SETTING OF STABILIZERS IN POWER SYSTEMS WEAKLY LINK COUPLING.

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Abstract: - In this work a methodology is exposed to adjust stabilizers, based on measurements, simulations and field tests. Results of simulations and test, designed to illustrate the influence of power system stabilizers (PSS) on inter-area and local oscillations in interconnected power system, are reported. It is shown that the PSS location and the voltage characteristics of the system loads are significant factors in the ability of a PSS to increase the damping of inter-area oscillations. This procedure was implemented in the Interconnected Venezuelan System (CADAFE, EDELCA and Electricity of Caracas) with satisfactory results. It studied the dynamic problem of the Interconnected Venezuelan System, in particular when after settling exciters of solid state with high speed response in the Hydroelectric Power station San Agatón, belonging to the Hydroelectric Complex Uribante, Doradas, Camburito and Caparo, were begun to experience sustained oscillations, additionally this particular area has as characteristic a weak coupling with respect to the rest of the interconnected system.

Key – Words:- . Adjust stabilizers, synchronous generator, weakly link coupling.

1 Introduction

A system of power when being altered for perturbation in balance condition, reacts with the dynamics characteristics of all its elements and controls. As the result of this answer, self-sustained oscillations can be presented. Typically these variations will spread to eliminate with the time, until to arrive or not finally to another balance condition. For this reason, it is important to have a wide panorama of possible types of oscillations that can be presented in a power system and to identify those relationated with the dynamics of the rotors generator.

Synchronous generator amortisseur windings, governor controls and automatic voltage regulators are three important devices influencing the damping of power oscillations. However, these devices have limitations in the amortisseur action for frequencies above a 3 Hz. The objective in the application of stabilizers is to improve the damping of oscillations.

In studies of dynamic stability, where problems of oscillations reduction are presented, it is important to consider the use of supplementary stabilizers signals to eliminate sustained electromechanical oscillations for to increase the damping of the same ones. In general, the excitation system controls have modules stabilizers that if try to improve the excitation systems response when perturbations in the power system are presented. A problem that has been detected through the time, is the negative impact of the automatic voltage regulators, in the damping of rotor's oscillations in generating units, this situation can get worse, in the case of power systems connecting through weakening coupling and a particularly oscillatory character has been specially critical, when quick excitement systems, with high gains and high speed response are presented. The use of additional stabilizers signals should be recommended, through voltage regulation system, such as to provide control over undamped oscillations.

2 Calculation Methodology

In power systems stability analysis, the model for small perturbation must be linealized and it is possible applying techniques of lineal control. It is important to point out that each element of control has a response time characteristic in the dynamics. In the analysis of transitory stability and dynamics is necessary to use an appropriate representation of the synchronous generator. A comprehensible model is required, for easy implementation in digital computer and the same time, should be compatible with the control models and elements in the system. The characteristics of the problems of dynamic stability, it require that the generator model be linealized for a condition of specific operation. After an exhaustive analysis the use of the model linealized of the generator in configuration machine - infinite bar, was selected.

A good representation of excitation systems in generating units is indispensable if it is wished a realistic simulation of the transient's phenomena of electromecanics nature that define the power stability system. The dynamic simulation studies of the Venezuelan Interconnected System began many years ago using representative parameters for excitation systems supplied by manufacturers and experienced annalists. As a logic step for the evaluation of the digital simulation studies of the system, it was considered necessary verify the precision of the models employed, beginning a field test program of the most representative excitation systems, with the goal of adjusting the models to reality. In this test program the excitation systems was externally disturbed, and at the same time, the evolution in time of excitation voltage and the terminal voltage of the generating units were oscillographly registered. Subsequently, the digital test was simulated changing the system parameters, until a correspondence in accord with the test simulation was found.

The dynamic behavior for small perturbances, of a synchronous generator connected isolated to system of great capacity (at least an order of more magnitude that of the generator), it can be studied using the model developed for Demello and Concordia, described by a diagram of blocks in the Fig 1, where the loops of feedback of the automatic voltage regulator, speed governor and power stabilizer are also pointed out. Still when this model is enough simplified (for example, neither the transmission system, neither damper winding, are simulated in detail), it helps to visualize the relative more important conceptual aspects to the influence of the diverse feedback loop on the dynamic characteristics of a real generator.

With this model has been demonstrated that the closed feedback loop through the automatic voltage regulator can be a source of negative damping, and to give place to divergent oscillations. In a real system, these divergent oscillations evolve in the time to a cycle limit, or in other words, to sustained oscillation. Using the same analysis methodology described for Demello and Concordia, it can be demonstrated that the closed feedback loop for the speed governor is also able to reduce the damping torque and therefore to impact negatively in the dynamic stability of the generator in a certain range of frequencies.

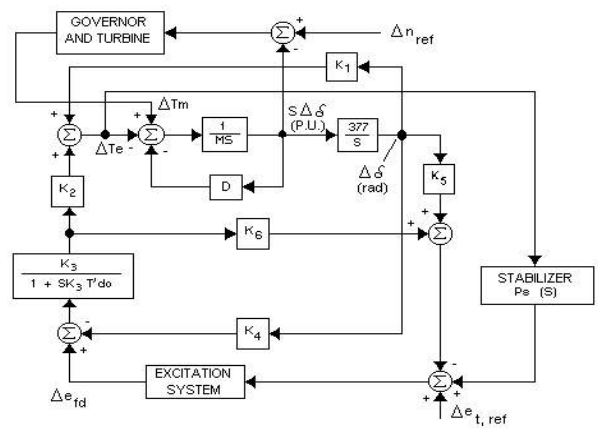


Fig 1. Blocks Diagram linealized model of an isolated synchronous generator connected an infinite bus bar through an external reactance indicating the basic control equipment transfer functions.

The equations of the linealized model are the following:

Electric torque:

$$\Delta T_e = K_1\,\Delta\delta + K_2\,\Delta E'_q \qquad (1)$$

Connection of flow:

$$\Delta E'_q(s) = -\frac{K_3}{(1 + T'_{zo}\,s)}\,\Delta E_{fd}(s) - \frac{K_3\,K_4}{(1 + T'_{zo}\,s)}\,\Delta\delta(s) \qquad (2)$$

Where $T'_{zo} = K_3\,T'_{do}$. Applying the one Laplace´s transformer and substituting Eq. (2) in Eq. (1):

$$\Delta T_e(s) = \left(K_1 - \frac{K_2\,K_3\,K_4}{(1 + T'_{zo}\,s)}\right)\Delta\delta(s) - \frac{K_2\,K_3}{(1 + T'_{zo}\,s)}\,\Delta E_{fd}(s) \qquad (3)$$

The generator's voltage when applying Laplace´s transformer, it is obtained:

$$\Delta V_t\,(s) = K_5\,\Delta\delta(s) + K_6\,\Delta E'_q(s) \qquad (4)$$

The generator's voltage V_t and the internal voltage E_{fd} are related through the excitation system. The Fig 1 shows the blocks diagram that to conform the equations of the linealized model of machine. This model plus all its equations was developed in the software's, for the realization of this study, serving like base for the digital simulation made. When including the effect of the variation on the field voltage (ΔE_{fd}), the electric torque's equation is written as:

$$\Delta T_e(s) = \left[K_1 - \frac{K_2 K_3 K_4}{1 + K_3 T'_{do} s}\right]\Delta\delta(s) + \left[\frac{K_2 K_3}{1 + K_3 T'_{do} s}\right]\Delta E_{fd}(s) \qquad (5)$$

This way it is possible to include the effect of the excitation system in the electric torque. The relationship among the terminal voltage (V_t) and the field voltage is:

$$\Delta E_{fd} = - \frac{K_E}{1 + T_E s} \Delta V_t \qquad (6)$$

The sign minus in Eq. (6) indicates opposed reaction from the field voltage to change in the generator's voltage. It is included in this basic model a time constant (T_E) and the gain of the excitation system (K_E). These parameters are important in the dynamics generator before different operative conditions. The relationship of the generatoe's voltage with other variables of the machine is obtained of the linealized generator model.

$$\Delta E_{fd}(s) = - \frac{K_E}{1 + T_E s}\left(K_5 \Delta\delta(s) + K_6 \Delta E'_q(s)\right) \qquad (7)$$

This way it's had the effect of the excitation system through the basic variables $(\Delta\delta \text{ y } \Delta E'_q)$.

In the Eq. (5) it's had the expression that allows to analyze the effect of the excitation system in function of the synchronization components and reduction.

This way, for very small oscillation frequencies (**s** $\rightarrow$ 0) the following relationship is obtained

$$\Delta T(\omega_a = 0) = \left[K_1 - \frac{K_2 K_3 K_E K_5}{1 + K_E K_6 K_3}\right]\Delta\delta \qquad (8)$$

If they are considered high values of gain in the excitement system (K_E), the Eq. (8) it transforms in:

$$\Delta T(\omega_a = 0) = \left[K_1 - \frac{K_2 K_5}{K_6}\right]\Delta\delta \qquad (9)$$

The Eq. (9) allows to conclude the following thing, to very low frequencies, synchronization component only exists. The synchronization component can be positive or negative depending on the values of the constants of the machine and of the point of operation δo. The constants K_1, K_2 and K_6 are generally positive, instead K_5 can be positive or negative. When K_5 are positive, the second term inside to the parenthesis in the Eq. (9) reduces the synchronization component. When K_5 are negative, the synchronization coefficient is increased by effect of the excitation system. In summary, to very low frequencies the problem of stability you can present for lack of restoring forces of synchronization, condition that you can only present with positive values of K_5. However, these values are had when the connection with the external system is very robust (strong), or it stops conditions of moderate load, in these cases it is expected that the value K_1 is big and dominate the coefficient of total synchronization.

3 Experimental Methodology

The power system stabilizers for San Agaton generators numbers 1-2 were adjusted in the field applying the following procedure:

3.1 Obtainig pure damping from supplementary signals at the critical frequency oscillation mode.

This is achieved taking into account the addition component torque at the frequency oscillation mode poorly damped of from stabilizer action should lag the power signal by 90 degrees.

For San Agaton generators numbers 1-2, the following transfer functions apply:

$$P_S(s) = K_P \frac{S}{(1 + ST_1)(1 + ST_2)} \qquad (10)$$

$$G(s) = K_e \frac{(1+ST_a)}{(1+ST_b)(1+ST_e)} \qquad (11)$$

$$H(s) = \frac{G(s)\dfrac{K_3}{1 + S K_3 T'_{d0}}}{1 + G(s)\dfrac{K_3 K_6}{1 + S K_3 T'_{d0}}} \qquad (12)$$

Where:

$P_S(s)$ = Stabilizer transfer-function.

G(s) = Exciter and voltage regulator equipment transfer function.

H(s) = Closed loop autromatic voltage regulator transfer function under load conditions, and assuming constant rotor angle.

Substituting jw for s in the transfer functions the response to a sinusoidal forcing function (of frecuency w) can be evaluated.

$$P_S\ (jw) = P_S\ (w)\ e^{J\phi\, p(w)} \tag{13}$$

$$H(jw) = H(w)\ e^{J\phi\, h(w)} \tag{14}$$

The condition for pure damping, from power system stabilizer action at the frequency (ω_c) of the poorly damped mode of oscillation, ca be written mathematically as.

$$\phi_p\ (\omega_c) + \phi_h\ (\omega_c) = -\ \pi / 2 \tag{15}$$

3.2 Maximizing the gain Kp of the stabilizer.
The system is now represented as a plant and a controller. The equivalent plant and the controller are assumed now as single input/single output devices.

The frequency response of the equivalent plant can be determined analytically, taking into account the complete power system using Fast Fourier Transform techniques, but it con also is measured using special frequency-response analyzers.

After the frequency response of the equivalent plant is known, the gain K_p of the power system stabilizer transfer function is chosen, to provide enough stability margin using classical control system theory for single input/single output controllers.

3.3 Maximizing the damping available from power system stabilizers.
For a given stabilizer transfer-function, such as the one shown in Eq. (10), there is in infinite number of pair of values T_1 and T_2 satisfying Eq. (15), and associated with each pair there is a maximum gain that provides an adequate stability margin. If really maximum damping is required, the best stabilizer set of parameters for the structure defined by Eq. (1), is the one defined by that pair of values T_1 and T_2 capable of introducing the largest amount of added damping at the frequency of the poorly damped mode of oscillation of the system. The amount of added damping ($\triangle D$) introduced by the power system stabilizer can be estimated with the following equation.

$$\triangle D = P_S(w_C)\ H(w_C)\ K_2\ M\ w_C . \tag{16}$$

Although this discussion has limited to the case of the stabilizer described by Eq. (10), the techniques can be used for more complicated transfer-functions.

4 An example

4.1 Dynamic Stability of Venezuelan Power Interconnected System.
Since the setting in commercial operation of the first development of the Hydroelectric Complex "Uribante-Caparo, in the South-West of Venezuela, the generation units at San Agatón Power Plant, they come experiencing oscillations poorly damping after such interferences like, faults in the regional transmission system, National Interconnected System, sudden turn off generation units in another plants etc. This condition had been corroborated through simulations that indicated the particularly oscillatory character of the one referred plant, limiting to consequence, its nominal capacity of 300 MW to 150 MW. The present work picks up the most important aspects in an orderly investigation for the Venezuelan state company CADAFE to achieve the damping of these oscillations, given the case that the units of San Agatón were endowed with Power Stabilizers, but they had never been put in operation by the ignorance of the appropriate adjustments.

4.2 Experimental Procedure
The experimental procedure proposed to adjust stabilizers was used for to calculate the adjustments based simulations and field tests mensurations, This method is carried out basically in four stages:

1) Excitation and government tests of the generators whose objectives are to verify the answers of the equipments automatic regulators voltage so much like that of the speed governors from the point of view of stability, to determine the dynamic parameters to be used in the stability analysis and to produce experimental information to the groups of simulation work.

2) Simulation and test excitation systems and speed governor for to allow to syntonize the models used by the software, until to achieve to produce very similar answers to those gotten in the tests.

3) Simulation and test of the Power System. The first step is to determine the frequency of the poorly

damped mode. Calculation of the adjustments of the stabilizers of the units 1 and 2 of the plant San Agatón. This analysis allowed to define a reliable model for the stabilizers design and a single combination of adjustments was selected so that it represents the condition of maximum damping. The power system stabilizers are then designed to maximize the added damping at this frequency and are placed in those generators where their actions will be most effective.

4) Setting up in service of the stabilizers. When the stabilizers design carry out, are implanted in place the calculated adjustments, being practiced a series of tests that they confirmed the capacity of the Stabilizers to damping the oscillations of the Electric System of that moment.

4.3 Test to achieve.

No load test excitation. For the elaboration of this test, it must be injected a voltage step on the reference signal of automatic voltage regulator unit, such as to obtain appreciable variations in the generating unit output voltage. The regulating unit must to be in manual and automatic position. To this test must to register by means Oscillograph the next variations; the step voltage, the excitation current, the excitation voltage and the generator voltage.

Speed government test. In this test, must be injected a voltage step in the reference signal of speed sensor comparator circuit, until to obtain appreciable variations in the generating unit output electric power. This test must to register by means Oscillograph the next variations; the step voltage and the generating unit output electric power.

System test. The tests to evaluate the dynamic behavior of the western power system, were executed considering the applications and conditions made by the personnel Dispatch Center, due to the experience that they have had with the different problems analyzed in this work. Such as it is shown in the Oscillographic record Nº 2, the general response is poorly damping, even when self-sustained oscillations are not observed. With this test could be determined a critical oscillation frequency in 0.51 Hz.

4.4 Digital simulation of excitation test, government test and Venezuelan western power system test.

These simulations allowed setting the models used by the software, until to achieve to obtain response very similar to those gotten in the tests. The referred models allowed to simulate; the generator and their basic control systems, the automatic voltage regulator and the governor plus the turbine with very accuracy. The dynamic power system characteristics were processed,. With the critical frequency oscillation mode (wc = 0.51 Hz) was carried out a theoretical design of the stabilizers. The characteristics on this design were added to the digital simulation.

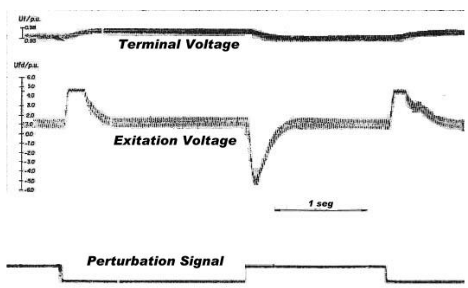
4.5 Adjust of the stabilizers.

The following expression simplified was the transfer function used in the calculation.

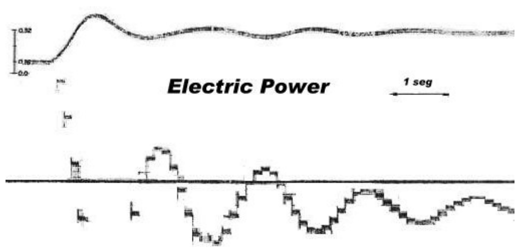
$$\text{Auxiliary sign} = KP * \frac{S}{(1+ST1)*(1+ST2)} * Pe \qquad (17)$$

In the Eq. (17) the Auxiliary Sign is the introduced in the point of reference of the automatic voltage regulator like stabilization mechanism, T1 and T2 are adjustable time constant in the stabilizer, Kp is the stabilizer adjustable gain and Pe electric power. A combination of values T1 and T2, associate a Kp value, they provide the phase margin required to improve the damping "D", appropriate to the critical oscillation frequency "wc" were considered. For determine the values mentioned it proceeded to; the analyses of twelve typical cases representing the operation characteristic conditions "load flow" were considered, calculation of the external impedance required by the model shown in Fig 1, for each one of the cases considered, calculation of the critical frequencies of the group generator–governor, for these twelve cases. The above implied twelve calculations of adjustments for the stabilizers. The selected adjustments, because with them the biggest damping was obtained, were; T1 = 0.9, T2 = 0.884, Kp = -2.950 and D = 4.00225.

Is important to mention that the values of T1 and T2 were calculated, taking into account ϕ p (wc) + ϕ m (wc) = $\pi/2$. ϕp(wc) is the phase angle introduced by the transfer function from the power stabilizer and ϕm(wc) is the phase angle introduced by the entirety of the excitation system to the value ωc. Additionally the local load was considered in the calculation of external impedance and it was necessary to reduce the Power System in order to concentrate the whole load of the same area on a single bus bar, the equivalent net is shown in the Fig 2. This Fig indicates the power station, the local load (Z load), external impedance (Xcc) and the infinite bus bar that represent the Venezuelan National Electric System “SEN”.



Oscillographic record Nª 1. Results of the excitation test to the generation unit Nº 1 of the plant San Agaton.



Oscillographic record Nº 2. Western Power system test at El Vigía substation.

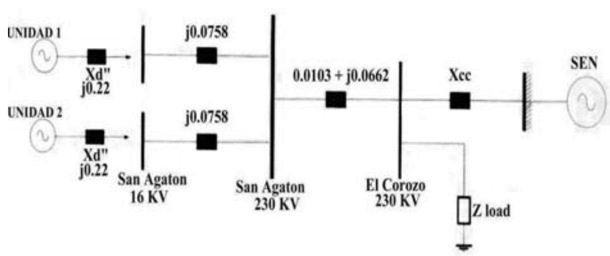


Fig 2. Equivalent net of the Venezuelan Western Electric Power System.

With the objective to corroborate the validate of these adjustments calculations, it was simulated the time responses of the load angle, electric power, voltage generator and the excitation voltage.

4.6 Setting in service of power stabilizers.

Initially it proceeded to verify at the plant, the calculation of the parameters the stabilizer transfer function, in such a way of obtaining a good phase margin to the critical frequency (0.51 Hz) of oscillation of the system. To probe the basic control systems, was applied a step voltage on the sensor circuit of automatic voltage regulator, measuring by means oscillographic like functions of time, voltage generator, excitation voltage and the electric power. The evidence was registered in the Oscillographic record Nº 3. Then was caused, with and without stabilizer, the sudden turn off of San Agatón the unit Nº 1 with 40 MW, maintaining the unit Nº 2 with 100 MW, here also were registered the voltage generator, excitation voltage and electric power. For evaluate the dynamic behavior of the system, was caused the sudden turn off of the line La Grita -Tovar I, registering the evolution in the time of the electric power in the line II in the Tovar substation, with both lines loaded to 50 MW each one. The evidence Oscillographic of evolution is shown in the Oscillographic record Nº 4 and Nº 5.

The definitive adjustments of the transfer function (18), with which were put in service the stabilizers are shown next:

$$Pss(s) = Kp \frac{STs}{(1+STs)} \frac{(1+ST1)\,(1+ST3)}{(1+ST2)\,(1+ST4)} \qquad (18)$$

Where:
Kp = 0.60 (Variable). T3 = 0.05 (fixed).
Ts = 5.60 (Fixed). T4 = 0.20 (fixed).
T1 = 0.05 (variable). Vmax = 3.25.
T2 = 0.20 (variable). Vmin = -3.25.

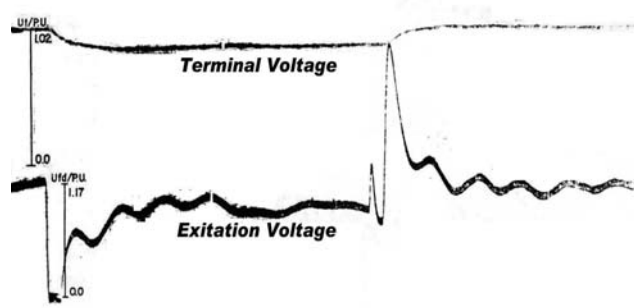


Fig 3. Oscillographic record Nº 3. Test of excitation system Generator Nº 2, with stabilizers.

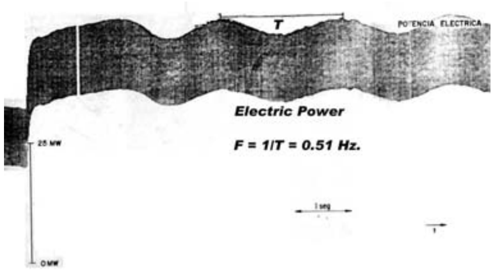


Fig 4. Oscillographic record Nº 4. Electric Power in the line La Grita - Tovar II, the line I with 25 MW turn off sudden, without stabilizers.

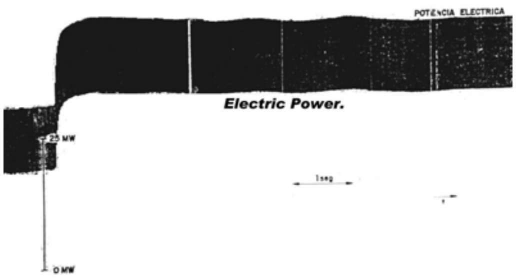


Fig 5. Oscillographic record Nº 5. Electric Power in the line La Grita–Tovar II, the line I with 25 MW turn off sudden, with stabilizers.

5 Conclusions

The stabilizers adjustments are critical and any alteration in the same ones can cause conditions of uncertainty, therefore, every time that happens a bigger change in the topological configuration of the net system, it will should be determined the new natural frequency of oscillation modo on the system and calculate the stabilizers adjustments again by means of the described process. The two waited objectives from the field tests performed to the excitation systems were obtained, noting that they served to detect different defects in some excitation systems, which were corrected during the test or after it. In fact, the high time responses found on any excitation systems, as well as the complete deficiency of action for operating in manual form, cause a negative influence to the voltage regulation of the Interconnected System, particularly in post-deficiency dynamic conditions. Given that in the Interconnected System, the dynamic behaviour is governed by instability voltage conditions, it can be appreciated the importance of an optimal and adequate response of the excitation systems.

The second objective, consist in obtaining a best knowledge of the different excitation systems installed in the generating units, from the modelation viewpoint, as well as from the equipment physical knowledge. It has been traduced in that the digital representation of them and by consequence the dynamic response of the Interconnected System approach to reality. As a consequence of the above, it is considered and it is recommended that is it essential to perform periodically dynamic tests to excitation systems to verify, if they are properly adjusted and if its operation is satisfactory.

The results of the field tests, justify that the stabilizers remain in service and they corroborate the simulation studies results carried out. The quality of the adjustments was demonstrated with the mensurations electric power registered at Tovar substation, when the line La Grita -Tovar I turn off suddenly, being measured the flow of power by the line La Grita - Tovar II at Tovar substation. **“It is evident the effect damper that is obtained, when these maneuvers are carried out being the stabilizers with their respective adjustments in service, just as it is shown in the Oscillographic record Nº 5.”**

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