MODELLING AND CONTROL TECHNIQUES FOR TUNING STABILIZERS IN POWER SYSTEMS.

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Abstract: - Tuning of supplementary excitation controls for stabilizing system modes of oscillation has been the subject of much research during the past years.Two basic tuning techniques have been successfully utilized with power system stabilizer applications: phase compensation and nyquist. Phase compensation consists of adjusting the stabilizer to compensate for the phase lags through the generator, excitation system, and power system such that the stabilizer path provides torque changes which are in phase with speed changes. This is the most straightforward approach, easily understood and implemented in the field, and the most widely used. In this paper 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 Interconnected Systems with satisfactory results.

Key – Words:- . Adjust stabilizers, synchronous generator.

1 Introduction

A fundamental study of the nature of inter-area oscillations in power systems is presented. The effects of the system structure, generator modelling, excitation type, and system loads are discussed in detail. A power system when have been altered for perturbation in balance condition, reacts with the dynamics characteristics of all its elements and controls. Typically these variations will spread to eliminate with the time, until to arrive or not finally to another balance condition. In the study, both small signal and transient stability analyses are used to determine the characteristics of the system. Electro-mechanical oscillations between interconnected synchronous generators are phenomena inherent to power systems. The stability of these oscillations is of vital concern, and is a prerequisite for secure system operation. For many years, the oscillations observed to be troublesome in power systems, were associated with a single generator, or a very closely connected group of unitsat a generating plant. Some low frequency unstable oscillations were also observed when large systems were connected by relatively weak tie lines, and special control methods were used to stabilize the interconnected system. These low frequency modes were found to involve groups of generators, or generating plants, on one side of the tie oscillating against groups of generators on the other side of the tie. Oscillations associated with a single generator or a single plant are called local modes, or plant modes. Local modes normally have frequencies in the range 0.7 to 2.0 Hz. The characteristics of these oscillations are well understood. They may be studied adequately, and satisfactory solutions to stability problems developed, from a system which has detailed representation only in the neighborhood of the plant. Oscillations associated with groups of generators, or groups of plants, are called inter-area modes. Inter-area modes have frequencies in the range 0.1 to 0.8 Hz. The characteristics of these modes of oscillation, and the factors influencing them, are not fully understood. They are far more complex to study, and to control.

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.

2 Modelling and Control Techniques.

In power systems stability analysis, the model for small perturbation must be linealized and it is possible applying techniques of lineal control. 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. After an exhaustive analysis the use of the model linealized of the generator in configuration machine - infinite bar, was selected. 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.

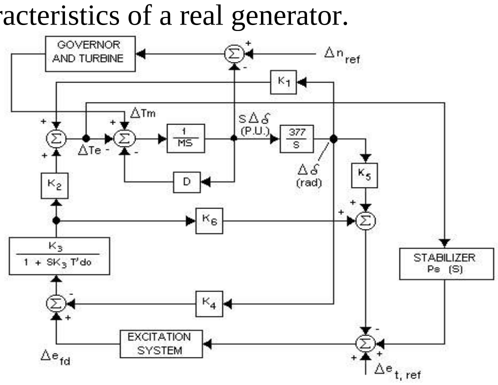


Fig 1. Blocks Diagram linealized model of an isolated synchronous generator connected an infinite bus bar through an external reactance.

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. 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

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

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

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

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

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. A tipical stabilizers transfer functions is:

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

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

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

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.

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

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

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.

$$\phi_p(\omega_c) + \phi_h(\omega_c) = -\pi/2 \quad (15)$$

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 (ΔD) introduced by the power system stabilizer can be estimated with the following equation.

$$\Delta D = P_S(w_C)\ H(w_C)\ K_2\ M\ w_C. \quad (16)$$

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 application.

4.1 Dynamic Stability of Venezuelan Power Interconnected System.

Since the 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 shooting down 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.

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, 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 tuning the models used by the software, until to achieve to produce the match time responses with the tests.

3) Simulation and test of the Power System. The first step was to determine the frequency of the poorly damped mode. 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 at this frequency.

4) Tuning stabilizers.

4.3 Test to develop.

No load test excitation. For this test, it must apply a voltage step on the reference signal of automatic voltage regulator to obtain appreciable variations in the generating unit output terminal and exitation voltage, in this test must to record oscillography.

Speed government test. In this test, must to apply a voltage step on the signal reference of governor speed sensor comparator circuit and to record variations in the generating unit output electric power.

System test. The tests to evaluate the power system dynamic behavior, were applied considering the applications and conditions made by the personnel Dispatch Center according yours experience. An example of test is shown in the Oscillographic record Nº 2, the general is poorly damping, even when self-sustained oscillations are 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 match s with 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 and applied in the digital simulation.

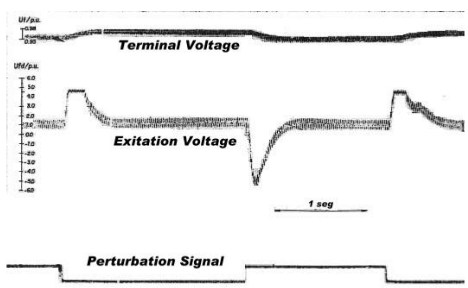
4.5 Calculations.

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

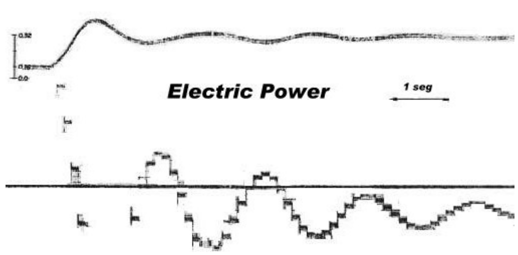
$$\text{Auxiliary sign} = KP * \frac{S}{(1+ST1)*(1+ST2)} * Pe \qquad (17)$$

In the Eq. (17) the Auxiliary Sign is the introduced in the reference of 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. To determine the values mentioned in the procedure, twelve typical cases representing the characteristics operation 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 Figure 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.

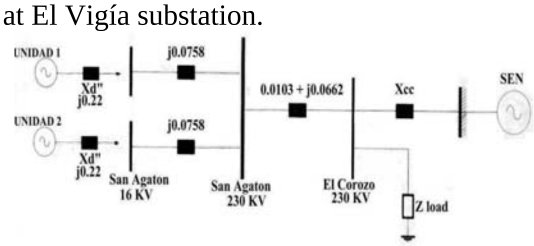


Fig 2. Equivalent net of the Venezuelan Western Electric Power System.

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

4.6 Tuning 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, disconnecting San Agatón`s 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 disconnecting La Grita - Tovar I line transmission, registering the evolution in the time of the electric power in the line transmission II in the Tovar substation, with both lines loaded to 50 MW each one. The evidence Oscillographic time is shown in the Oscillographic record Nº 4 and Nº 5.

The definitive adjustments of the transfer function (18), the stabilizers are shown next:

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

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.

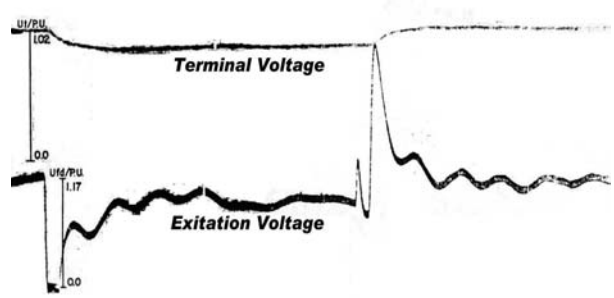


Fig 3. Oscillographic record Nº 3. Test of excitation system Generator Nº 2, with stabilizers.

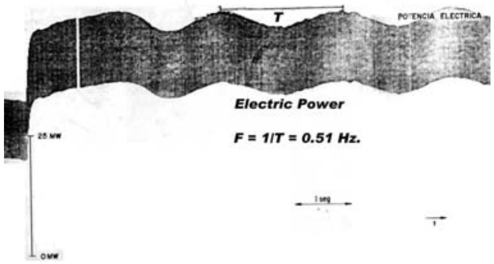


Fig 4. Oscillographic record Nº 4. Electric Power in the line La Grita - Tovar II, the line I with 25 MW turn off sudden, without stabilizers.

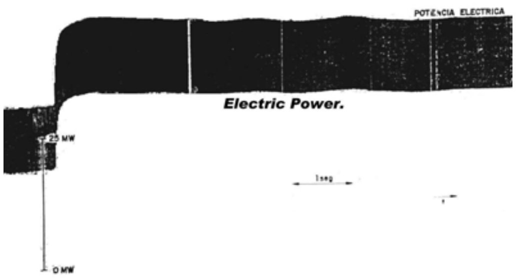


Fig 5. Oscillographic record Nº 5. Electric Power in the line La Grita–Tovar II, the line I with 25 MW turn off sudden, with stabilizers.

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 net configuration system, it will should be determined the new natural frequency of oscillation local modes in 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 s 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 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 point of view, as well as from the equipment physical knowledge. 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 La Grita -Tovar I disconnecting the line transmission, being measured the 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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