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PSS Design of the Combined Cycle Power Station (CCPS)

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Abstract—**The paper presents the project to Power System Stabilizer applied to the generators of the gas turbines of Combined Cycle Power Station. The project developed used MATLAB software for the stabilizer's parameters calculation. The calculation was gotten from the linear model based on a machine connected on an infinite-bus. The stabilizers had been used to increase the machine eletromechanic oscillation damping. The model's validation was given for disturbances simulation as load step and lines open. The calculated parameters were compared with that are implemented in field and the ones that are supplied by the manufacturer. The results show that it is possible to improve the power system dynamic performance with this modeling.**

Index Terms—**Combined Cycle Plants, Dynamic Stability, Power System Stabilizer.**

I. INTRODUCTION

The high financier, ecologic and socials costs result of the big hydroelectric's construction and long transmission's line have stimulated the electric energy distributed generation, with the plant localized close to consumers.

For big urban centers, the most efficient alternative is a Combined Cycle Power Station - CCPS, which utilizes gas turbines and steam turbine associated in the same plant, both electric energy generation by natural gas. For that, the heat in the gas turbine's exhaustion gases is used to advantage, through of Heat Recovery Steam Generator- HRSG, producing the necessary steam to the steam turbine's drive.

The natural gas is exempt of sulphur and ashes, what it becomes dispensable the expensive installations of desulphurization and ashes elimination that is demanded in coal and oil thermal. The acid rain problem is minimum in a natural gas thermal, and the contribution for the global heating, for generated kW, is very lesser that in the correspondents the coal and oil, for the best thermal efficiency.

The plant in study is composed for: two gas turbine, each one with a nominal power of 112,8MW; a steam turbine with nominal power of 113,1MW; two heat recovery boilers; a cooling tower; an elevating substation of 310MVA; two generators with nominal power of 133,8MVA and a generator with nominal power of 147MVA.

The Combined Cycle System is a relatively recent technology, it has chances opened for improvement, either in a thermal efficiency and the performance of the equipment. The safe efficiency of a complex structure CCPS depends on theirs automatic controllers, to guarantee the operation's stability.

In this paper are presented mathematical and computational models development of the control systems synchronous generators, considering the specific characteristics of this equipment type and its use in thermoelectric. The simulations results are used for projected controllers' validation.

II. SYSTEM'S STABILITY

The demand for the energy generation situated next to the consumption place it comes growing stimulated, however, for the governmental and public pressure for the energy matrix's diversification. The Distributed Generation not only aims at the generation's decentralization as also the biggest trustworthiness in the electric energy supply. Therefore, the combined cycle thermoelectric plants had started to gain greater force in Brazil, which had mainly to the technological evolution and the gas-lines mesh's growth.

The majority of the energy companies adopt established computational modeling based in hydroelectric plants models for the power system dynamics' analysis. However, this technology can be significantly different of used in combined cycle thermal plants because of the parameters' tuning of the plants' controllers. Not considering this difference, the system's damping is deadening.

The power systems stability relates the capacity that the systems keeps acceptable permanent voltage in all the bus under normal operation and after disturbance occurs. A power system is totally dependent of synchronous machines to electric power generation. A necessary condition for the satisfactory operation is that all the machines remain in synchronism, or

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either, that they operate with the same speed. This aspect of the stability is conducted by the dynamics of the synchronous generators rotor angles and has been related in literature as rotor angle [7].

A soft variation in the system loading, considered as a small disturbance can generate electromechanical oscillations decurrent of the electromechanical torque unbalance in the synchronous generators [2].

The use of voltage regulators provides the increase of the generators synchronism torques, however, reduces the liquid system damping, causing the dynamic instability. With the creating electromechanical oscillations little damping became necessary to implement measured corrective to control these situations. The problem has been solved through the introduction of PSS's - Power System Stabilizers [3], [5] and [8].

III. MODELING OF THE SYNCHRONOUS MACHINE AND ITS CONTROLLERS

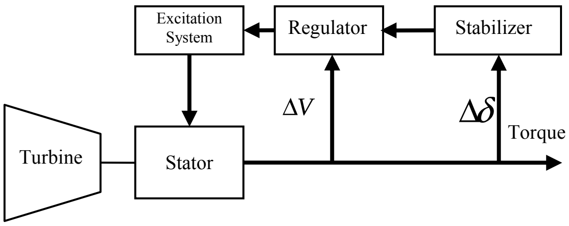


Fig. 1. Machine's representation in block diagrams.

Figure 1 represents the turbine, generator and its controllers. The generated voltage is controlled by regulating the system excitation. As soon as the magnitude of the system excitation increases, the generated tension and the reactive power of exit increase. The voltage regulator verifies the difference between the machines' output voltage and a reference voltage. This difference or voltage error is compensated through the excitation system control.

The use of fast excitation systems can after become unsatisfactory the machines' damping level when the disturbance occurs [1]. In steady state, when the shunting line of the speed is zero or approximately zero, the voltage regulator depends only on the voltage error.

In transitory, the generator's speed is not constant and the rotor angle varies, causing oscillations in the rotor's movement. The PSS's purpose is to use the generator's excitation system to regulate the power oscillations and consequently to increase its stability. The PSS operates through the voltage regulator, influencing its tuning point.

The machine's 3rd order model connected an infinite bus through an impedance equivalent is presented in Fig. 2. The model's constants linearized for an operation point are represented by the equations K_1 to K_6. In Fig. 2, it is enclosed the voltage regulator, showed for a K_e gain and a time constant ΔT_E. This model is related in literature for [4].

$$K_1 = \frac{\Delta T_e}{\Delta \delta}\bigg|_{e_q^{'}=cte}$$
$$= K_I V_\infty \{V_{x0}[R_e sen\delta_0 + (x_d^{'} + x_e)\cos\gamma] + I_{q0}(x_q - x_d^{'})[(x_q + x_e)sen\gamma - R_e\cos\gamma]\} \quad (1)$$

$$K_2 = \frac{\Delta T_e}{\Delta e_q^{'}}\bigg|_{\delta=cte}$$
$$= K_i\{R_e V_{x0} + I_{q0}[R_e^2 + (x_q + x_e)^2]\} \quad (2)$$

$$K_3 = \frac{1}{[1 + K_i(x_d - x_d^{'})(x_q + x_e)]} \quad (3)$$

$$K_4 = \frac{1}{K_3}\frac{\Delta e_q^{'}}{\Delta\delta}\bigg|_{E_{fd}=cte}$$
$$= V_\infty K_i(x_d + x_d^{'})[(x_q + x_e)sen\gamma - R_e\cos\gamma]\} \quad (4)$$

$$K_5 = \frac{\Delta V_t}{\Delta\delta}\bigg|_{e_q^{'}=cte}$$

$$= \left(\frac{V_\infty K_i}{V_{t0}}\right)\{x_d^{'} V_{q0}[R_e\cos\gamma - (x_q + x_e)\ldots \quad (5)$$

$$\ldots sen\gamma]\} - (x_d^{'} - x_e)\cos\gamma + R_e sen\gamma$$

$$K_6 = \frac{\Delta V_t}{\Delta e_q^{'}}\bigg|_{\delta=cte}$$
$$= \left(\frac{V_{q0}}{V_{t0}}\right)[1 - K_i x_d^{'}(x_q + x_e)] - K_i x_q R_e\left(\frac{V_{d0}}{V_{t0}}\right) \quad (6)$$

$$K_i = \frac{1}{[R_e^2 + (x_q + x_e)(x_d^{'} + x_e]} \quad (7)$$

Being:
V_∞ = infinite bus voltage.
V_{x0} = voltage that defines the axle position and that it supplies the torque angle initial value.
δ_0 = initial torque angle.
x_d = direct axle reactance.
$x_d^{'}$ = direct axle transitory reactance.
x_q = quadrature axle reactance.
$x_q^{'}$ = quadrature axle transitory reactance.

x_e = circuit's proper reactance of the rotor's iron.

γ = admittance angle series equivalent less the torque angle.

I_{q0} = current component in the quadrature axle.

V_{q0} = terminal voltage's component of the generator in the quadrature axle in the machine's reference.

V_{d0} = terminal voltage's component of the generator in the direct axle at machine's reference.

V_{t0} = generator's terminal voltage in permanent regimen (absolute value).

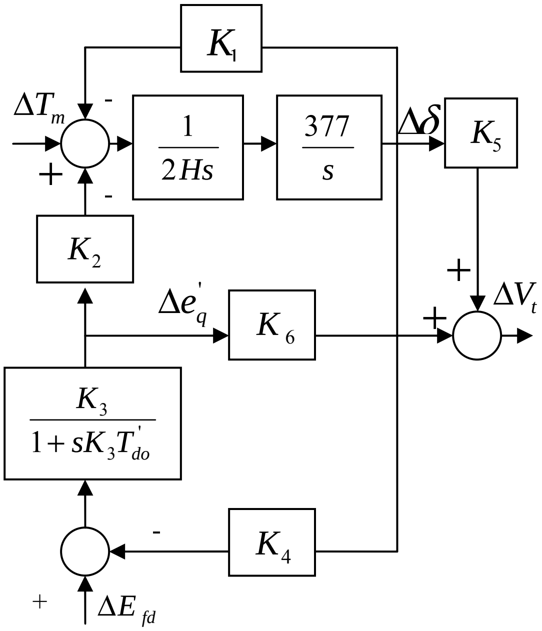


Fig. 2. Machine infinite bus blocks diagram.

IV. PSS PROJECT

The PSS is an element that supplies an additional input to the regulator. It is projected to compensate the delays that occur in the voltage control mesh, whose purpose is to improve the power systems' dynamic performance. The phase's compensation is carried through by the use of lead-lag functions, which supply phase advance on the interest frequency scale.

The system was shaped through three generating bus, which represented two generators of the gas turbines and one generator of the steam turbine, and the infinite bus that was used as reference bus. The simulation, for load flow's attainment, was made in analysis of nets software (ANAREDE).

The data gotten through the flow are: voltage module, voltage angle, active and reactive power. They had served of input for the PSS parameters' calculation, which was described inside of shown MATLAB software and as in Fig. 4, illustrate the screens of the developed program.

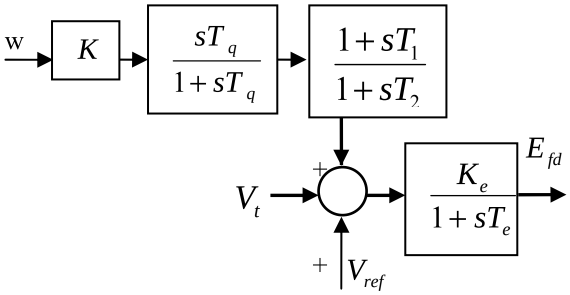
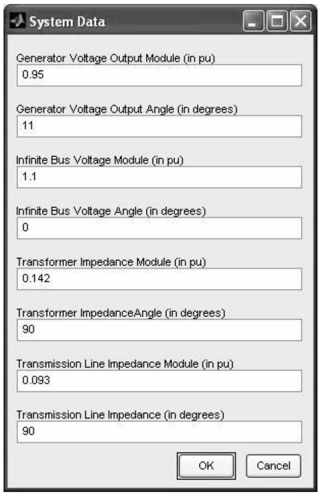


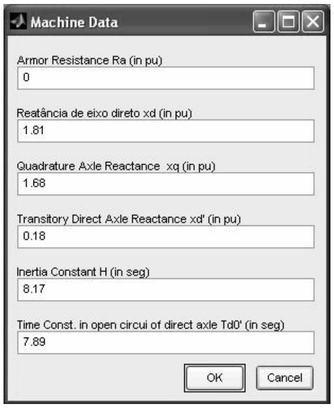
Fig. 3. PSS's blocks Diagram.



Generator Voltage Output Module (in pu)
0.95
Generator Voltage Output Angle (in degrees)
11
Infinite Bus Voltage Module (in pu)
1.1
Infinite Bus Voltage Angle (in degrees)
0
Transformer Impedance Module (in pu)
0.142
Transformer ImpedanceAngle (in degrees)
90
Transmission Line Impedance Module (in pu)
0.093
Transmission Line Impedance (in degrees)
90

Fig. 4. System Data.

Beyond the load flow data it was include as input data the gas turbine generator parameters, Fig. 5, all the parameters in pu and referenced base of 13,8kV and 100MVA.



Armor Resistance Ra (in pu)
0
Reatância de eixo direto xd (in pu)
1.81
Quadrature Axle Reactance xq (in pu)
1.68
Transitory Direct Axle Reactance xd' (in pu)
0.18
Inertia Constant H (in seg)
8.17
Time Const. in open circui of direct axle Td0' (in seg)
7.89

Fig. 5. Machine's Data.

Initially, a 2% voltage step in the gas turbine was applied without the PSS, and through of the electric power's graph, shown in Fig. 6, the system's dominant frequency was calculated.

$$\omega_{osc} = \frac{2\pi}{9{,}38 - 8{,}58} = 7{,}85 rad / s \qquad (8)$$

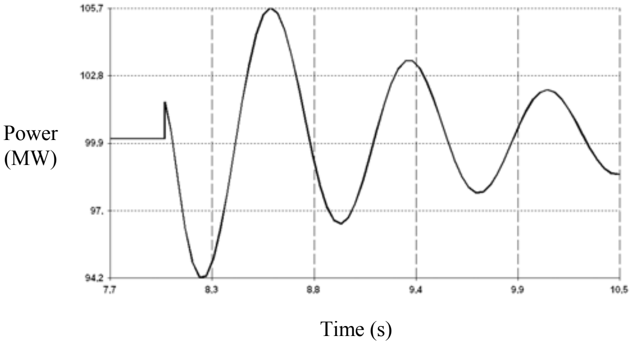


Fig. 6. Electric Power in Gas Turbine Generator.

With the frequency calculated in 8 and being, s = $j(w_{osc})$ the delay angle of excitation system's phase θ, calculated through 9, equal s to 39,25°.

$$\frac{K_2 K_A / T'_{d0} T_A}{s^2 + [(T_A + K_3 T'_{d0}) / K_3 T'_{d0} T_A] s + (K_6 K_A / T'_{d0} T_A)} \qquad (9)$$

This delay will be compensated by the lead-lag phase advance, advance delay, whose projected parameters, are the time constants T_1 and T_2 are equal to 0,2640 and 0,0554, respectively [6].

$$T_2 = \frac{1}{\omega_{osc}\sqrt{a}} \qquad T_1 = aT_2 \qquad (10)$$

$$a = \frac{1 + sen\,\theta}{1 - sen\,\theta} \qquad (11)$$

The PSS's gain, equal to 15, was adjusted through simulation using software ANATEM (Transitory Analysis of Electromechanical). As the oscillation frequency is below of 8 rad/s, it was opted to the washout project that eliminated frequencies below of 0,67 rad/s, in accordance with 12. Being, w_c the cut frequency.

$$T_q = \frac{1}{\omega_c} = \frac{1}{0{,}67} = 1{,}5s \qquad (12)$$

Table 1 presents the PSS's parameters: (i) calculated by the manufacturer, (ii) used by the National System Operator (ONS) and applied in field and (iii) projected.

Table 1. PSS Parameters.

	K	T_1	T_2	T_3	T_4	T_q
Manufacturer	13,28	0,120	0,0400	0,12	0,04	-
ONS	10,00	0,120	0,0400	0,20	0,04	-
Design	15,00	0,264	0,0554	-	-	1,5

V. RESULTS AND DISCUSSION

The projected PSS's performance was compared with the one of the manufacturer and with the found one in field through simulation. The parameters tuning was validated using ANATEM software, for the system's dynamic analysis behavior.

The system was simulated for the situations: (i) 2% load step using the configuration generating connected the infinite bus, (ii) national linked system with opening of the line Cauipe to Fortaleza, (iii) national linked system with the Paulo Alfonso IV plant turn off and (iv) opening of the line Quixadá to Milagres.

Figure 7 illustrates the curve of electric power generated by the one of the generators of the gas Turbine. As it can be verified, the system without PSS, when submitted to a 2% load step, presented subsequent oscillations to the first one, what it can take the loss of machine's synchronism. However, with the enabled PSS, a damped response was gotten more, guaranteeing the stability.

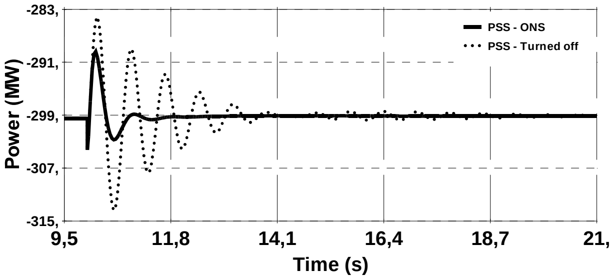


Fig. 7 Power with PSS ONS and PSS turned off.

In Figure 8, the projected PSS's performance is compared with the PSS implemented in the thermoelectric and the calculated for the manufacturer. On it is observed that the projected PSS presents a smaller overshoot and one better time of room for the system, what becomes viable the practical implementation of the projected parameters for use in field.

The Figures 9 and 10 are differentiated by the type of simulated situation. In the first one, the system is simulated with the opening of three lines of 230kV that connected Cauipe to Fortaleza.

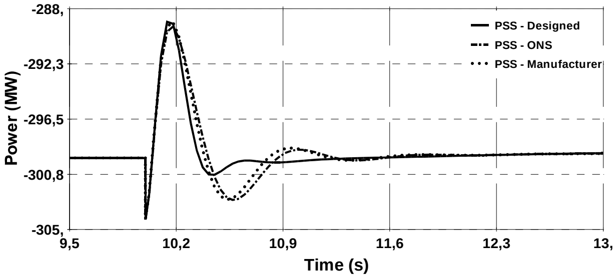


Fig. 8 Power with PSS Designed, ONS and Manufacturer's PSS.

In second one, the simulation was carried through removing the Paulo Alfonso IV Hydroelectric. Both show to the behavior of the gas turbines' generators. As it can be verified, the response is sufficiently oscillatory without the PSS, in compensation, the response becomes sufficiently damped with the use of any PSS. Also it is possible to verify that the designed PSS makes possible a damped response more than the PSS adopted in field.

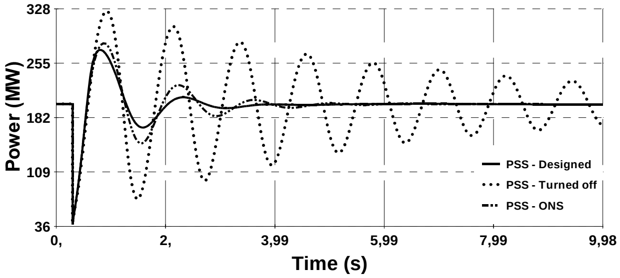


Fig. 9 Power without Cauipe – Fortaleza lines transmission.

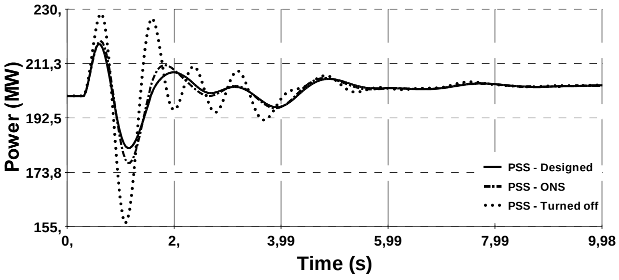


Fig. 10 Power oscillation in Paulo Alfonso IV plant.

The frequency oscillation of the generators in study with the Paulo Alfonso IV turn off is observed in Fig. 11. Through the graph, again, it proves efficiency of the projected model in relation to excessively.

Figure 12 illustrates the simulation the opening of the line of 500 kV that it binds Quixadá to Milagres. Analogic to the occurrence with the previous situations, verifies it importance of the adjustments of PSS's parameters, confirming that the best damping is gotten with the projected PSS.

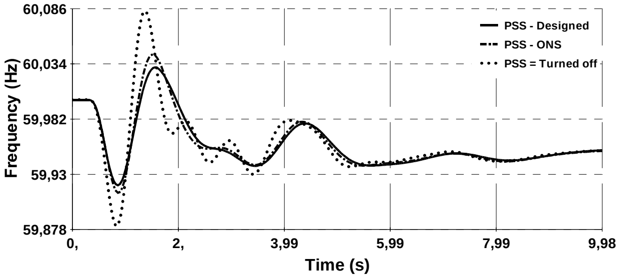


Fig. 11 Frequency oscillation in Paulo Alfonso IV plant.

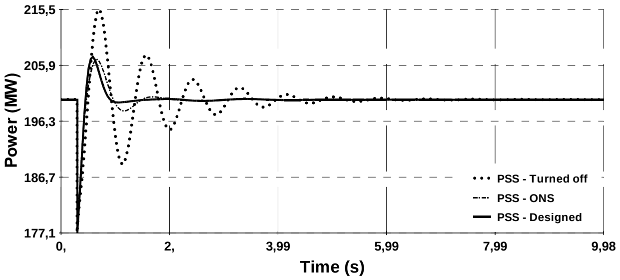


Fig. 12 Power without Quixada – Milagres lines transmission.

VI. CONCLUSION

In accordance with the results were verified the efficiency of the controller through digital simulation. The wave forms with the disabled PSS demonstrated a little damped response of the machine's torque angle.

For the presented simulations, concludes that the PSS design through the MATLAB, which used a model simplified for the system of machine's excitement, revealed satisfactory.

Through the computational modeling, it is obtained to simulate real systems and to get parameters capable to be inserted in normal conditions for the best control of the generators in combined cycle power station.

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