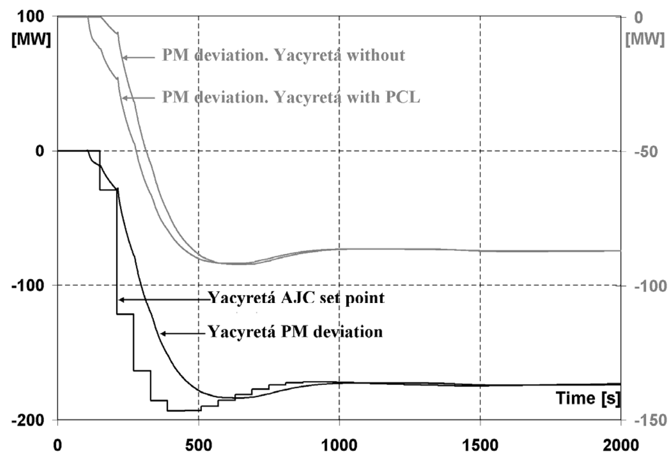

Fig. 17.b. SCL action with Yacyretá PCL Readjustment 1.
Lower curves in left scale. Upper curves in right scale.

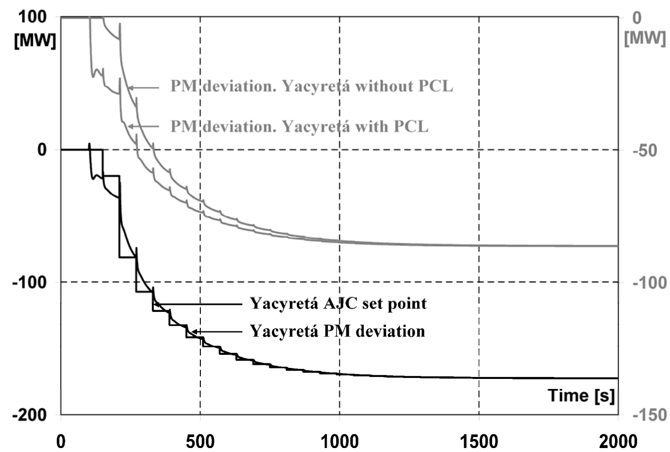

Fig. 18.b. SCL action with Yacyretá PCL Readjustment 2.
Lower curves in left scale. Upper curves in right scale.

For long times, Yacyretá power plant decreased its Mechanical Power due to the action of its SCL and, consequently, all generators with PCL – except for those belonging to Yacyretá - recovered their initial Mechanical Powers and initial spinning reserves.

Finally, the grid frequency recovered its initial value and Yacyretá power plant reduced its Mechanical Power in the same amount as the load decreased.

Parts b) of Fig 17 and Fig 18 show the Mechanical Power deviation provided by generators inside the Yacyretá power plant. It can be seen that generators with active PCL initially reacted to the frequency perturbation.

For long times and due to the action of its SCL, all power plant generators decreased their Mechanical Power in the same way to reach finally the same Mechanical Power deviation value.

Also it can be seen that the evolution of the Mechanical Power of power plant follows the evolution of the Power set point of the power plant.

Comparing Fig 17.b and Fig. 18.b it can be seen a better SCL performance in the second one.

This fact is due to a better tuning in both the PCL and SCL of Yacyretá power plant.

VI. Conclusions

The analyses reported allowed the following conclusions about the procedure for tuning control loops for frequency control:

- A simplified procedure for analysis and tuning of SCL was presented.
- The procedure is based on the determination of equivalent for PCL, typifying equivalent PCL for hydraulic and thermal prime movers and their governors.
- This procedure is valid for small signal analyses, when spinning reserve for PFC or SFC is not exhausted.
- Examples of application of this procedure over the major grid in Argentina were presented.
- With this simplified model it was possible to tune the SCL located in the major power plant of the grid.
- The tuning for SCL takes into account several compositions of generation and demand on the grid.
- Simulations with this model were presented.
- Simulations showing the corresponding behaviors of PCL and SCL located in the power plant under analyses for different tuning were presented.

VII. ACKNOWLEDGEMENTS

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