Combined Cycle Plants: Models and In-Situ Reliability Tests

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Abstract: This paper presents models of Boiler and Steam Turbine of combined cycle plants that can be used with any type of Gas Turbine models for grid dynamics studies. These models were obtained through a review of characteristics of large steam turbine and heat recovery boilers that define the behavior of combined cycle plants. Also is presented a Gas Turbine model of a combined cycle plant that was validated by tests developed and applied to evaluate reliability of combined cycle plants that are being installed in Argentinean electric system. Reliability test goals are the behavior characterization of combined cycle plants during large systems disturbances.

Keywords: Combined Cycle Plants - Frequency - Frequency Test Waveform – Gas Turbine - Heat Recovery Boiler - Steam Turbine - Governor - Models.

I. INTRODUCTION

Two isolated parts compose the Argentinean electric system, the biggest one named "Sistema Argentino de Interconección" or SADI in the north, and the smallest one named "Sistema Eléctrico Patagónico Interconectado" or SEPI in the south.

Control and supervision, from the technical point of view, and the management of transactions between companies were assigned to Wholesale Electric Market Managing Company (CAMMESA), whose board all Agents form and whose chair is held by a State organization.

In the last years, the installed number of large gas turbines alone or in combined cycles has been increased remarkably and will be over 30% of installed power in a couple of years.

In first term, this growing generated the necessity of reliability operation of these units, especially when large frequency dips or sustained frequency falls happens in the electric system. In second term, there is necessary a correct modeling of this type of units for grid stability studies.

Technical Procedures were updated by CAMMESA to take into account operation reliability of combined cycle plants and large gas turbines [1].

II. COMBINED CYCLE PLANTS

In [2] there is a very good description of combined cycle plants configurations, operations and models.

A) CONFIGURATION

In Argentinean electric system almost all combined cycle plants are multi-shaft kind, particularly those of greatest power. As a general rule, the exhaust heat of each gas turbine is enough to feed a steam turbine of near a half of its own power.

Majority of combined power plants has two gas turbines and one steam turbine, and each turbine drives a similar power generator.

Several of them have additional fires at boilers. Only a few has steam extraction for process use.

Few plants have damper on the exhaust gas that allows operating the gas turbines non-coupled from steam turbine (open cycle). Some of them have steam by-pass to condenser that allows operation of the gas turbines to reduced powers when there is some trouble in the steam turbine.

B) OPERATION

Gas Turbine

Gas turbines are normally operated at a few percents below of their base load to have enough spinning reserve for primary frequency regulation. At base load the output is limited by the maximum allowed temperature at turbine inlet.

At this operation point the guide vanes are full open and has not effect on turbine temperature, being base load operation strongly depending of ambient temperature and compressor speed. Inlet turbine temperature is proportional to a corrected exhaust temperature and this last temperature controls fuel flow.

Steam Turbine

At stationary state, steam turbine consumption follows exactly the steam production. Heat on exhausted gas turbine output fixes this steam production.

Steam turbine can operate: with the regulating valves fixes, so that steam pressure varies as steam production varies; or with regulating valves position controlled to maintain constant the pressure up-stream that valves.

In both cases the speed governor is not controlling regulating valves. Although very fast changes of gas turbine power produces fast changes in drums levels, steam turbine power varies more slowly than those of gas turbine, due to very large storage volumes in drums and piping.

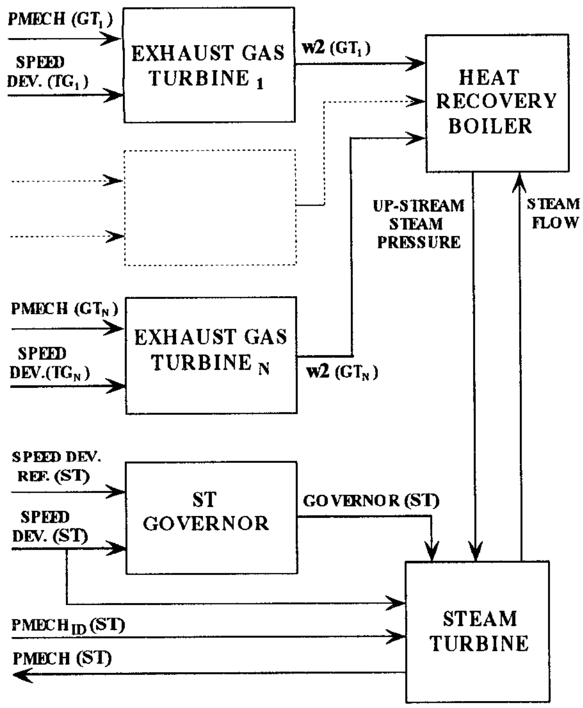

Fig. 1. Boiler and Steam Turbine. Model block diagram.

C) BOILER AND STEAM TURBINE MODEL

Model described herein has been developed as a User Model for stability program PSS from PTI Inc., because this program is used by CAMMESA.

This model can be used with any type of gas turbine models or any combination of them, because it is coupled to gas turbine models trough the Mechanical Power and Speed Deviation.

In **Fig. 1** is a block diagram of the Boiler and Steam Turbine model showing the relations between each part?

Boiler model

Its is common for each boiler to have high, intermediate and low-pressure drums.

There may be high and intermediate pressure evaporators, and may be regulating valves to control pressure in the intermediate or low-pressure drums. As a consequence there is not a single steam flow applied to steam turbine.

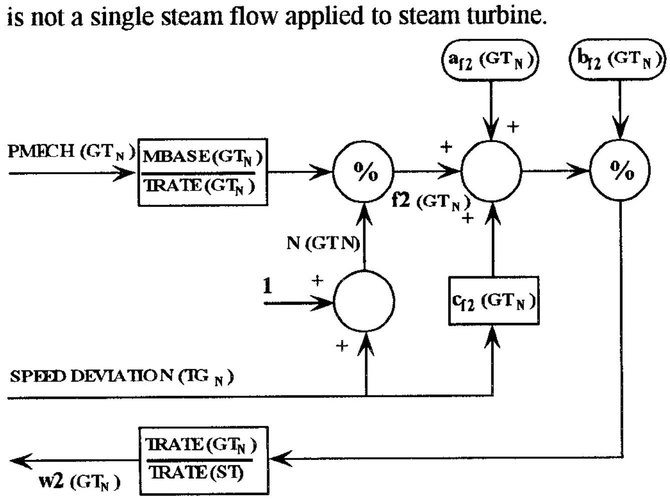

Fig. 2. Exhaust Gas Turbine model.

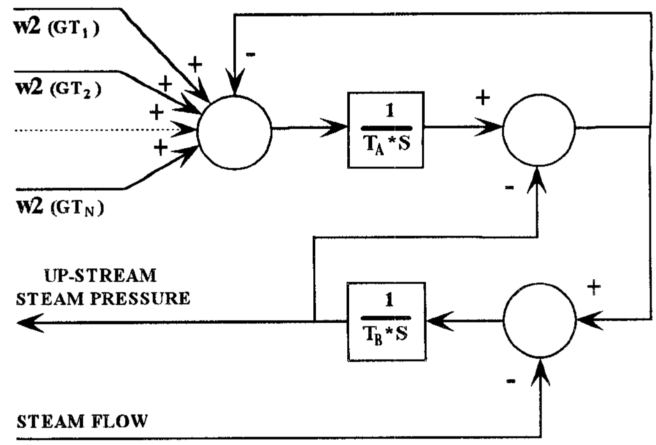

Fig. 3. Heat Recovery Boiler model.

Due to the slow boiler dynamic compared with the grid dynamic behavior, it is not necessary to reproduce boiler in details. In **Fig. 2** is the model of Exhaust Gas Turbine. Inputs are the Mechanical Power and the Speed Deviation from one generic gas turbine.

Output named w2 and rated at steam turbine power, feed the input of heat recovery boiler.

In this way the model estimates heat in exhausted gas from gas turbine, and makes a thermal coupling between steam turbine and gas turbines.

In the actually model version it is possible to couple two gas turbine to steam turbine, but is very easy to increase that number.

In **Fig. 3** is the model of Heat Recovery Boiler. Inputs are all the outputs from model of Exhaust Gas Turbine. Steam consumption is also inputted. Output is the Up-Stream Steam Pressure.

It is possible to take into account additional fires in the model in a very easy form, summing at boiler output the additional steam production.

Steam Turbine Governor model

In **Fig. 4** is the model of Steam Turbine Governor. Inputs are the speed deviation and the speed reference. Output could be used to control regulating valves.

Steam Turbine model

In **Fig. 5** is the model of Steam Turbine. Model reproduces the principal features of steam turbine behavior but not internal details. Inputs are the Up-Stream Steam Pressure, the Speed Deviation, the Governor Output and the Initial Deviation of Mechanical Power.

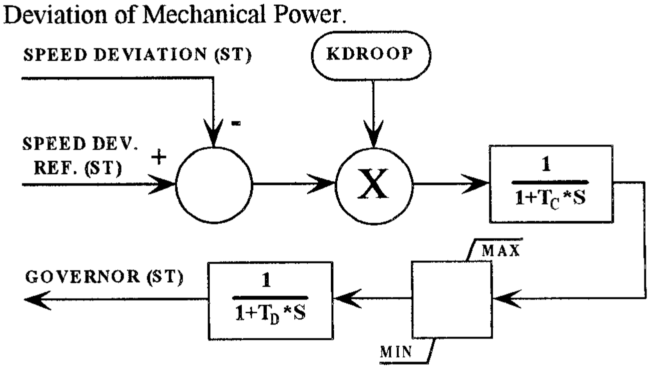

Fig. 4. Steam Turbine Governor model.

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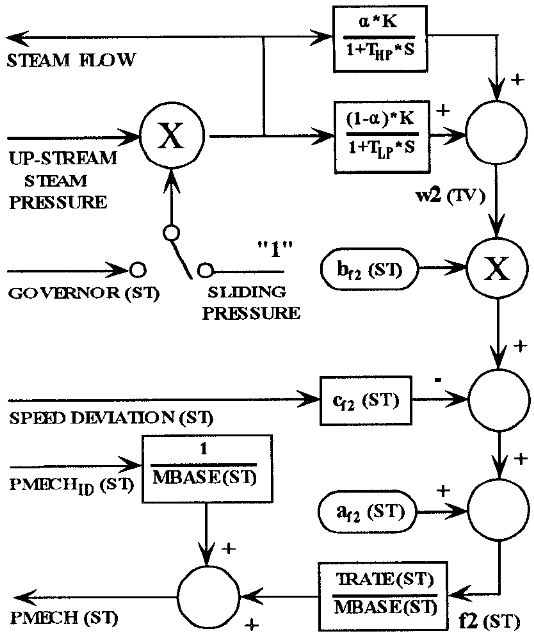

Fig. 5. Steam Turbine model.

This last input take into account as a constant, the small difference in power flow running between dispatched powers of gas and steam turbines against the same variable of steam turbine obtained with the model for dynamic running.

Model outputs are the Mechanical Power and the Steam Flow (steam consumption).

Like steam plants with fired boiler there are several control modes, but it is not necessary to cover all them in the model.

It is possible to disable the governor with the selector switch. In this way speed governor is not controlling regulating valves.

Only sliding pressure mode is present in model, but is easy to add others modes like pressure control, which can be inputted through same selector switch.

D) GAS TURBINE MODEL

For an adequate modeling it is necessary to take into account, with some details, operations of temperature control.

At low loads the guide vanes are open at its minimum value, being airflow non-load dependent and temperature raises almost linearly with turbine power until temperature reaches its maximum value.

Then, as output power increases, the guide vanes begin to open increasing airflow and taken temperature control by this way.

Most critical temperature is located at turbine inlet. Ratio between exhaust and critical temperature increases as turbine power increases.

This critical temperature is calculated trough pressure ratios along compressor and is controlled by decreasing temperature reference.

When guide vanes are full open it has not control of airflow and consequently of temperature. Critical temperature is controlled by fuel flow at this operating point.

Maximum fuel flow depends of ambient temperature and of compressor speed when turbine output is limited by temperature. This operation mode is called Base Load.

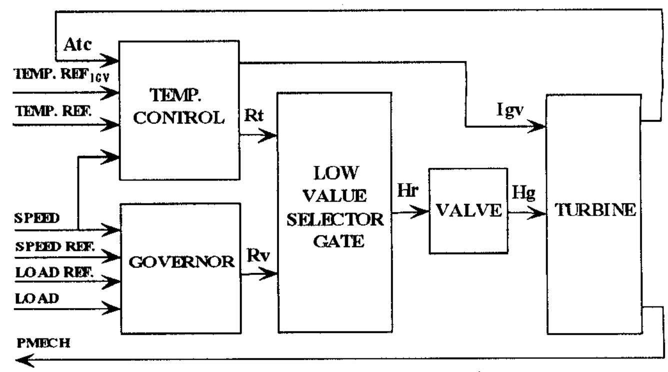

Fig. 6. Gas Turbine. Model block diagram.

Dependence of Base Load with ambient temperature is well knows and easy to verify in normal operating conditions. Instead, dependence of Base Load with compressor speed is knows trough data design and not easy to obtain or to verify by tests made in operating conditions.

However in Argentinean electric system, as a rule of thumb, there are frequency dips of 0.5 Hz daily, of 1 Hz weekly, and more than 1 Hz monthly.

If such events are acquired, triggering the records with these frequency dips, it is possible to gather data to verify such dependence.

Model described herein has been developed to describe the behavior of gas turbines of combined cycles when sudden and deeps frequency dips happens in an electric system.

This model corresponds to V94.2 Siemens gas turbines.

In **Fig. 6** is a block diagram of Gas Turbine model showing relations between each part.

Outputs from Temperature Control and Governor compete to control fuel valve trough a Low Value Selector Gate, gaining the control the most restrictive signal.

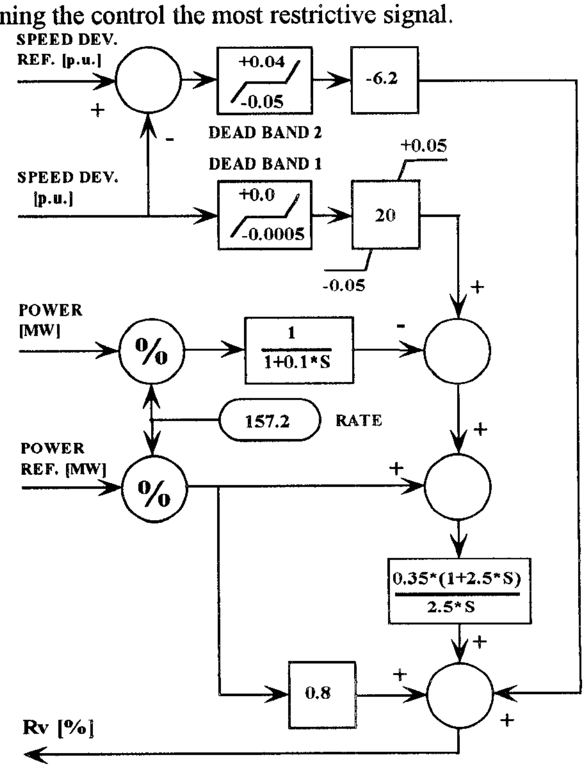

Fig. 7. Gas Turbine Governor model.

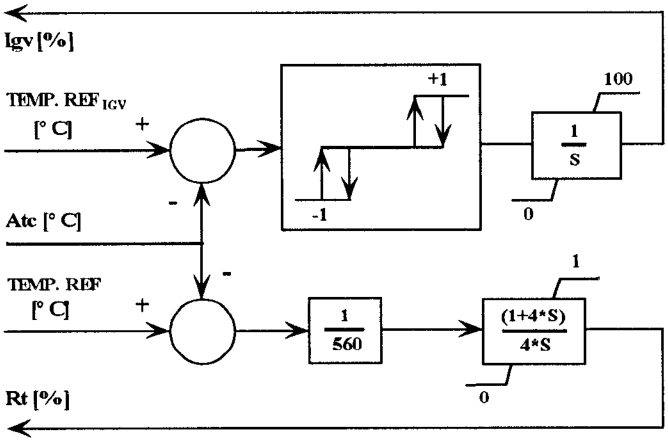

Fig. 8. Gas Turbine Temperature Control model.

Gas Turbine Governor model

In **Fig.** 7 is the model of Gas Turbine Governor. Inputs are the speed deviation and the power output together with its references or set point values. Output (Rv) is a demand to open fuel valve. This governor model handles the standard speed/load/droop control function.

Temperature Control model

In **Fig. 8** is the model of Temperature Control. Inputs are the corrected temperature (Atc), the speed and the two temperature references or set point values (Temp. Ref. and Temp. $Ref._{IGV}$). One output (Rt) is a demand to open the fuel valve and the another output is a demand to open the guide vanes. There are two temperature controls, one is through fuel valve and the another is through guide vanes, both controls tries to get control of temperature but the first has a higher set point.

Output of temperature control through fuel valve (Rt) is another demand to open fuel valve that competes with governor output.

When power is lower than maximum the temperature control through guide vanes takes temperature control moving guide vanes, being corrected temperature equal to temperature set point (Temp. $Ref._{IGV}$) of this controller. As this temperature set point is lower than the another one (Temp. Ref.), output from temperature controller through fuel valve (Rt) is higher than governor output (Rv), then governor output takes control of fuel valve.

When power increases the guide vanes continues opening until its are full open. Until this operating point corrected temperature tries to remain equal to temperature set point (Temp. $Ref._{IGV}$) of temperature control through guides vanes.

If power increases over previously mentioned operating point then corrected temperature (Atc) begins to increase too, and output (Rt) from temperature control through fuel valve decrease. When this output (Rt) is lower than governor control (Rv) it takes control of fuel valve and corrected temperature tries to remain equal to temperature set point (Temp. Ref.) of temperature control through fuel valve. This operation point is called Base Load.

Servo-Valve model

In **Fig. 9** is the model of Servo-Valve. Input (Hr) is a demand to open fuel valve from a Low Value Selector Gate. Output (Hg) is fuel valve aperture.

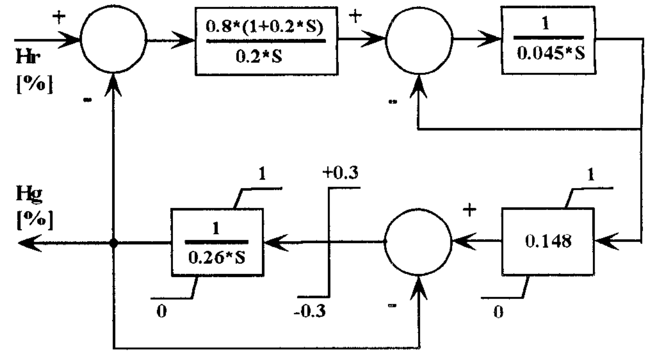

Fig. 9. Gas Turbine Servo-Valve model.

Gas Turbine model

In **Fig. 10** is the model of Gas Turbine. Inputs are the fuel valve aperture (Hg), the aperture of guide vanes (Igv) and the speed. Outputs are the power and the corrected temperature (Atc).

Output power is proportional to gas flow (Pq) minus power compressor consumption (P_0). Power also depends of ambient temperature. Due to of slow rate variations of ambient temperatures its effect can be consider changing the model variable RATE.

Airflow (Qa_0) at nominal speed and in stationary state can be varies between 70% and 100% by guide vanes aperture between 0% and 100% respectively. Actual airflow (Qa) depends on speed.

Exhaust temperature (At) increases with fuel flow and decreases with airflow. Measurement time constant of exhaust temperature is 10 s. Corrected temperature (Atc) is calculated from exhaust temperature and speed.

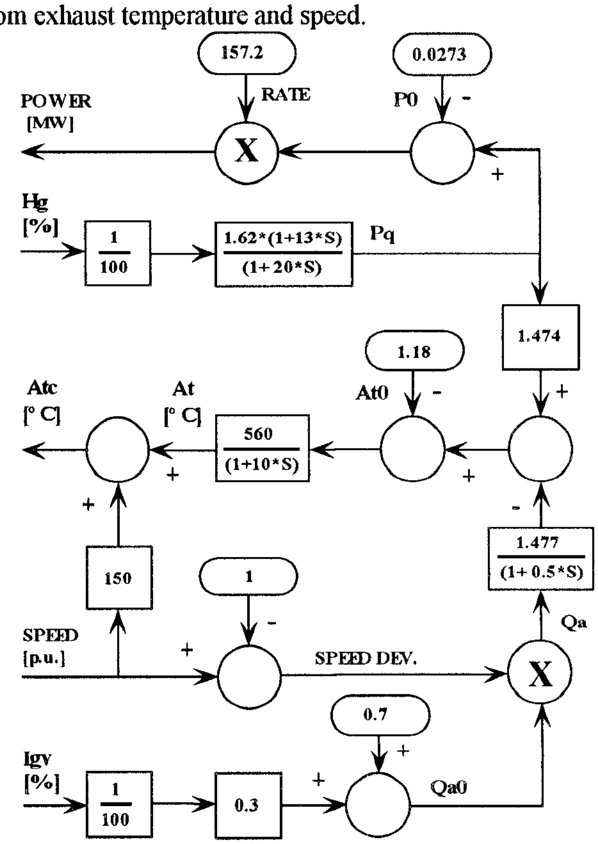

Fig. 10. Gas Turbine model.

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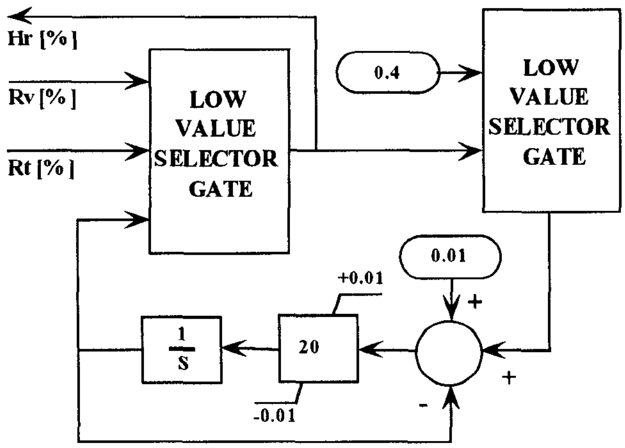

Fig. 11. Valve Speed Limiter model.

Speed Limiter of Valve Aperture model

In **Fig. 11** is the model of Speed Limiter of Valve Aperture. Manufacturer added this block to avoid turbine overheating and consequently turbine tripping.

This modification was proved as a consequence of reliability test described below. Limit on valve aperture speed is disabled for valve apertures below 40%.

III. RELIABILITY TEST DESCRIPTION

In **[1]** there are prescribed reliability test to be made at combined cycle plants. One of these tests consists in the injection into speed/frequency reference governor of a test waveform superimposed to speed/frequency reference.

Test waveform has 2 Hz of initial fall in 2 seconds (-1 Hz/s slope). Then it increases 1 Hz in 30 seconds and it holds for 100 seconds when it reaches -1 Hz value. Finally it goes to 0 Hz in 100-200 seconds.

Test has to be made with the gas turbine operating with a power near to 95% of Base Load and having near to 5% of spinning reserve. Governor output must control fuel valve at the test start. Also this test has to be made at Base Load operation.

Test has to be made on Gas Turbines of combined cycle plants and it serves to estimate turbine behavior when there are large frequency dips in the electrical system.

The goal test is to verify if there is any possibilities of overheat turbine trip due to non-adequately control action.

Because system frequency is not perturbed during test it is not possible to note compressor influences into exhaust temperature. This is done through simulations on a good model of gas turbine validated by tests previously made.

IV. RELIABILITY TEST RESULTS

Tests and simulations result presented herein has been made at two V94.2 Siemens gas turbine of a combined cycle plant. All register show has 0 to 200 seconds of time scale, and registered signals and its scales are:

- Frequency Deviation (**Δf**). Scale: -0.06/+0.02 p.u.
- Output Power (**P**). Scale: 120/140 MW.
- Exhaust Temperature (**At**). Scale: 500/600°C.
- Corrected Temperature (**Atc**). Scale 500/600 °C.
- Guide Vanes Aperture (**Igv**). Scale: 50/100 %.
- Fuel Valve Aperture (**Hg**). Scale 45/55 %.

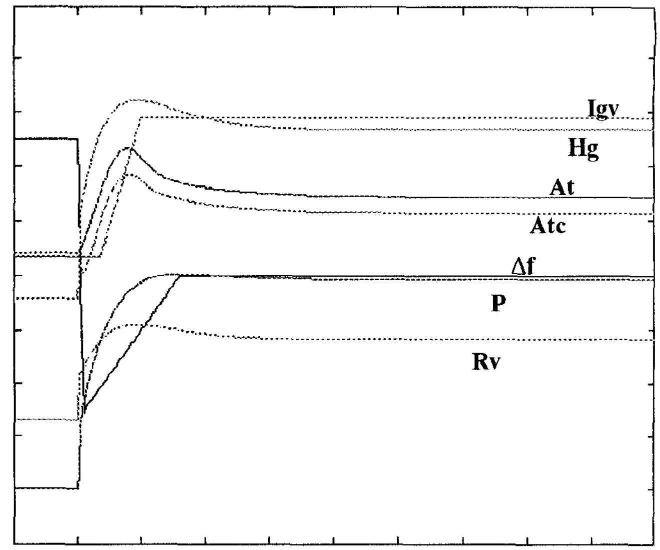

Fig. 12. Gas turbine. Reliability test.

- Governor Output (**Rv**). Scale: 45/65 %.
- Control Temperature Output (**Rt**). Scale: 45/65 %.

Tests and simulations result presented herein has been done with the gas turbine output at 122 MW and with 7% of spinning reserve. Also the Dead Band 2 of Governor was readjusted to values showed in **Fig.** 7.

In **Fig. 12** is the test result that was made without the Speed Limiter of Valve Aperture shows in **Fig. 11**. The exhaust temperature reached the alarm condition being the trip condition 26 °C above.

In **Fig. 13** is the simulation made inputting to model a frequency dip like test waveform at same test condition. The temperature reaches a value 15 °C higher than in test case because the airflow diminishes due to speed compressor slow-down. The result obtained gives good confidence in turbine gas behavior.

In **Fig. 14** is the simulation made at same previous condition but with original adjusts of Dead Band 2 (±0.01 p.u.). In this case temperature over-comes trigger value.

In **Fig. 15** is the simulation with Speed Limiter of Valve Aperture shows in **Fig. 11**.

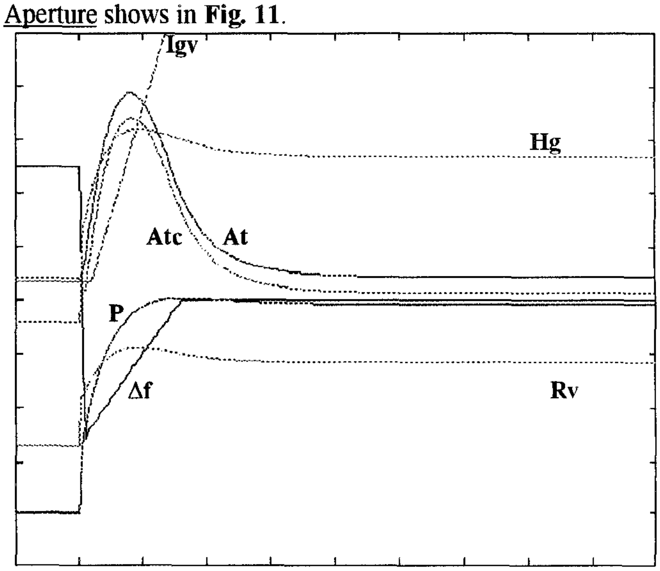

Fig. 13. Gas turbine. Simulation with governor final adjusts.

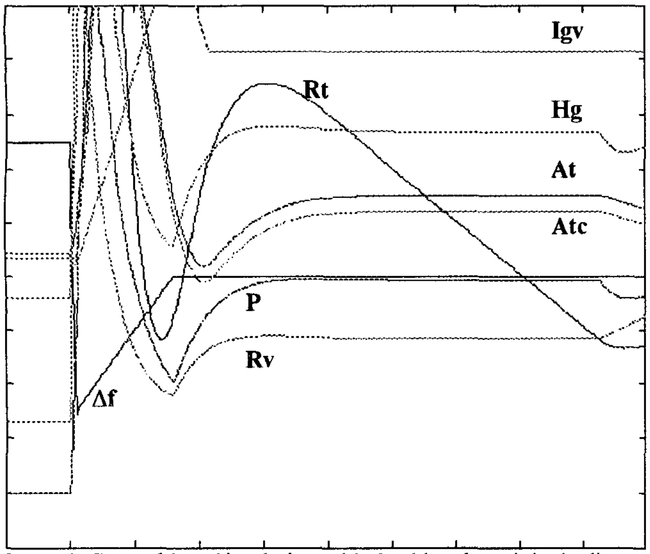

Fig. 14. Gas turbine. Simulation with dead band 2 original adjusts.

Fuel valve opens more slowly at transient start due to Limiter but then it remains opening at maximum allowed speed during more time. Temperature raised a little more than it does without Limiter.

V. CONCLUSION

Modeling of combined cycle plants is a complex nature work. Although for grid dynamics studies it is not necessary to model in detail boiler and steam turbine because they have slow dynamic characteristic.

A model of boiler and steam turbine was presented that can be used with confidence. Model may be used with any type of gas turbine models or any combination of them, because it is coupled to gas turbine models trough Mechanical Power and Speed Deviation. Boiler and steam turbine model has been developed as a User Model for the stability program PSS from PTI Inc.

Also was presented a gas turbine model of a combined cycle plant. This model was validated by test and represents in detail the gas turbines behavior for large-scale grid dynamics studies.

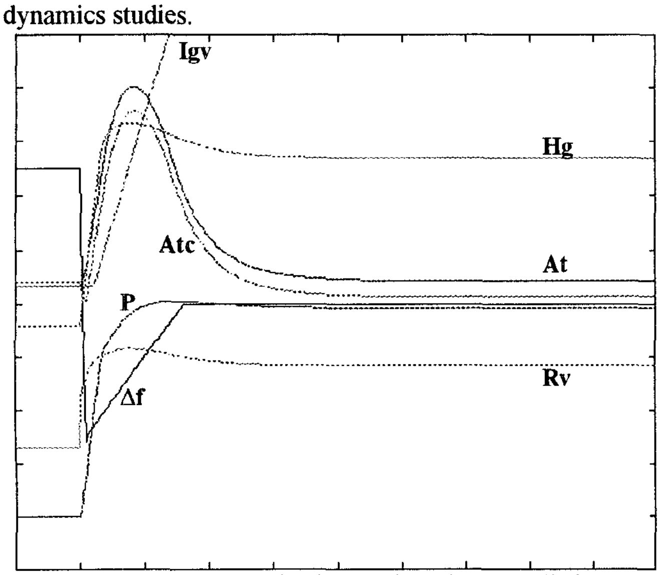

Fig. 15. Gas turbine. Simulation with valve speed limiter.

This model was validated with Reliability Test made at two gas turbines of a combined cycle plant and used to describe gas turbine behavior when large frequency dips happens in the electric system.

This model allowed to probe and to validate same modifications in gas turbine governor to avoid turbine tripping by high temperature. This procedure has proved that it is better to modify the dead Band 2 settings instead of adding a Speed Limiter of Valve Aperture.

VI. ACKNOWLEDGEMENT

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All three authors acknowledge to CAMMESA for allows showing results of some Reliability Tests.

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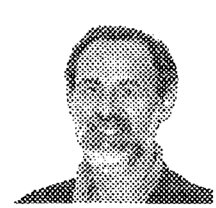
VIII. BIOGRAPHIES

Jorge Luis Agüero: was born in Mar del Plata, Argentina, on January 31, 1953. He received the Engineer degree from Engineering Faculty of La Plata National University, Buenos Aires, Argentina, in 1976. He was Adjunct Professor since 1983, and Titular Professor since 1996, in the Department of Electrical and Electronic Engineering, La Plata University. He was elected Engineering Faculty Vicedean in 1997, and re-elected in 1998.

He was elected Argentina PES Chapter Vicechair in 1997 and chair in 1998 and 1999. He is member of Load Modeling Working Group of Power System Stability Subcommittee of PES.

Since his graduation he works for the IITREE-LAT, a research and development university institute. His first research was on with electronic equipment development for non-conventional electrical measurements. His present research interest includes power system operation, dynamics, and control transient and dynamic behavior of electric power systems, particularly in the modeling and systems tests development.



Mario César Beroqui: was born in La Plata, Argentina, on April 10, 1952. He received the Engineer degree from Engineering Faculty of La Plata National University, Buenos Aires Province, Argentine, in 1976. Since his graduation he works in the Engineering Faculty of La Plata National University. He works since 1986 for the IITREE-LAT, a research and development university institutes. His first research was on in the Control Process area.

His present research interest includes powers systems operations, dynamics, and control, especially in the area of frequency control.

Roberto Molina: was born in Rosario, Argentina, on April 12, 1956. He received the Engineer degree from Engineering Faculty of Rosario National University, Santa Fe, Argentine, in 1980. He works as Electric Power System Senior Engineer at CAMMESA. He is an specialist in security and dynamic analysis of the Argentinean power system (SADI) on topics like transient electromechanical studies, transmission limits, network expansion, modal analysis, power system stabilizer, voltage and frequency control.