Design of power system stabilizers in variable speed wind generators using remote signals

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Abstract: *This work aims the description, modeling and simulation of the incorporation of a power system stabilizer (PSS) in variable speed wind turbines in order to dampen oscillation in power grids. The proposed PSS aims to alter the nature of the electric power injected by the wind farms to, in some sense, mimic the oscillatory behavior of synchronous generators and allows dampening these transient oscillations. The main advantage of this stabilizing action lies in the fact that the wind turbines, by decoupling the electrical frequency of the network respect its rotational speed by the inclusion of power electronic converters, allows the injection of oscillating power without risk of suffering stability issues. This allows to improve the oscillation damping between different synchronous generators.The proposed PSS has been analyzed in a grid of three areas: an area comprises the infinite bus; the second one a synchronous generator and the third one contains a synchronous generator and a wind farm. The PSS takes as reference the active power injected by the synchronous generator of the third area using synchrophasors. Finally, it is studied the performance of the PSS for a particular case of the Uruguayan power grid. In this scenario, the second area is composed by the hydro power plant Baygorria; the third area is comprised by the hydro power plant Terra and the wind farms Palmatir and Agua Leguas; finally, the first area is the rest of the power system.*

Keywords: *Angle stability, power system stabilizers, PMU, variable speed wind turbines, wind farms.*

I. NOMENCLATURE

δ_S: Internal angle of Baygorria
δ_m: Internal angle of Terra
δ_1: Angle of Baygorria voltage in the interconnection node
δ_2: Angle of Terra voltage in the interconnection node
t_d: PMU delay
D: Damping constant
M: Inertia constant
U: Voltage magnitude in the interconnection node (Terra and Baygorria)
U_∞: Voltage magnitude in the infinite bus
E_t: Voltage magnitude phase to earth in the interconnection node (Terra).
V_∞: Voltage magnitude in the infinite bus
E_s: Internal voltage magnitude in Baygorria.
E_m: Internal voltage magnitude in Terra.
X_s: Internal reactance, Baygorria.
X_m: Internal reactance, Terra.

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II. INTRODUCTION

Variable speed wind turbines in its most basic form of control have the particularity to decouple the shaft speed from the frequency of the network to which they are interconnected. The reactive power control loop establishes the exchange of this power according to the operating policy adopted, and the active power control loop is designed to maximize the energy extraction process from the wind.The wind turbines are not tipically involved in the oscillating power exchange with the power grid, but if they are located close to the synchronous generators, they will modify the oscillation patterns by changing the operating point. This situation can be improved considering the possibility of include power stabilizers in their control loops, to contribute to the damping system in various ways. Such as in the case of synchronous generators and FACTS devices, the implementation of a PSS involves the addition of an external signal that allows the injection of an oscillating power in case of the occurrence of disturbances. This allows the improvement of poorly damped oscillations.

In this paper the study of a PSS implemented at the electronic control level of wind farms is addressed. The control strategy will allow the turbines to operate at its point of maximum power extraction taking the necessary energy to dampen oscillations from the stored energy in the inertia of the turbines. This study takes as a reference the remote active power injected from a power plant composed of synchronous generators. The implementation of these stabilizers has the advantage of having a very fast response time, in the order of milliseconds, allowing the damping of electromechanical oscillations in a wide range of frequencies.

III. OBJECTIVE

In the particular case of the power grid illustrated in figure 1, the inclusion of the wind farm without reactive power exchange in its most basic form of control will improve the damping of the interarea mode (power plant 1 swinging against power plant 2) and worsen the common mode damping (power plant 1 and 2 oscillating together against the power grid) that involves the synchronous power plants, being the latter which dominates the transient response of the system when subjected to disturbances [1]. The particular focus of this study is to modify the active power control loop of the wind farm in order to model a PSS control action that modulates the active power injected to the grid, allowing the dampening of both oscillatory modes. The PSS will take as reference, i.e. as input signal, the active power injected by the second power plant. This reference will affect the active power control loop of the electronic converters in order to extract a portion of kinetic energy stored in the rotor of the wind turbines generators and allow the oscillating power injection.

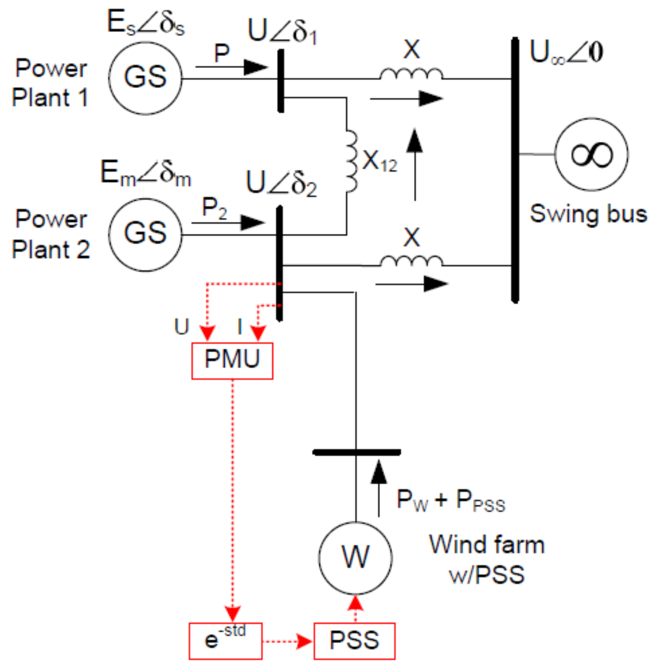

Figure 1: Simplified single line diagram of the system analyzed

IV. Theoretical Foundation

The proposed PSS input signal is the active power injected by the power plant number 2 (P_2) and it is used to modulate the active power injected to the network. With this reference, the wind farm will emulate the dynamic behavior of the power plant number 2 if any disturbance deviate the latter from its equilibrium point, actively participating in the power oscillations.

Figure 2 shows the active power control loop of a wind farm based on full-load converter generators, and the point where the stabilizing signal is inserted, changing the active power order imposed to the grid side converter. It is important to note that the model prioritizes the reactive power injection in case that a severe disturbance takes place, allowing the wind farm to meet the grid codes. This implies that when a fault occurs close to the wind farm, the latter will inject the highest level of reactive power as possible to increase the voltage level in the nearby nodes, and only when the fault is cleared, the PSS will act to increase the damping of power oscillations caused by the disturbance.

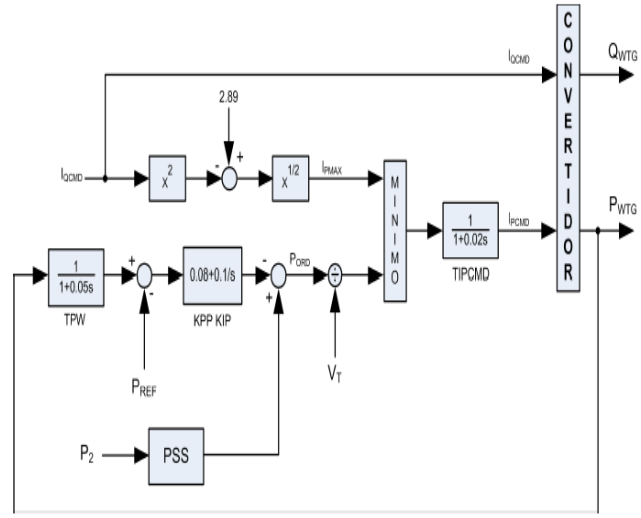

Figure 2: Simplified diagram of active power control loop with the inclusion of PSS

Considering Figure 1, the relationships governing the power flow and the dynamics of the power plants 1 and 2 can be established as follows:

$$\frac{E_s U}{X_s} sen\left(\delta_s - \delta_1\right) = \frac{U U_\infty}{X} sen\delta_1 + \frac{U^2}{X_{12}} sen\left(\delta_1 - \delta_2\right) = P \qquad (1)$$

$$\frac{E_m U}{X_s} sen\left(\delta_m - \delta_2\right) + P_{W0} + P_{PSS}(\delta_m, \delta_2) = \frac{U U_\infty}{X} sen\delta_2 + \frac{U^2}{X_{12}} sen\left(\delta_2 - \delta_1\right) \qquad (2)$$

Linearize equations (1) and (2) around the equilibrium , and consider the swing equation of both machines to get:

$$\begin{aligned} &k_1\left(\delta_s - \delta_1\right) = k_{s1}\delta_1 + k_i\left(\delta_1 - \delta_2\right) \\ &k_2\left(\delta_m - \delta_2\right) + G\left(\delta_m - \delta_2\right) = k_{s2}\delta_2 + k_i\left(\delta_2 - \delta_1\right) \\ &M\ddot{\delta}_s + D\dot{\delta}_s = -k_1\left(\delta_s - \delta_1\right) \\ &M\ddot{\delta}_m + D\dot{\delta}_m = -k_2\left(\delta_m - \delta_2\right) \end{aligned} \qquad (3)$$

where:

$$\begin{aligned} k_{s1} &= \frac{U U_\infty}{X} cos\delta_{10} \\ k_{s2} &= \frac{U U_\infty}{X} cos\delta_{20} \\ k_i &= \frac{U^2}{X_{12}} cos\left(\delta_{20} - \delta_{10}\right) \\ k_1 &= \frac{E_s U}{X_s} cos\left(\delta_{s0} - \delta_{10}\right) \\ k_2 &= \frac{E_m U}{X_m} cos\left(\delta_{m0} - \delta_{20}\right) \end{aligned} \qquad (4)$$

In the set of equations (3), G represents the gain of the PSS in small signal. These expressions allow visualizing clearly the participation of wind farm in power fluctuations, and that they are in phase with the synchronous generators of power plant number 2. Removing the angles δ_1 and δ_2 and assuming that the link between the areas 1 and 2 is weak (k_i is small), the equations of motion of the synchronous generators are the following:

$$
\begin{aligned}
&M\ddot{\delta}_s + D\dot{\delta}_s + \frac{kk_s}{k+k_s}\delta_s - \frac{kk_i(G+k)}{(k_s+k)^2+G(k_s+k)}\delta_m = 0 \\
&M\ddot{\delta}_m + D\dot{\delta}_m + \frac{kk_s}{k+k_s+G}\delta_m - \frac{k^2k_i}{(k_s+k)^2+G(k_s+k)}\delta_s = 0
\end{aligned} \quad (5)
$$

Moreover, the oscillating power injected by the wind farm is expressed in equation (6):

$$
P_W = \frac{2kk_sG}{(k_s+k)^2+(k_s+k)G}\delta_m - \frac{kk_iG}{(k_s+k)^2+(k_s+k)G}\delta_s \quad (6)
$$

From equations (5) and (6) it can be seen that the wind farm will dynamically behave in the same way as synchronous generator 2 does. This means that it will exchange energy with the power plant 1 allowing a minor energy interchange between both machines. This will improve the damping of both oscillatory modes since the power plants retain the same damping torque level.

Moreover, in equation (5) it can be seen that the terms $\frac{kk_S}{k+k_S}\delta_s$ and $\frac{kk_S}{k+k_S+G}\delta_m$ are preserved or decreased by increasing the gain G, while the oscillating power of the wind turbine increases proportional to δ_m. It can be concluded that there will be an increase in the damping of the common mode, since the participation of the wind turbine is increased. This will enhance the participation of the wind farm in the oscillations of power plants 1 and 2 against the rest of the power system. Also, it is important to observe that the term decreases with an increment of the gain G, decoupling the oscillatory link between the two power plants.

The implementation of this PSS will improve the damping of the common and interarea modes simultaneously, since the wind farm will inject the necessary oscillating power in phase with the power plant 2, but decoupling the speed rotation of the wind generators respect of the grid frequency imposed by the synchronous generators.

V. PSS Design

The PSS was designed according to the following criteria:

1. The oscillating power contribution of the wind farm should be $G(\delta_m - \delta_2)$ at the point of interconnection of the power plant 2. For this reason, it shall be necessary to implement phase compensation due to the phase shifts inherents to the active power control loop. The compensation will be made at the frequency of the common mode, which is dominant in the dynamics of this subsystem.
2. The reference signal P_2 is a remote signal. Taking this in account, the inherent delay in the transmission and processing of this signal by the PMU should be contemplated.
3. The gain G must be adjusted to achieve an acceptable damping for both oscillation modes and simultaneously ensure an acceptable output power oscillation from the wind farm during severe disturbances.

The block diagram of the proposed PSS is illustrated in Figure 3:

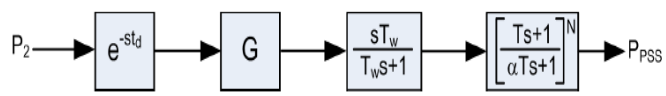

Figure 3: Control structure of PSS

In this diagram it can be identified the following blocks:

- A delay block to model t_d, the necessary time for the PMU to transmit the signal P_2 [4].
- The gain block G.
- A high pass filter which eliminates the influence of PSS in steady state, allowing its operation to higher frequency components of a particular design value.
- The compensator block, should be adjusted in a way that the output power of the wind farm P_{WTG} is in phase with the reference power P_2 at the common mode frequency. Fulfilling this condition will allow the operation of the PSS according to the description above, since the dynamic behavior is dominated by the common mode. For the purpose of carrying out the calculations, this frequency is referred to as ω_i.

The compensator is designed according to the classical control criteria [3]. By knowing the phase difference between P_2 and P_{WTG} power, which will be referred as θ_{PSS}, calculation of the parameters N, T and α will be according to equations (7) and (8):

$$
\begin{aligned}
&\theta_{PSS} \le 60^\circ \rightarrow N = 1 \\
&\theta_{PSS} \le 120^\circ \rightarrow N = 2 \\
&120^\circ < \theta_{PSS} \le 180^\circ \rightarrow N = 3
\end{aligned} \quad (7)
$$

$$
\alpha = \frac{1 - sen\left(\frac{\theta_{PSS}}{N}\right)}{1 + sen\left(\frac{\theta_{PSS}}{N}\right)} \quad (8)
$$

$$
T = \frac{1}{\omega_i\sqrt{\alpha}}
$$

The phase shift θ_{PSS} was calculated using SSAT [5].

VI. CASE STUDY - 1

The performance of the proposed PSS will be studied for a particular scenario of the Uruguayan power grid, corresponding to the maximum demand of 2017, which assumes that wind farms Palmatir and Agua Leguas are operative. For the purposes of the study, the hydro power plant Baygorria and Terra will respectively be power plant 1 and 2. The common mode in this case is named RN and interarea mode is named BY-T. To evaluate the effect of the incorporation of wind farms near Terra and Baygorria, particularly considering the effect of the inclusion of PSS, modal analysis was done to assess the evolution of the eigenvalues for RN and BY-T. In addition, the transient behavior of hydro power plants has been studied in order to validate the modal analysis. The event under study is a three-phase short circuit on the line Terra-Young, self-cleared in 100ms. These studies were performed for the scenarios described below:

- **Scenario 1: c**orresponds to the peak demand in 2017 without incorporation of wind power.
- **Scenario 2:** corresponds to peak demand in 2017 with the incorporation of wind farms Palmatir and Agua Leguas, but without incorporating PSS.
- **Scenario 3:** In contrast to the previous scenario, the PSS proposed is incorporated in Palmatir, while Agua Leguas keeps its standard control.
- **Scenario 4:** In this last scenario, the proposed PSS is included in all wind farms.

The simplified single line diagram for scenarios 3 and 4 are depicted in figures 4 and 5 respectively. The PSS parameters can be found in Appendix A.

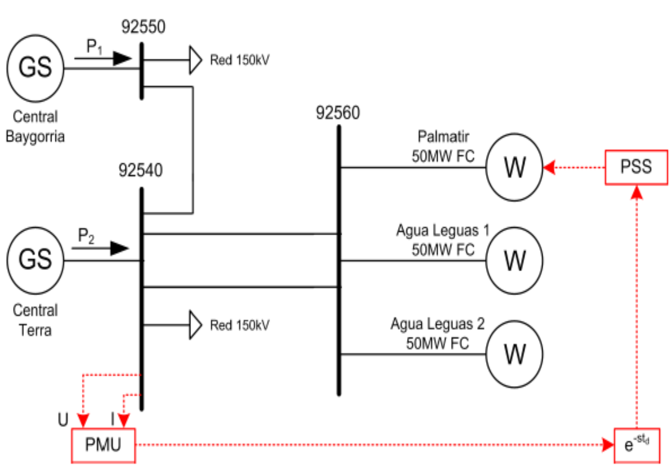

Figure 4: Case study with PSS included in Palmatir

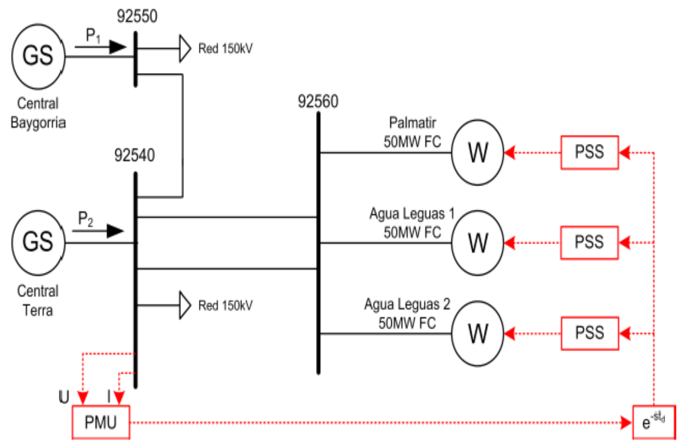

Figure 5: Case study with PSS included in Palmatir and Agua Leguas

A. *Modal analysis*

Table 1 shows the evolution of oscillatory modes and BY-T and RN for the scenarios referred.

Escenario	1		2		3		4	
Modo	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
RN	1.17	9.86	1.17	8.61	1.15	**12.36**	1.10	**25.22**
BY-T	1.30	8.02	1.29	8.73	1.29	**11.65**	1.25	**13.28**

Table 1: Evolution of oscillatory modes

In reference to scenario 1, the scenario 2 shows a degradation of RN damping, which dominantes the response, and an increase of BY-T damping. This performance was reported in [1]. With the incorporation of the proposed PSS, according to scenarios 3 and 4, a simultaneous increase of damping of the two oscillatory modes, particularly in RN, may be observed as expected. Also, it can be seen a decrement in the oscillation frequency, denoting a reduction in synchonizing torque of Terra.

In table 2, the participation factors for RN oscillatory mode are showed, for the different scenarios analyzed. From this table, it can be observed that from the scenario 1 to 2, the increased participation of Terra in the oscillatory mode helps to decrease its damping. When including the PSS in wind farms, there is an increase in the participation of Terra, but at the same time, an increase in oscillatory activity of these wind farms that now act as synchronous generators but without adding inertia to the power system. This particularity is the reason behind the observed increase of the damping ratio.

B. *Transient behavior*

A three-phase short-circuit of 100ms in the 150kV line Young-Terra, near the point of interconnection of Terra for scenarios 2, 3 and 4, was simulated in order to study the performance of the PSS included in the last two scenarios. For these scenarios, the evolution of the inner angles of hydroelectric power plants Baygorria and Terra is monitored.

	ESCENARIO			
VARIABLE	1	2	3	4
98551 : BAYGORRIA ω_1	1.00	1.00	1.00	0.34
98552 : BAYGORRIA ω_2	1.00	1.00	1.00	0.34
98553 : BAYGORRIA ω_3	0.72	0.77	0.78	0.31
98541 : TERRA ω_1	0.16	0.34	0.48	1.00
98542 : TERRA ω_2	0.16	0.34	0.48	1.00
98543 : TERRA ω_3	0.16	0.34	0.48	1.00
98544 : TERRA ω_4	0.16	0.34	0.48	1.00
98560 : PALMATIR PSS	-	-	0.30	0.48
98560 : PALMATIR PMU	-	-	0.26	0.38
98561 : AGUA L.1 PSS	-	-	-	0.48
98561 : AGUA L.1 PMU	-	-	-	0.38
98562 : AGUA L.2 PSS	-	-	-	0.48
98562 : AGUA L.2 PMU	-	-	-	0.38
Amortiguamiento (%)	**9.86**	**8.61**	**12.36**	**25.22**
Frecuencia (Hz)	**1.17**	**1.17**	**1.15**	**1.10**

Table 2: Participation factors of oscillatory mode RN

In figures 6-7 it can be seen that there is a significant improvement in the damping of the angle oscillations for both Terra and Baygorria due to the inclusion of the PSS in the active power control loop of Palmatir and Agua Leguas wind farms. In particular, in scenario 4, there is a significant amount of oscillating power injected by the wind farms that helps to improve the settling time.

The active power swing in the wind farms including PSS, is examined in figure 8 for Palmatir wind farm. In Scenario 2 it is shown the non-participation of Palmatir in the power swings due to the no decoupled control strategy of wind farms; on scenario 3 a significant power oscillation in Palmatir it is observed, that helps to improve the damping of Terra and Baygorria presented in figures 6 and 7; finally in scenario 4 the power swings are smaller due to the inclusion of Agua Leguas, which helps Palmatir to damp the oscillation of the hydroelectric power stations.

Particularly, it is interesting to compare the evolution of the power oscillations between power plants Palmatir, Terra and Baygorria to verify the transient behavior of the wind farm. For this purpose, figure 9 plots the evolution of the active power of the power plants for scenario 3. It can be observed that the oscillatory mode RN is dominant in the transient response, where Terra, Palmatir and Baygorria oscillate in phase few milliseconds after the fault has been cleared.

However, it can be seen in more detail in figure 10 that immediately after the fault has been cleared, there are clearly two nonlinear behaviors:

1. It is observed between 1.4s and 1.6s the saturation of active power injection, because the power order requested exceeds the limit established by the power converter. This is a protective measure to conserve the integrity of the power converters and establishes a limit of oscillating power contribution from the wind farm.
2. There is a significant drop in the active power injected from the wind farm immediately after clearing the fault, which oscillates in phase opposition with respect to the power injected by Terra and Baygorria.

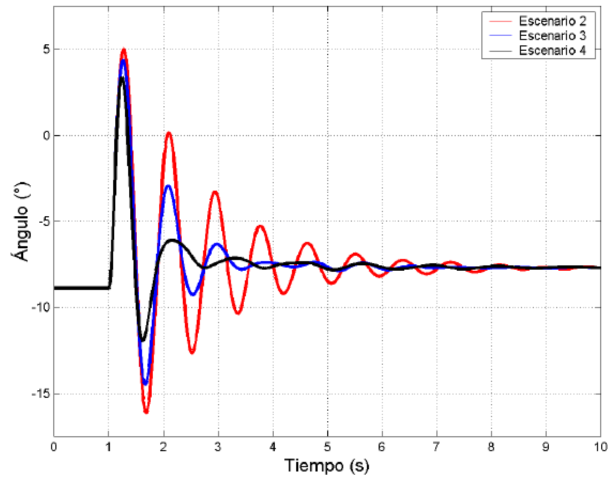

Figure 6: Angle oscillations in Terra

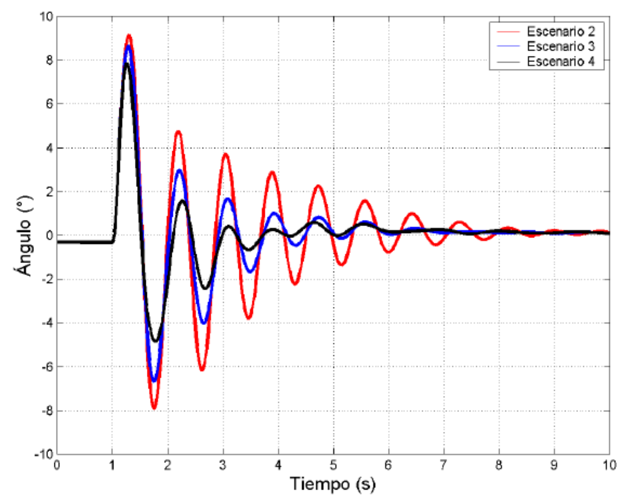

Figure 7: Angle oscillations in Baygorria

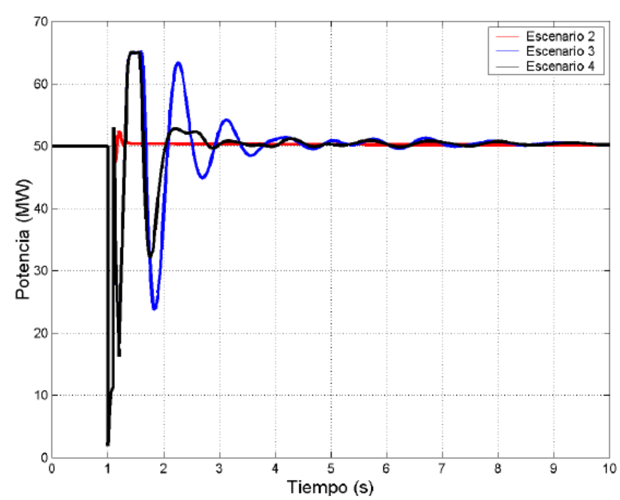

Figure 8: Active power injected by Palmatir

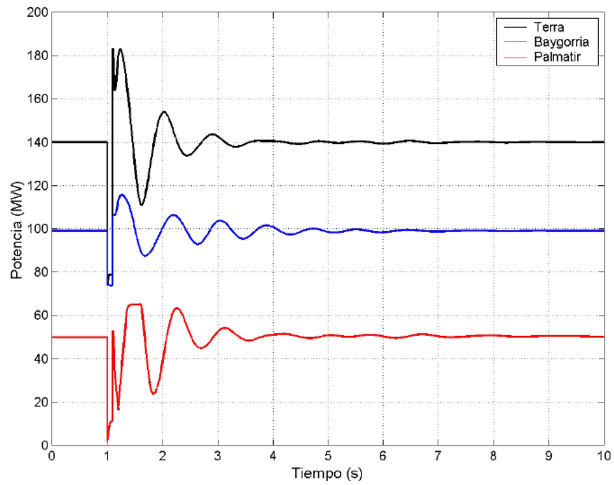

Figure 9: Power oscillations in Terra, Baygorria and Palmatir (scenario 3)

This latter phenomenon may be clearly understood when considering the evolution of active and reactive power injected by the wind farm, as well as the voltage of the wind generators, which are plotted in figure 11.

It can be clearly observed that in the transient response, the wind farm prioritizes the reactive power injection in front of active power injection, in order to contribute to the increase of voltage in the vicinity of the point of interconnection. When the fault is cleared, there will be an overshoot of active and reactive power that not only exceeds the capacity of the grid side converter, but also it will cause a voltage spike that would be inadmissible. This behavior is due to the fact that the wind park adjusts the injected active and reactive power set points, in order to assist the voltage to return to an acceptable value as soon as possible. This behavior is reasonable, and due to the fact that the wind turbine generators act as current sources [2].

Therefore, although it has been previously observed that the PSS is effective in the case of the occurrence of a severe disturbance due to the priority of reactive power injection, the PSS will act as soon as the voltage acquires an acceptable value and do not restricts the injection of active power. This is consistent when looking at the Terra and Baygorria angle oscillations in figures 6 and 7: they do not begin to exhibit a substantial improvement in the damping before 1.2 seconds, when the voltage is stabilized and the restrictions of active power injection are released.

VII. Case Study - 2

As was reported in [1]; the reactive power consumption by the wind farms in the described system will improve the synchronizing torque that is slightly reduced due to the incorporation of the PSS, as was stated before. Taking this into account, similar studies have been performed in slightly different scenarios, in order to analyze this improvement of the synchronizing torque:

- **Scenario 5:** This scenario is similar to scenario 3, except that wind farms Palmatir and Agua Leguas absorbs reactive power, fulfilling a power factor set-point of 0.95.

- **Scenario 6:** This scenario is similar to scenario 4, except that wind farms Palmatir and Agua Leguas absorbs reactive power, fulfilling a power factor set-point of 0.95.

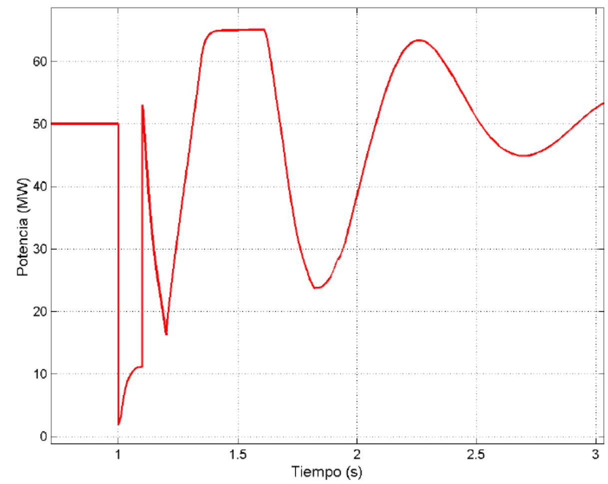

Figure 10: Power oscillations details in Palmatir (scenario 3)

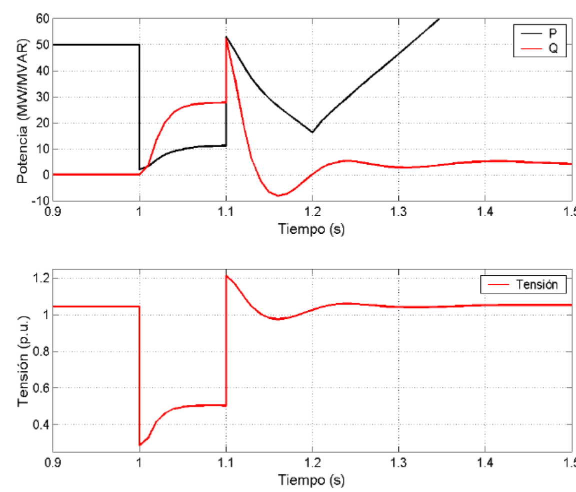

Figure 11: Active, reactive power and voltage in Palmatir (scenario 3)

A. *Modal analysis*

Table 3 shows the evolution of oscillatory modes and BY-T and RN for the scenarios 3, 4, 5 and 6.

Escenario	3		4		5		6	
Modo	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
RN	1.15	12.36	1.10	25.22	1.17	11.86	1.20	23.42
BY-T	1.29	11.65	1.25	13.28	1.35	11.49	1.23	16.51

Table 3: Evolution of oscillatory modes

Comparing scenarios 3 and 4 with scenarios 5 and 6 respectively, the most important finding is that there is a slight degradation of the damping of RN, but a significant increase in the frequency, and thus in the synchronizing torque. This implies that in the transient response, it should be noted an improvement in the angle response when a severe disturbance occurs, as it is reported in the next section.

B. Transient behavior

In figures 12 and 13 it is observed the angle response of Terra and Baygorria for scenarios 3 and 5. In figure 14 it is observed the active power injection of the wind farm for both scenarios.

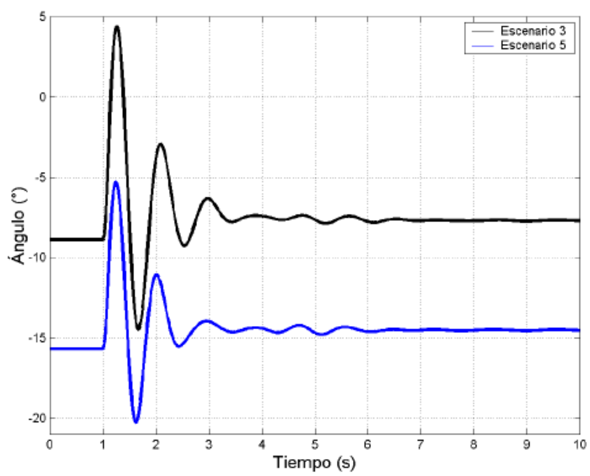

Figure 12: Angle oscillations in Terra

From these figures it can be seen that there is a noticeable improvement in the synchronizing torque and damping in Terra, which can be observable in the decrease of the peak to peak oscillation of angle response. At the same time, it can be seen that the oscillations are less damped in Baygorria in scenario 5, although this decrease is slight, in accordance with the modal analysis previously presented. In addition, it is important to note that thanks to the improvement in the synchronizing torque in Terra, the power oscillations in Palmatir are better damped.

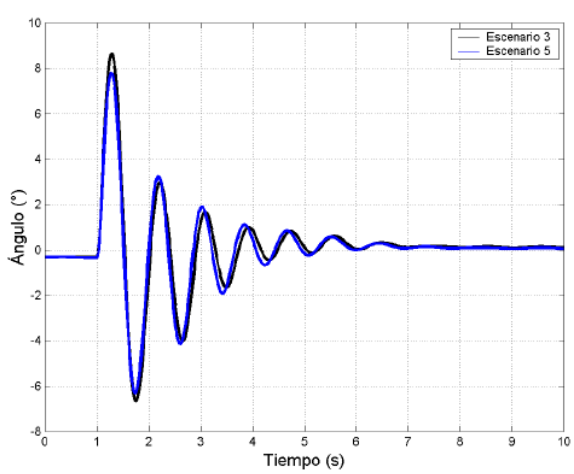

Figure 13: Angle oscillations in Baygorria

Finally, in figures 15 and 16 it is observed the angle response of Terra and Baygorria for scenarios 4 and 6. Figure 17 shows the active power injection of the wind farm for both scenarios. The tendency is the same as observed in the transient performance of scenario 5, except that in this case, there are no important differences in the power injected by Palmatir, since the PSS is included in the three wind farms, and thus, the reactive power consumption by themselves it is not as important for damping the active power oscillations of the wind farms.

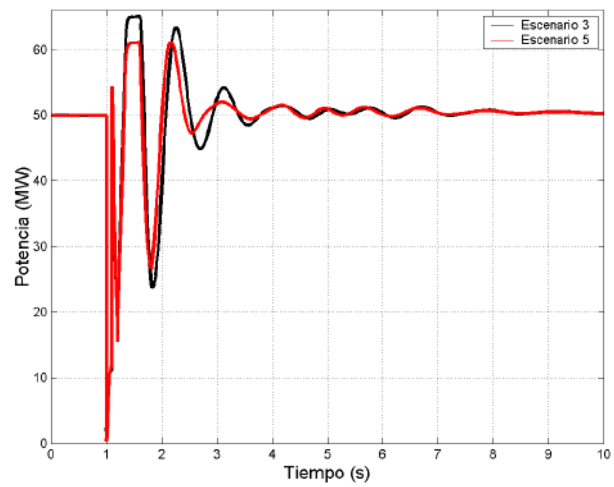

Figure 14: Active power injection by Palmatir

VIII. CONCLUSIONS

This paper proposes the design of a wind farm PSS that, in some sense, mimics the oscillatory behavior of synchronous generators and allows dampening the transient oscillations in the system. Effectively, from the studies performed, it is possible to conclude that the inclusion of PSS in wind farms can substantially improve the damping of the two oscillatory modes that characterize the dynamics of synchronous generators. This was theoretically analyzed and simulated in the context of a particular portion of the Uruguayan power grid. When the proposed PSS is modeled in the wind farms it is possible to increase the damping of the common mode (RN) from 9% to 25% and the damping of the interarea can be increased from 8% to about 13%. This improvement was also observed in the transient response of these generators during and after short circuits, where the PSS starts working when the fault is cleared, prioritizing reactive power injection in order to control the voltage sag at the interconnection point. Since the inclusion of PSS decreases slightly the synchronizing torque in the common mode, an operating restriction on wind farms was analyzed: they also must absorb reactive power in order to induce an increase in synchronizing torque of the hydroelectr1ic power generators [1]. This synchronizing torque boost has the advantage that dampens the oscillations of power injected by the wind farms, reducing the mechanical stresses suffered by the wind turbine generators.

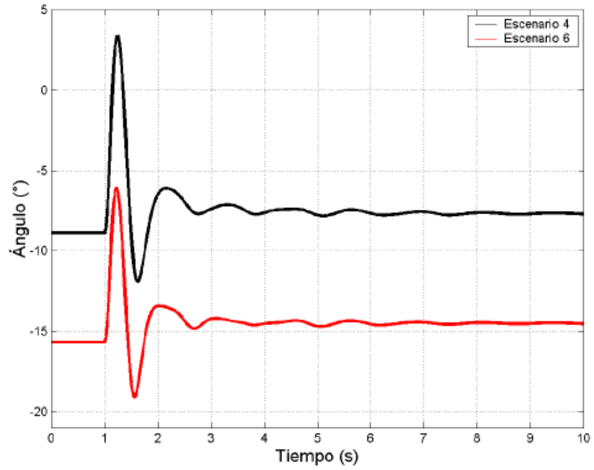

Figure 15: Angle oscillations in Terra

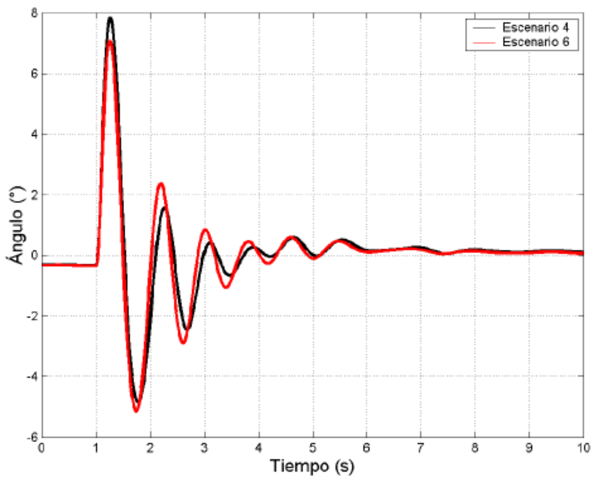

Figure 16: Angle oscillations in Baygorria

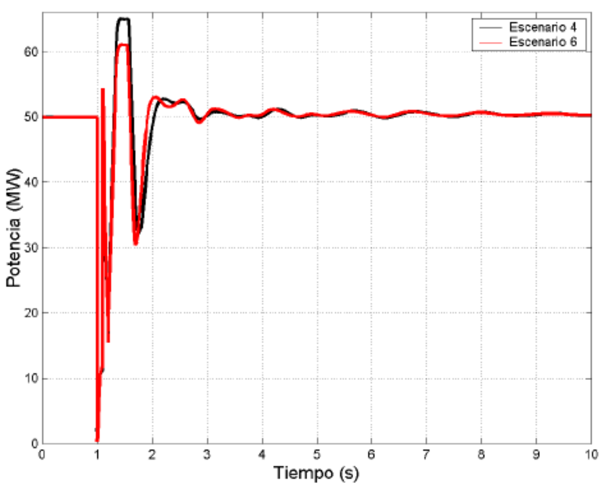

Figure 17: Active power injection by Palmatir

IX. APPENDIX: PSS DESIGN PARAMETERS

t_d = 100ms; G = 5; T_W = 10s; T = 0.0592s; α = 5.25; N = 1.

X. REFERENCES

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